UNIVERSITY OF CALIFORNIA
SANTA CRUZ

Biodiversity, Biogeography, and Conservation of Freshwater Fishes in Gabon

A dissertation submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

ECOLOGY AND EVOLUTIONARY BIOLOGY

By

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September 2019

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Abstract

Biodiversity, Biogeography, and Conservation of Freshwater Fishes in Gabon

Joseph S. Cutler

Freshwater ecosystems cover less than 0.01% of Earth's surface but are home to nearly one-quarter of all vertebrate diversity. Much of this diversity is concentrated in large tropical rivers, including the Amazon (961 species), Mekong (309 species), Congo (375 species), and the Ogooué River in Gabon (351 species), but these large rivers are threatened by proposed dam development. Globally, freshwater ecosystems are highly threatened and 36% of freshwater fishes are considered endangered, but efforts to protect freshwaters are poorly developed.

With over 400 species of fresh and brackish water fishes, Gabon, represents a freshwater biodiversity hotspot. But Gabon's freshwater species are threatened by proposed dam development including a total of 38 potential hydropower dam sites across the country, and 28 in the Ogooué watershed. We know comparatively little about the biodiversity and biogeography in Gabon's freshwater ecosystems, so I have used a combination of field work, taxonomy, and modeling to determine the distribution of freshwater biodiversity in Gabon. We developed a novel application of MaxEnt Modelling and a new metric, species pseudorichness index, to assess the impacts of proposed dam development and provide clear guidance for freshwater conservation in Gabon.

Acknowledgements

I would like to thank my dissertation committee D. Croll, B. Tershy, E. Palkovacs, G. Bernardi and B. Sidlauskas for critical review and comments on the included manuscripts. I thank The Nature Conservancy, particularly Colin Apse, and National Geographic for financing portions of the field sampling associated with my thesis. Thanks to Gabon's CENAREST (Centre National de la Recherche Scientifique et Technologiques) and ANPN (Agence National des Parcs Nationaux) who have been excellent collaborators and mentors throughout my thesis and have facilitated the research permits and authorizations required to carry out fieldwork and export specimens. In particular, I would like to acknowledge Lee White, Jean-Daniel Mbega, Jean-Herve Mvé Beh, Hans Kevin Mipounga, Marie-Louise Yedi, Edouard Nzengue and Franck Nzigou for their long-term support of freshwater research in Gabon. I would also like to thank the ichthyological community including Melanie Stiassny, Carl Hopkins, Jouke Van der Zee, Paul Skelton, John Sullivan, and Sebastien Lavoue, who contributed to this effort through their collaborative taxonomic guidance. I would like to express my sincere gratitude to local authorities and community leaders in Cameroon and Gabon for their welcome, and support. The text of this dissertation includes reprints of the following previously published material: Mipounga H.K., Cutler J., Mve-Beh J. H., and Sidlauslas B.L. (2019) *Enteromius pinnimaculatus* (Cypriniformes: Cyprinidae), a new species from southern Gabon. Journal of Fish Biology. DOI: 10.1111/jfb.13995. The co-authors listed in this publication have given their approval for the material to be used.

Introduction

Freshwater ecosystems cover less than 0.01% of Earth's surface but are home to approximately 40% percent of the world's fish biodiversity. Much of this diversity is concentrated in large tropical rivers, including the Amazon (961 species), Mekong (309 species), Congo (375 species), and the Ogooué River in Gabon (351 species). Freshwater ecosystems are among the most threatened in the world and 36% of freshwater fishes that have been evaluated qualify as endangered by the IUCN. Human development, in particular dam construction, has changed the morphology, hydrology, and functioning of many freshwater ecosystems which has influenced the structure and dynamics of biological communities and ecosystem services. But the impacts of dam development on diverse tropical river systems remain poorly understood. In the central African nation of Gabon, a total of 38 potential hydropower dam sites have been identified, including 28 in the Ogooué watershed. Gabon's Ogooué River harbors at least 350 species of fish and is the 4th largest river in Africa by discharge (following the Congo, Niger, and Zambezi). The Ogooué flows for 1,200 km and drains roughly 75% of the country of Gabon, but with a rural density of <5 inhabitant/km2 and only one dam in the watershed, the Ogooué is considered one of the world's most pristine large tropical rivers (Braun et al. 2017). Proposed dams and their reservoirs will increase Gabon's energy production but threaten to fragment and alter several major free-flowing rivers. In view of these challenges, I focused my PhD thesis on assessing patterns of biodiversity and biogeography in Gabon’s freshwater ecosystems and the threats associated with proposed hydropower development.

In Chapter 1, my colleagues and I describe a new species of cyprinid fish, *Enteromius pinnimaculatus*, from Southern Gabon. This species is clearly distinguished from all other congeneric species by the combination of 3-4 spots on the flanks, multiple dark spots on the dorsal fin and relatively short barbels. Despite extensive collections in the Louetsi, Ngounie, and Nyanga drainages, *E. pinnimaculatus* is known from only two localities, suggesting the importance of its conservation. We therefore assessed this species with IUCN (2001) Red List criteria, and recommend that the species be classified as Vulnerable, because it is known from fewer than five localities. Given proposed dam development in the region, the species at substantial risk of becoming endangered due to modifications to its habitat.

Chapter 2 focuses on describing the fish diversity in the Rapides de Mboungou Badouma et de Doume Ramsar site. The Government of Gabon declared the Rapids of Mboungou Badouma and Doumé Ramsar site in 2005 to protect part of the Ogooué river. This Ramsar site encompasses the mainstem Ogooué between Lastoursville and Moanda, stretches for 140 km and extends 2 km in both directions from the Ogooué, covering a total of 59,500 ha of river and riparian habitat. The Rapids of Mboungou-Badouma and Doumé Ramsar site has been very poorly sampled for fishes in comparison to other regions of the Ogooué basin. Therefore, we conducted a sampling expedition into the region in 2014. My colleagues and I surveyed 31 sites and collected 2,634 fish specimens representing 97 species, 18 families and 9 orders. The new genus and species *Cryptomyrus ogoouensis* was described from specimens collected on this expedition, as was *Paramormyrops ntotom*. Seven other species in the collection are potentially new to science. These include three undescribed *Paramormyrops*, two species of *Plataplochilus*, an enigmatic alestid species tentatively assigned to *Phenacogrammus*, and a dwarf *Enteromius* that is either a new species or an aberrant color morph of *Enteromius jae*. We provide point localities, descriptions of the species collected and high-quality color photographs of each species. We discuss threats to the Rapides de Mboungou-Badouma et de Doumé Ramsar site, including overexploitation, invasive species, habitat destruction and pollution.

Chapter 3 focuses on assessing the distribution of freshwater habitat suitability across Gabon and assessing the potential impacts of 39 proposed dams on fish diversity. We developed a novel multiple-species MaxEnt distribution modeling approach to assess habitat suitability for multiple fish species at the landscape level and demonstrate its utility in identifying proposed dam sites in Gabon that fall in areas of high habitat suitability. We predicted habitat suitability for 113 of Gabon's fresh and brackish water fish species based on presence data linked to ecological data and overlaid the resulting maps to assess overall habitat suitability for freshwater fishes across Gabon. Model performance at the species level was good, with a mean AUC = 0.85 (min. 0.75, max., 0.98). Highly suitable habitats (pR >39) identified using this method lie in every coastal watershed, the Nyanga drainage, and throughout the Ogooué system, including its major tributaries the Ivindo and

Ngounie. Biodiversity appears elevated near the coast and in main river channels but reduced in smaller streams and the high elevation areas in central Gabon. Of the 39 potential dam sites, 32 are sited in areas of high habitat suitability, implying that planned hydroelectric development in Gabon may disproportionately impact high biodiversity areas. This approach is rapid, cost-effective, open-source and transferable to other areas of the world with limited biogeographic information and can help identify and mitigate negative impacts on freshwater ecosystems.

In Chapter 4, we use maximum entropy predictive occupancy modeling to predict the distribution of marine-associate fishes in Gabon's freshwater ecosystems. Many of Gabon's most culturally and economically important fish species move between marine or brackish ecosystems and freshwater ecosystems including Giant African Threadfin (*Polydactylus quadrifilis*), Snappers (*Lutjanus* sp.), Croakers (*Pseudotolithus* sp.), Sardines (*Ethmalosa fimbriata*), Mullets (*Neochelon* sp.), Tarpon (*Megalops atlanticus*), Tongue sole (*Cynoglossus* sp.) and Stingrays (*Fontitrygon* sp.). These fishes, and the free-flowing rivers they depend upon, may be threatened by proposed hydropower development. But there have been no formal studies of fish movement within Gabon's freshwater ecosystems, therefore assessing the potential impacts of dam development on biodiversity and fisheries is challenging. We present a novel application of MaxEnt predictive occupancy modeling at the guild level, to predict the distribution of marine-associated fishes in Gabon's freshwater ecosystems. Marine-associated fishes are predicted to occur in every coastal watershed and extend at least 400 km into Gabon's Ogooué River and its major tributaries. We conclude that proposed dam development on the Nyanga, the Mbei, the Komo, the Abanga, the Ogooué downstream of the Chutes de Booué, and on the Ngounie downstream of the Chutes de l'Imperatrice would affect marine-associated fish species, their fisheries and local economies.

Chapter 1:

Title: *Enteromius pinnimaculatus* (Cypriniformes: Cyprinidae), a new species from southern Gabon

Published: Journal of Fish Biology May 2019. DOI: 10.1111/jfb.13995

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Abstract

With more than 407 species of freshwater and brackish water fishes, Gabon is a country rich in ichthyological biodiversity, but its aquatic environments remain poorly explored. We present and describe a new species of *Enteromius*, adding to the 16 species of *Enteromius* currently recorded from that country. This new species is distinguished from all other Gabonese *Enteromius* by the presence of several distinct spots on the dorsal fin in combination with three or four round spots on the flanks. In Africa, it is superficially similar to *Enteromius walkeri*, and shares with that species an unusual allometry in which the proportional length of the barbels decreases as the fish grows. Nevertheless, one can distinguish these species by vertebral number, maximum standard length, the length of the anterior barbels, the length of the caudal peduncle, and in most specimens, the number of lateral-line and circumpeduncular scales. These two species also inhabit widely separated drainages, with *E. walkeri* occurring in coastal drainages of Ghana including the Pra and Ankobra Rivers, and the new species occurring in tributaries of the Louetsi and Bibaka rivers of Gabon, which are part of the Ogowe and Nyanga drainages, respectively. Despite extensive collections in those drainages the new species is known from only two localities, suggesting the importance of conservation of its known habitat.

Significance Statement

This contribution recognizes and describes a new species of *Enteromius* from just two locations in southern Gabon, one of which is in proximity to a planned hydroelectric dam site. The discovery highlights our incomplete knowledge of the central African fish fauna and underscores the importance of conserving the known habitat of this newly discovered, range restricted and vulnerable animal.

Key Words

Allometry, biodiversity, conservation, Central Africa, morphometrics, Ngounié, systematics

Introduction

The African country of Gabon extends overly nearly 270,000 km^2 and possesses exceptional natural resources (Fermon, 2013). Gabon protects nature in the form of national parks and reserves, but also exploits natural resources through forestry, agriculture, and oil and mineral extraction (Gabon MAEPDR, 2011). Though rich with 407 known fresh and brackish water species (Stiassny *et al.*, 2007; Fermon, 2013), Gabon's fish fauna nevertheless remains poorly inventoried as evidenced by the discovery of many new species over the last twenty years (e.g. *Chromidotilapia mrac* Lamboj 2002, *Aphyosemion etsamense* Sonnenberg & Blum 2005, *Episemion krystallinoron* Sonnenberg *et al.* 2006, *Synodontus woleunensis* Friel & Vigliotta 2006, *Atopodontus adriaensi* Friel & Sullivan, 2008, *S. acanthoperca* Friel & Vigliotta, 2008, *S. punu* Vreven & Milondo 2009 and *Cryptomyrus ogoouensis* Sullivan *et al*., 2018).

Cypriniformes represents about 7% of Gabon's freshwater fish fauna. Its largest family Cyprinidae (30 species in Gabon), represents the third richest family overall, after Nothobranchidae (53 species) and Cichlidae (31 species). After the recent shift of *Raiamas* and *Opsaridium* into Danionidae (Tan & Armbruster, 2018), the remaining cyprinids of Gabon are distributed among three genera: *Labeobarbus*, *Labeo* and *Enteromius*.

Enteromius Cope 1867 was until recently subsumed under *Barbus* Cuvier and Cloquet 1816 (Yang *et al.*, 2015). Revisionary work by Yang et al. (2015), Stiassny & Sakharova (2016), and Hayes & Armbruster (2017) used new genetic tools to clarify the systematics of its containing tribe Smiliogastrini Bleeker, 1863, and assigned the majority of African species to *Enteromius,* with some species placed in *Barboides*, *Barbopsis*, *Caecobarbus*, *Clypeobarbus* and *Pseudobarbus*. Following this revision, *Enteromius* became the most diverse cyprinid genus in Africa with 350 nominal species (Eschmeyer *et al.*, 2018) and 216 valid species (Hayes & Armbruster, 2017). These all possess small or moderate adult body size, a diploid genome, few striations on the scales, 7 or 8 branched rays in the dorsal fin, weakly developed gill rakers, zero, one or two pairs of barbels, and weakly developed lips (De Werdt & Teugels, 2007).

Due to its great diversity, this group of fishes has posed a systematic challenge for decades (Lévêque *et al.*, 1987; Berrebi *et al.*, 1996; Berrebi & Tsigenopoulos, 2003). Nevertheless, those early revisions and more recent work (Lederoun & Vreven, 2016; Stiassny & Sakharova, 2016; Van Ginneken *et al.*, 2017; Schmidt *et al.*, 2018) have permitted the recognition of numerous synonyms among the 350 nominal species.

They have also recognized and described many new species, such as *E. validus* Stiassny *et al.* 2016, *Enteromius vandewallei* Lederoun & Vreven 2016 and *E. walshae* Mamonekene et al. 2018. Such revisions typically depend upon morphological characteristics and coloration for the identification and classification of newly collected specimens (Lévéque *et al.*, 1990; Stiassny *et al.*, 2007). This work continues along a similar perspective, and adds to the 16 *Enteromius* species known currently from Gabon (Mbega, 2004; Stiassny *et al.*, 2007).

Among the specimens collected during an inventory of the Louetsi River (Ngounie subdrainage of the Ogowe) of southern Gabon in April and May of 2017, before the potential construction of a planned hydroelectric dam at or in the vicinity of the Mioki Rapids (les Chutes de Mioki), two specimens of *Enteromius* from near Ndoubi village stood out. These specimens possessed three or four small round spots on the flanks, two pairs of moderately developed barbels, and multiple dark markings on the dorsal fin: a combination of characters otherwise unknown among the *Enteromius* of Gabon. A second sampling expedition at the same site during September 2017 increased the sample size of this important and interesting fish. In November of the same year, the consulting company BIOTOPE completed an inventory of the ichthyofauna and herpetofauna of the Birougou RAMSAR site, approximately 65 kilometers to the east. That mission to the Ngounié and Nyanga watersheds (Mbigou - Malinga sector), collected several individuals in the catchment of the Bissina River, which flows into the Bibaka River (Nyanga drainage), that appeared identical to those collected near the Mioki Rapids (Fig. 1.1). After a suite of morphometric, meristic, geographic and color-based comparisons reported herein, the team concluded that this enigmatic *Enteromius* was undescribed. This contribution demonstrates the evidence and formally describes the species.

Figure 1.1. Live coloration of Enteromius pinnimaculatus sp. nov. Uncatalogued specimen collected in a swampy lowland tributary of the Bissina River, Nyanga River Drainage, Gabon. 2.208614° S, 12.178365° E

Methods

Specimen Collection

Field collections (Figure 1.2) in the Louetsi area were carried out under research permits AR0019/17 and AR0035/17 from MESRSFC/CENAREST/CG/CST/CSAR, while those in the Nyanga (Bissina) drainage were conducted under permit AR0044/17 from MESRSFC/CENAREST/CG/CST/CSAR and AE/17027 from Parcs Gabon. Specimens were collected using dip nets and a Halltech HT-2000 backpack electrofisher. All activities followed Animal Care and Use Protocol (ACUP) 4909, authorized by Oregon State University, with the exception that the BIOTOPE team used eugenol rather than MS-222 as the euthanizing agent. Specimens were euthanized, provisionally identified to species and counted. Some were photographed in an immersion tank following the protocol of Sabaj Perez (2009), and muscle and fin samples were preserved in cryotubes containing 95% ethanol. Samples from the Louetsi were transported to Oregon State University under export permits 12/05/2017/MESRFC/CENAREST/IRAF/LHI and 001/01/2018/MESRS/CENAREST/IRAF/LHI/JDM for laboratory identification.

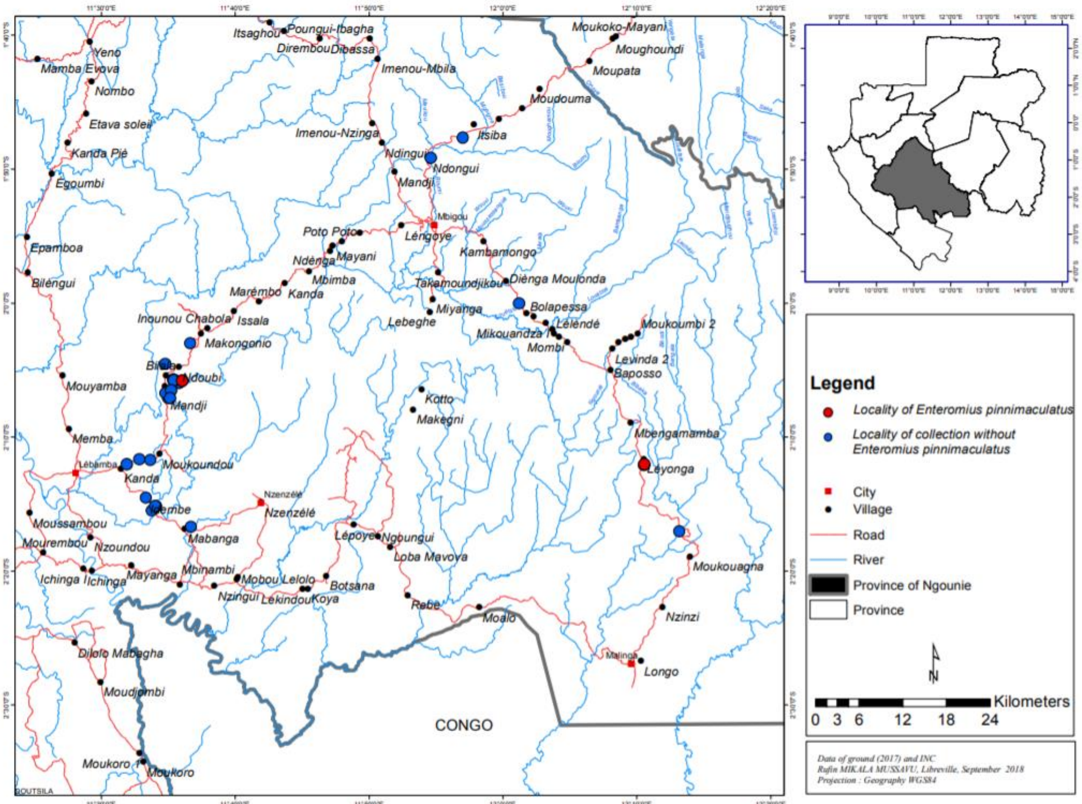

Figure 1.2. Distribution map for Enteromius pinnimaculatus sp. nov., illustrating the Bissina River and Nyanga River drainage with two known collection localities and nearby localities at which comprehensive sampling did not capture this species.

Data Collection

Fourteen morphometrics and nine meristic counts followed the method of Lévêque *et al.* (1987). Total lateral-line scale counts following Lévêque et al. (1987) included all elements in the series, typically including one or two scales posterior to the structural base of the caudal fin. We also report scale lateral line scale counts to the point of caudal flexion, as many recent *Enteromius* descriptions (e.g. Mamonekene et al. 2018) use that version of the count. Transverse scale counts include the middorsal and midventral scales as a half element, which follows most revisionary or synthetic treatments of *Enteromius* (Lévêque *et al.*, 1987; Lévéque *et al.*, 1990; De Werdt & Teugels, 2007), though it is worth noting that Armbruster's (2012) general recommendations for cyprinids omit the half element at the midline. The Weberian Apparatus was counted as four vertebrae, and the terminal compound centrum as a single element. As customary in species descriptions for the genus *Enteromius*, the lengths of the anterior and posterior barbels were codified following Lévêque et al. (1987). These codes are as follows: 1 - the barbel not reaching the anterior border of the eye, 2 - the barbel reaching between the anterior border of the eye and the middle of the eye, 3 - the barbel reaching the posterior half of the eye, 4 - the barbel surpassing the posterior border of the eye. Certain individuals were photographed in an immersion tank following the protocol of Sabaj Perez (2009)

A literature search for *Enteromius* known from West and Central Africa was carried out, beginning with the most comprehensive systematic references for those regions

(Lévéque *et al.*, 1990; Stiassny *et al.*, 2007). The search then expanded to other more recent publications dealing with *Enteromius* in these parts of Africa (Dankwa *et al.*, 1999; Mamonekene & Stiassny, 2012; Munene & Stiassny, 2016; Mamonekene *et al.*, 2018). As much as possible, references dealing with other regions in Africa (Poll, 1967; Eccles, 1992; Skelton, 2001) were consulted as were the online databases Fishbase and Eschmeyer's Catalog of Fishes. The team sent photographs of the putatively new species to other specialists on this genus to inquire whether they had previously encountered the fish. This work determined that the combination of characters present in the specimens from southern Gabon does not match any other known species in Gabon or Central Africa.

The most morphologically similar species appears to be *Enteromius walkeri* (Boulenger, 1904), a species that occurs only in coastal rivers in Ghana. (Fig. 1.3). These species share possession of multiple black spots on the flanks, many spots on the dorsal fin, pigmentation associated with the anterior lateral-line pores, and two pairs of barbels (Boulenger, 1904; Lévêque *et al.*, 1987; Lévéque *et al.*, 1990; Dankwa *et al.*, 1999). These appear to be the only two *Enteromius* species that possess this combination of characters, and indeed the only two with more than one dark spot on the dorsal fin. The California Academy of Sciences (CAS) and the University of Michigan (UMMZ) loaned specimens of *Enteromius walkeri* for examination. Two co-occurring and phenetically similar *Enteromius, E. camptacanthus* (Bleeker, 1863) (Fig. 1.4) and *E. chiumbeensis* (Pellegrin, 1936) (Fig. 1.5) were also included in morphometric and meristic comparisons. The examined specimens of *E. camptacanthus* and *E. chiumbeensis* were captured during the same expedition to the Louetsi that yielded the specimens of the putatively new species and are accessioned and cataloged at Oregon State University (OS). Catalog numbers and full locality details of the examined material can be found at the end of the manuscript. Acronyms follow Sabaj (2016).

Figure 1.3. (a) Adult 58.96 mm standard length (LS) and (b) juvenile, 31.7 mm LS Enteromius walkeri specimens at the University of Michigan Museum of Zoology, Ann Arbor, Michigan (UMMZ 195011).

Figure 1.4. (a) Adult 89.0 mm standard length (LS), tissue voucher GAB17-999, and (b) juvenile 31.5mm LS Enteromius camptacanthus specimens at Oregon State University, Department of Fisheries and Wildlife, Corvallis, Oregon (OS 20935)

Figure 1.5. (a) Adult 55.1 mm standard length (LS), tissue voucher GAB17-282, and (b) juvenile 23.5 mm LS Enteromius chiumbeensis specimens at Oregon State University, Department of Fisheries and Wildlife, Corvallis, Oregon (OS 21879).

Data Analysis

The morphometric characteristics of the potentially new species and three others (*E. camptacanthus*, *E. chuimbeesis* and *E. walker*i) were compiled. Allometric coefficients for each nominal species were calculated via standardized major axis regression of the natural log transformed morphometrics versus the natural log of standard length in the SMATR package (Warton *et al.*, 2012) (citation) within the R computing environment (R Core Team, 2018). For tabular comparisons, measurements such as total length, body depth, and head length were expressed as percentages of standard length. Head width and the lengths of other elements of the head were expressed as percentages of head length.

Multivariate statistical analyses were conducted using Past 3 (Hammer *et al.*, 2001). The morphometrics were log10 transformed, and a principal component analysis (PCA) was completed using the variance-covariance matrix. This analysis requires a complete data matrix without missing values. Thus, total length was excluded from PCA due to the presence of several specimens with missing data due to damaged caudal fins. Two other specimens were removed from the multivariate analysis due to damaged dorsal fins. Because the four species differed greatly in the allometry of barbel length (see results), the morphospace could not be size standardized with those measurements included. Size-standardization methods such as Burnaby's projection against the first principal component (Burnaby, 1966), shearing (Humphries *et al.*, 1981), or analysis of the residuals from regression of each measurement against standard length assume that all nominal species share a common allometric coefficient (Klingenberg, 1996; McCoy *et al.*, 2006). Though discarding barbel length from the analysis would permit size-standardization of the remaining characters, the two barbel length measurements were among the most discriminatory variables. As such, we retained barbel length in the multivariate analysis and did not size-standardize the dataset.

A PCA also treated a subset of the meristic data. For this analysis, invariant characteristics (such the number of anal-fin rays) were removed, as were individuals with missing data for any count. These were typically specimens that has lost their circumpeduncular scales, or those for which no radiograph was available. The PCA revealed the lateral-line scale counts to be the most discriminatory variables. Thus, box-plots of those counts in all available specimens visualized those data.

A cleared and stained individual was prepared according the protocol of Taylor and Van Dyke (Taylor & Van Dyke, 1985). Photographs of the cleared and stained specimen were taken under a Zeiss V20 microscope with an Axiocam 105 color. An illustration of the left infraorbital series was prepared from a tracing of such a photograph in Adobe Illustrator. Finally, the GPS data were used to produce a map showing the sites inhabited by the putatively new species, as well as the sites where the teams sampled, but did not collect that species (Fig. 1.2).

Results

Meristic and Morphometric Analysis

Examination of meristic counts indicated that with the exception of one outlier, the putatively new species has fewer scales in the lateral line series (Fig. 1.6) and fewer circumpeduncular scales than *Enteromius walkeri* or either of the most similar species in Gabon. That outlier (OS22150) had 23 total lateral line scales (21 to the point of caudal flexion) and 12 circumpeduncular scales. All other individuals of the putatively new species had 19 or 20 total lateral line scales (18 or 19 to the point of caudal flexion) and 10 circumpeduncular scales.

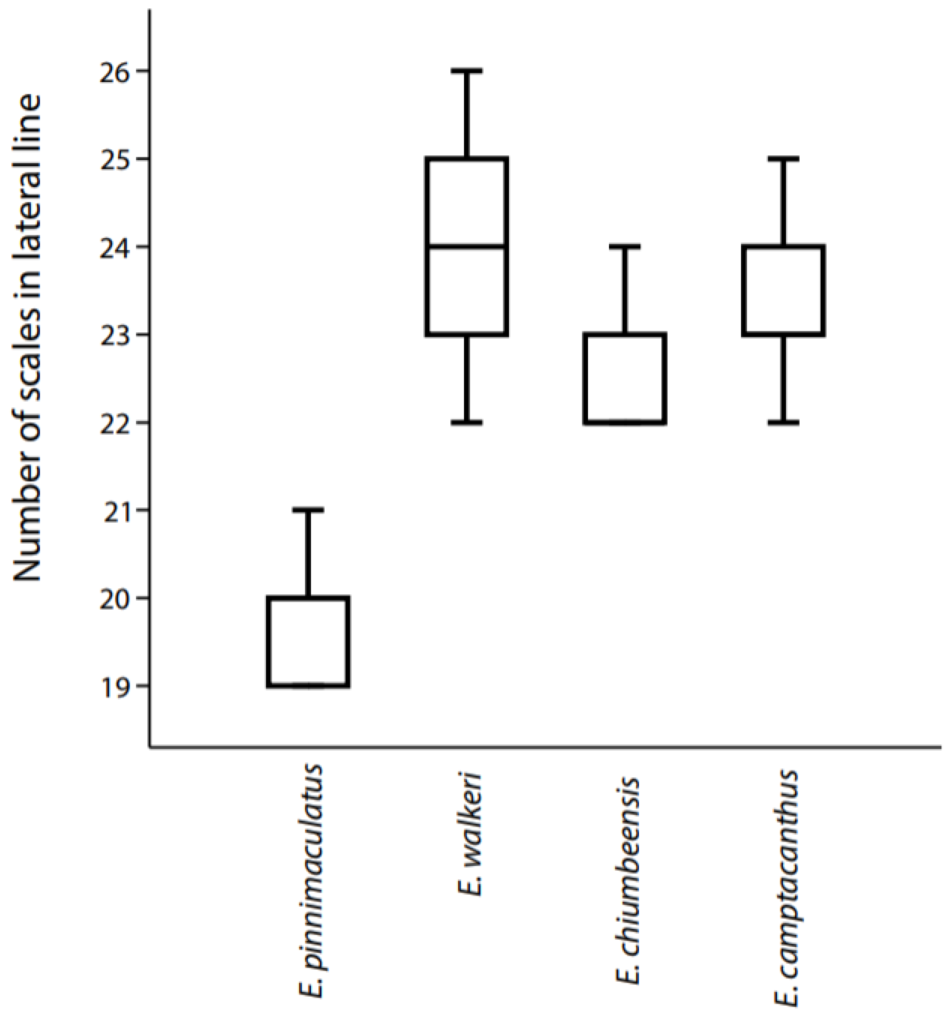

Figure 1.6. Boxplot of (a) lateral line scale counts for four species of Enteromius.

In the meristic PCA, the first axis indexed 71.4% variance and the second indexed 17.9% of the variance. The first axis described primarily the number of scales in the lateral-line, and also correlated positively with the number of circumpeduncular scales. Vertebral counts influenced the second axis most strongly, followed by the number of branched pectoral-fin rays. A scatterplot of these two axes (Fig. 1.7) revealed that all but the aberrant individual of the putatively new species segregated from the other three species on PC1. *Enteromius chiumbeensis* separated completely from the other three species on PC2, indicating a vertebral count of 32 in that species, versus 33 to 35 in the others.

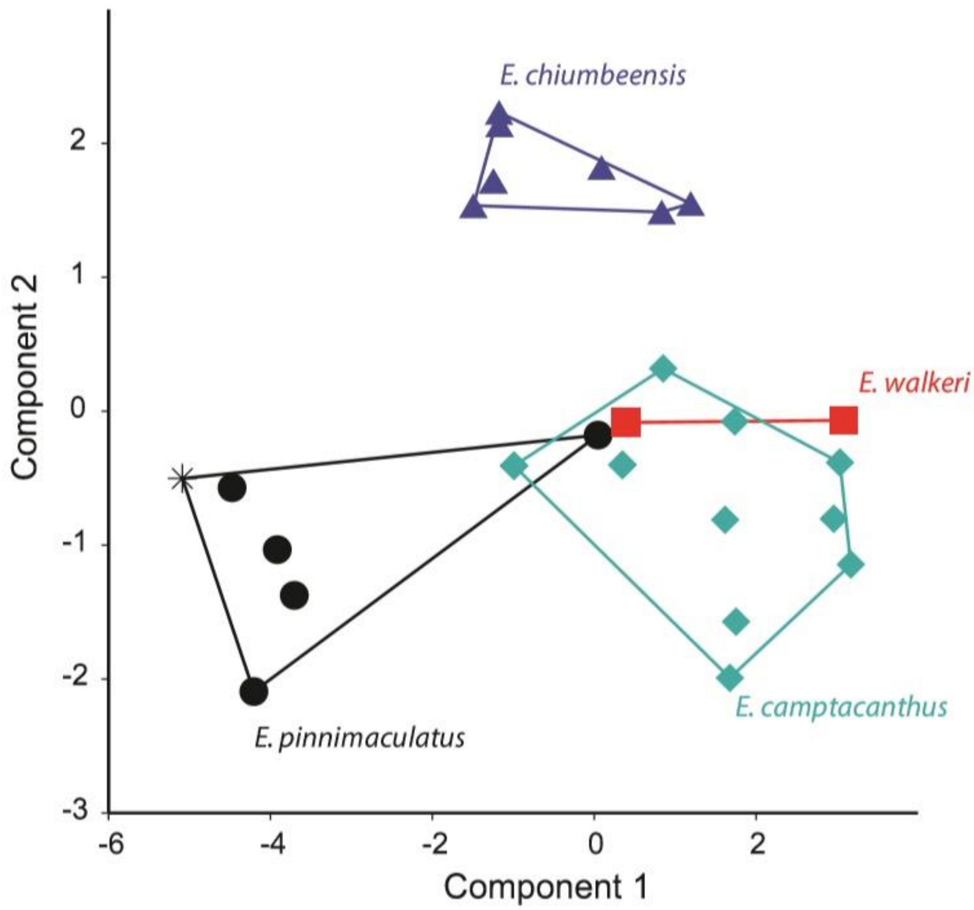

*Figure 1.7. Scatterplots showing results of principal components analysis of meristic data, colour coded by species and with minimum spanning polygons shown. *, The holotype of Enteromius pinnimaculatus sp. nov., which is the largest measured individual of that species. PC1 (71.4% variance) indexes the number of lateral line and circumpeduncular scales, and PC2 (17.9% variance) indexes primarily the number of vertebrae. All examined specimens of Enteromius walkeri have 34 vertebrae and vary little in other counts. Single points represent more than one individual; each species varies very little on the second axis.*

The standardized major axis regressions in SMATR indicated that the four species differ substantially ($p<0.001$) in the allometric trajectories of anterior and posterior barbel length (Fig. 1.8). Taking anterior barbel length as the example, *Enteromius chiumbeensis* and *E. camptacanthus* exhibit strong positive allometry (coefficients of 1.56 and 1.39, respectively) while the putatively new species and *E. walkeri* exhibit weak negative allometry (coefficients of 0.84 and 0.96, respectively). Thus, it was not possible to size-standardize the morphospace without distorting the differences among specimens (see discussion above under methods), and multivariate analyses did not incorporate an allometric correction. As a result, the first axis resulting from the principal components analysis indexes the size of the specimens and summarizes 96.11% of the total variance in the dataset. All variables load positively on this axis, and the largest individuals appear to the right of Figure 1.9

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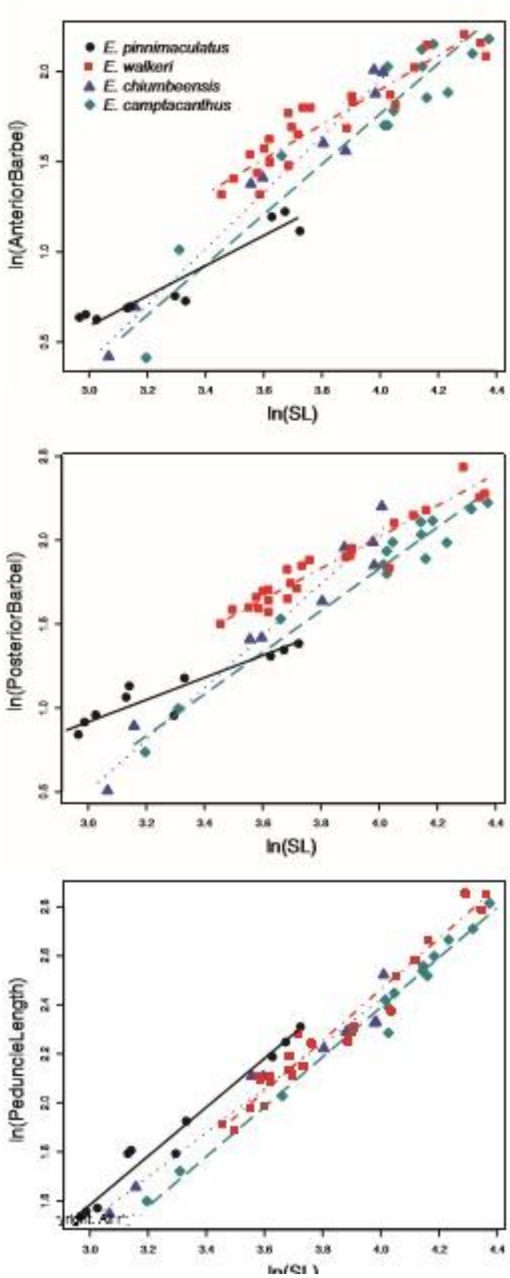

Figure 1.8. Standardized major axis regressions of the natural log of the lengths of the anterior and posterior barbels and the caudal peduncle against the natural log of standard length, color coded by species.

The second component, indexing 1.29% of the total variance (but a third of the variance remaining after excluding PC1), primarily describes the length of the barbels. Both the anterior and posterior barbel length load negatively on this axis, and as such the specimens with the most positive PC2 scores have the proportionally smallest barbels. A plot of PC2 versus PC1 (Fig. 1.9, lower panel) highlights the difference between the positive barbel allometry of *Enteromius camptacanthus* and *E. chiumbeensis* on one hand, and the negative barbel allometry of Enteromius *walkeri* and the potentially new species on the other. In other words, in the two species with hyaline dorsal fins, the proportional length of the barbels increases as the fish grows, while the reverse is true in the species with spotted dorsal fins.

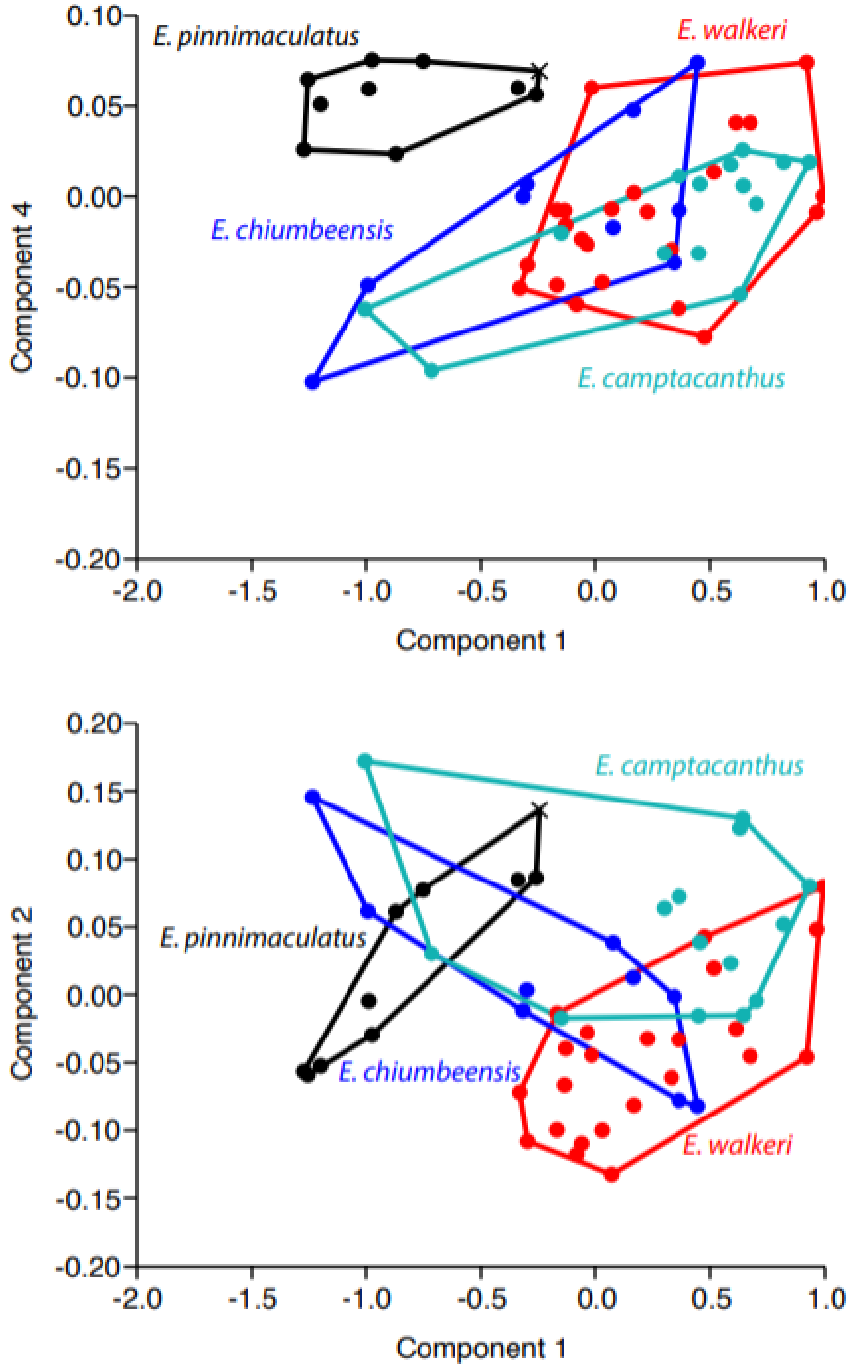

*Figure 1.9. Scatterplots showing results of principal components analysis of (a) length of the barbels (PC2, 1.26%) and (b) length of the caudal peduncle (PC4, 0.50%) against standard length of specimen (PC1, 96.11, colour coded by species and with minimum spanning polygons shown.*The holotype of Enteromius pinnimaculatus sp. nov., which is the largest measured individual of that species.*

Despite indexing relatively small percentages of the overall variance in the dataset, two additional axes contain interpretable information. The most important measurement on PC3 (0.66% of variance) is interorbital width, but this axis does not discriminate any groups and is not shown graphically. PC4 (0.50% of variance) primarily indexes the length of the caudal peduncle, which loads positively on this axis. A plot of PC4 versus PC1 (Fig. 1.9, upper panel) readily distinguishes the putatively new species from Gabon from the other three, as do univariate regressions of caudal peduncle length against standard length (Fig. 1.8, lower panel). These results indicate that the potentially new species can be separated morphometrically by a 3% proportionately longer caudal peduncle relative to similarly sized specimens of the other examined species. Based on these and several other discriminatory species, a formal taxonomic description of the new species appears below.

***Enteromius pinnimaculatus* sp. nov.**

Figure 1.20. (a) Adult Enteromius pinnimaculatus sp. nov. holotype, tissue voucher GAB17-486, 41.4 mm standard length (LS), Oregon State University, Department of Fisheries and Wildlife, Corvallis, Oregon specimen OS22149, (b) adult paratype, 37.6 mm LS (OS22153) and (c) juvenile paratype, 27.0 mm LS (OS22152) prior to clearing and staining.

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Figures 1.1, 1.10, 1.11, 1.12 and 1.13.

Holotype

OS 22149 (1 specimen, tissue voucher GAB17-486, 41.05 mm SL), Gabon, Province de la Ngounié, small swampy right bank affluent of the Louetsi River upstream from the Chutes de Mioki, 2.09669° S, 11.60085° E, collected April 30, 2017 by Hans Kevin Mipounga and Jean Hervé Mve Beh.

Paratypes

Thirteen specimens, same locality as holotype: OS21870, 1 specimen, 17.4 mm SL; OS21889, 1 specimen, 18.97 mm SL; OS 22150, 1 specimen, (tissue voucher GAB17-250), 39.94 mm SL; OS 22151, 3 specimens, 19.42-20.79 mm SL, collected September 3, 2017; OS 22152, 26.98 mm SL (cleared & stained female, CT scan Gabon 4T), collected with OS 22151. OS 22153, 38.27 mm SL, collected with OS 22151; OS 22154, 1 specimen, (tissue voucher GAB17-1378), 15.0 mm SL, fixed directly in 95% ethanol, collected with OS 2215; OS 22155, 1 specimen, (tissue voucher GAB17-1379), 17.0 mm SL, fixed directly in 95% ethanol, collected with OS 22151. CAS 245836, 1 specimen, 22.89 mm SL, out of OS 22151; MRAC 2018-030-P-0001, 1 specimen, 28.20 mm SL, out of OS 22151; UMMZ 251024, 1 specimen, 22.98 mm SL, out of OS 22151.

Non-type material

These specimens were collected by the separate expedition to the Bissina River (Nyanga drainage). Because they were placed directly in alcohol after euthanasia, they have experienced shrinkage and cannot be included in morphometric comparisons. Though they appear to be conspecific with the specimens from the Louetsi, they occur in an adjacent drainage that flows into the Nyanga River, not into the Ngounie and then the Ogowe. They are therefore excluded from the paratype series.

OS uncatalogued, (3 specimens, preserved directly in 90% ethanol), Gabon, Province de la Ngounié, swampy lowland stream in the Bissina River watershed, Nyanga River drainage. 2.20861°S, 12.17837°E. Collected November 11, 2017 by Benjamin Adam.

Differential Diagnosis

A series of three or four dark spots along the flanks and a dorsal fin with multiple dark spots separates *Enteromius pinnimaculatus* from all other known species of *Enteromius* except *E. walkeri*. Nevertheless, *E. pinnimaculatus* sometimes has one or more spots on the anal fin and lacks the dark spot immediately ventral to the dorsal-fin origin, while *Enteromius walkeri* lacks pigmentation on the anal fin and has an additional dark spot ventral to the dorsal fin origin. Larger *E. pinnimaculatus* have noticeable pigmentation along the dorsal and ventral margins of most scale rows (Fig 10A and 10B), while adult *Enteromius walkeri* have two narrow bands of dark pigmentation dorsal and ventral to the lateral-line scale series on the anterior part of the body (Fig. 1.3A), but much less pronounced pigmentation at the intersection of other scale rows. The two species separate on the number of branched pectoral fin rays (11-12 in *E. pinnimaculatus* versus 13-14 in *E. walkeri*) and the number of unbranched dorsal fin rays (iii in *E. pinnimaculatus* versus iv in *E. walkeri*), though the extra element at the anterior of the dorsal fin in *E. walkeri* is minute and only observed on radiographs. With the exception of developmentally aberrant individuals, specimens of *Enteromius pinnimaculatus* have 33 vertebrae, while specimens of *E. walkeri* have 34. *Enteromius pinnimaculatus* differs modally from *E. walkeri* in the number of total lateral line scales (mode 20 versus mode 24), the number of lateral line scales to the point of caudal flexion (mode 18 versus mode 22), the number of circumpeduncular scales (mode 10 versus mode 12), and the number of branched dorsal-fin rays (mode 7 verus mode 8). *Enteromius pinnimaculatus* reaches only half the maximum body size (41.4 mm SL) of E. *walkeri* (78.5 mm SL). *Enteromius pinnimaculatus* has smaller pectoral fins (20.4 ± 1.2% SL) than *Enteromius walkeri* (24.3 ± 1.3% SL) as well as shorter anterior barbels (32.5 ± 3.0% HL vs. 43.7 ± 4.5% HL), with the difference in barbel length very pronounced in individuals of similar size (Fig. 1.8). *Enteromius pinnimaculatus* also has, on average, a shallower body depth (28.0 ± 0.9% SL) than E. *walkeri* (30.0 ± 1.1% SL) and a longer caudal peduncle (24.3 ± 1.2% SL vs. 21.4 ± 1.3% SL).

Description

Relatively small species, maximum known standard length of 41.4 mm. Greatest body depth immediately anterior to dorsal-fin origin. Dorsal body profile convex anterior to dorsal fin and concave and slightly depressed immediately posterior to dorsal fin, then straight from that point to dorsal procurrent rays of caudal fin. Dorsal-fin origin positioned slightly in advance of midpoint between the snout and the base of the caudal fin, just barely anterior to the pelvic-fin origin. Anus situated one scale width anterior to anal-fin origin, and just posterior to tip of adpressed pelvic fin. Pelvic fins abdominal. Pectoral fin origin low on body, at horizontal through ventral procurrent rays of caudal fin and one scale's height ventral to lateral-line scale row. Three branchiostegal rays, with most of their margin free of the isthmus, but joined to isthmus at ventral midline. Mouth moderately sized and terminal, with posterior margin of maxilla at vertical through anterior margin of eye. Two pairs of moderately developed barbels. Posterior barbels extend beyond posterior margin of eye (27.1 – 35.6% SL, code 4 of Lévêque et al. 1987) and anterior barbels reach or exceed midpoint of eye (35.7 – 50.4% HL, code 2). Smallest specimens possessing proportionately longest barbels. Head and eye proportionately larger in smaller individuals. Eye diameter 27.2 – 38.9% of head length.

In cleared and stained specimen (OS22152) cranial fontanelle entirely closed, with sinuous medial suture between contralateral frontals and parietals. Infraorbital series broad and platelike, with clear flanges flanking sensory canal (Fig. 1.11). Two sensory pores on first infraorbital, one pore on second infraorbital, three pores on third infraorbital, one pore on fourth infraorbital, and none on fifth infraorbital (Fig.

1.11). Five triangular gill rakers on lateral ceratobranchial. Pharyngeal teeth in three rows, with five teeth in medial row, three teeth in central row, and one or two teeth in lateral row (contralateral sides of the cleared and stained specimen differ in the tooth count on this third row).

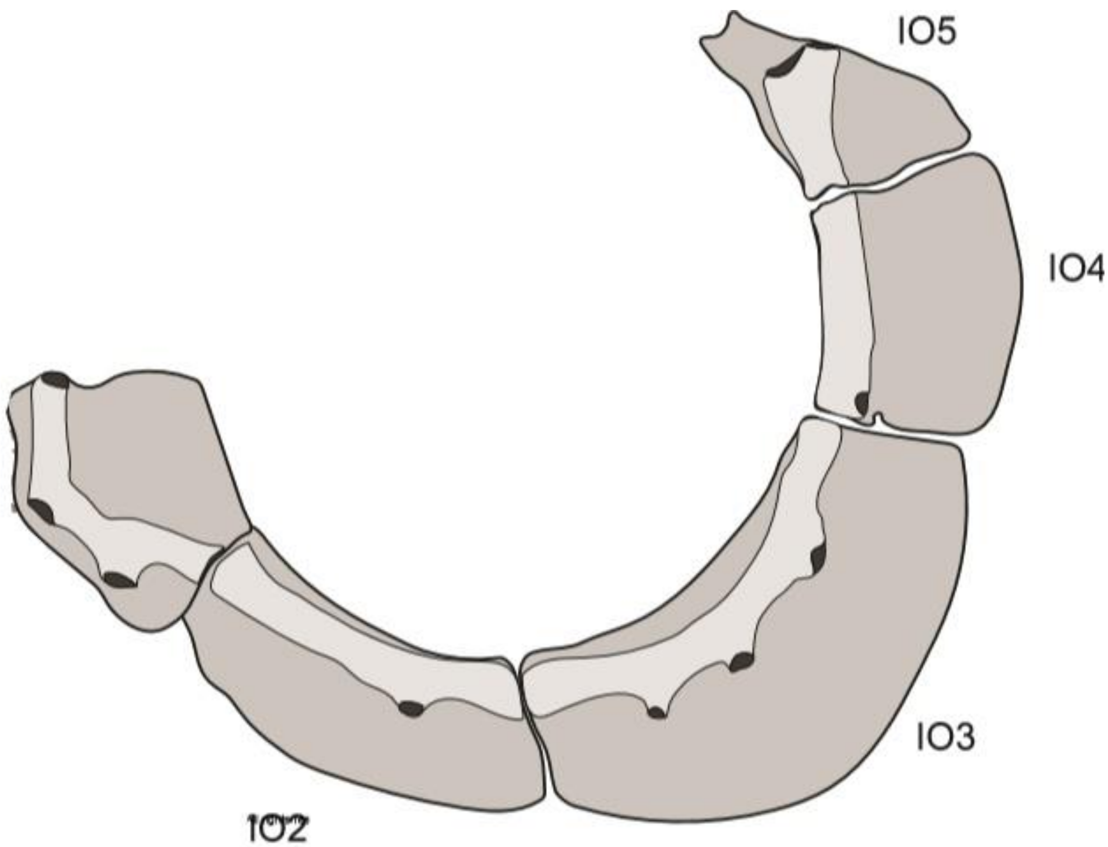

Figure 1.11. Left infraorbital series of, Enteromius pinnimaculatus sp. nov. specimen OS22152 at Oregon State University, Department of Fisheries and Wildlife, Corvallis, Oregon

Typically, iii,7 dorsal-fin rays, including an unbranched rudiment and two longer unbranched soft rays (Fig. 1.12). Eighth branched ray present in holotype. Longest unbranched dorsal-fin ray flexible and non-serrate. Four supraneurals in cleared and stained specimen. Typically, iii,5 rays on the anal fin, with unbranched count including one rudiment and two longer unbranched rays. Cleared and stained specimen (OS22152) exhibits tiny additional rudiment buried beneath skin and anterior to counted elements of anal fin, not included in meristic count. Thirteen (rarely twelve) pectoral-fin rays, of which dorsalmost unbranched and remainder branched. One unbranched and seven branched pelvic-fin rays. Nine upper and nine lower principal caudal-fin rays. Eight upper procurrent and eight lower procurrent caudal-fin rays in cleared-and-stained specimen. Lateral line complete and runs along midlateral scale row without ventral deflection, 19 or 20 total scales in most specimens. Count includes one full sized scale posterior to posterior margin of hypural plate, and sometimes one smaller terminal scale. One specimen has 23 total lateral line scales, including two posterior of point of caudal flexion. 3.5 scales between lateral line and dorsal midline; 4.5 scales between lateral line and ventral midline; 2.5 between lateral line and pelvic-fin origin; 10 circumpeduncular scales in most specimens (12 in specimen with unusually high lateral-line scale count). Scale formula and fin-ray counts of three specimens from the Nyanga drainage verified by B.A. to match ranges reported herein for Louetsi (Ogowe) specimens. Typically thirty-three vertebrae, and exceptionally 35 in individual with visible spinal malformation on radiograph (OS22153). Twelve pairs of full pleural ribs in cleared and stained specimen, not including elements of Weberian Apparatus.

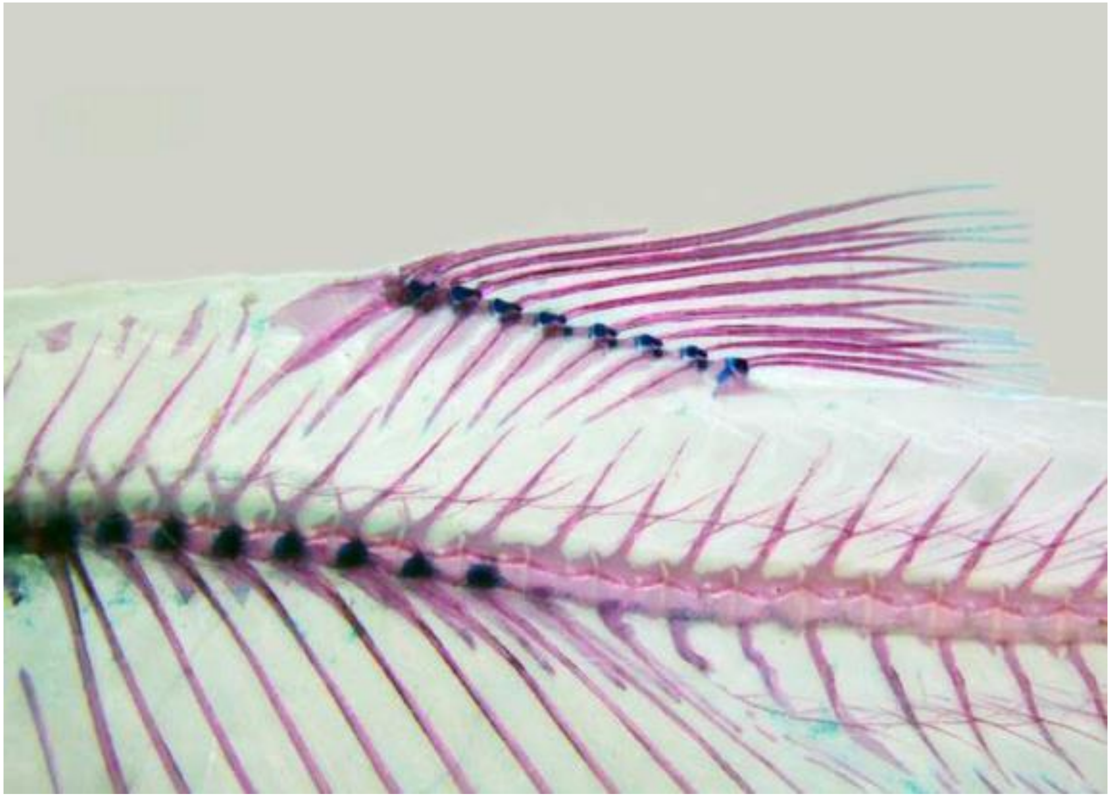

Figure 1.32. Dorsal fin, supraneurals and pterygiophores of Enteromius pinnimaculatus sp. nov. specimen OS22152 at Oregon State University, Department of Fisheries and Wildlife, Corvallis, Oregon.

Internal Soft Anatomy

Gas bladder two chambered, with anterior chamber slightly smaller and posterior chamber tapering posteriorly. Stomach without clear differentiation from intestine. Intestine S-shaped. From pharynx, gastrointestinal track runs posteroventrally, then bends towards left lateral flank and runs anteriorly almost to anterior margin of stomach, then turns dorsally and reverses direction, continuing straight from that point to vent (Fig. 1.13). Spleen darkly pigmented and triangular, positioned dorsomedial to anterior bend in gastrointestinal tract. Ovaries elongate, positioned ventral to gasbladder and dorsal to intestine. Eggs relatively large (roughly 0.1 millimeters in diameter) and easily visible within ovary at 100x magnification. All observations of internal anatomy based on viscera removed from OS22152, an adult female specimen 27.0 mm standard length, prior to clearing and staining.

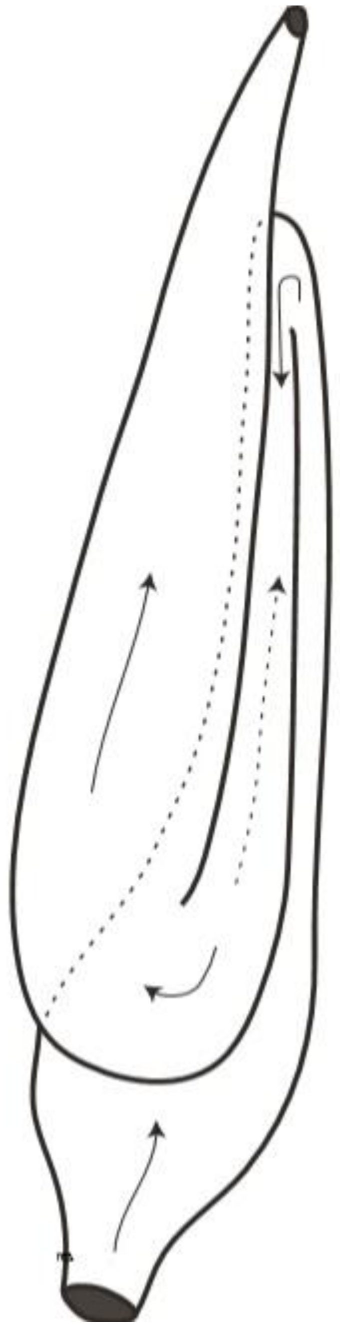

Figure 1.43. Schematic drawing of gasterointestinal tract removed from, Enteromius pinnimaculatus sp. nov. specimen OS22152 at Oregon State University, Department of Fisheries and Wildlife, Corvallis, Oregon. ←, Direction of food passage.

Coloration in Preservative

In preservation (Fig. 1.10), dorsum dark black to dark brown, particularly dark at dorsal-fin base. Flanks brown to yellowish, ventrum mustard yellow. Three or four round black spots on flanks: first anterior to dorsal-fin origin and centered on third and fourth scale in scale row dorsal to lateral-line scale row. Second spot posterior to dorsal-fin insertion, overlapping lateral line and centered on ninth or tenth scale of scale row dorsal to lateral-line scale row. Third (when present) faintest, dorsal to anal-fin insertion when present and centered on 13th or 14th scale. Third spot absent in some small individuals. Fourth intensely dark and located at posterior of caudal peduncle, centered on lateral-line scale row between procurrent caudal-fin rays. Lateral-line scales dark proximally around pores, forming a thin dotted line beginning just posterior to opercle and running to 14th or 16th lateral-line scales, typically reaching position of third major spot when four spots present on flanks. Numerous small black spots on all dorsal-fin rays and extending onto membranes, sometimes forming two lines (Fig. 1.10B). One or several small black spots at midpoint of anal fin in most specimens, though holotype with only a single faint spot (Fig. 1.10A). Anal-fin otherwise hyaline with a dusky margin. Caudal-fin rays slightly dark at bases. Pectoral and pelvic fins hyaline.

Coloration in Life

The only photograph of *Enteromius pinnimaculatus* in life (Fig. 1.1) is of an individual from the Bibaka population (Bissina subdrainage of the Nyanga drainage). Opercule red, body color ranging from white on ventrum to light pink at midflank, dorsum light brown. Multiple small black spots over dorsal fin. Fins otherwise yellowish, with color most intense near bases and middle sections of paired and anal fins. Lateral-line scales with black spots on bases and surrounding pores, forming dashed black line along lateral-line scale row. Three to four dark spots on flanks, less intensely obvious in life than in preservative.

Generic Placement

The pigmentation along the scales of the lateral line series in *Enteromius pinnimaculatus* is reminiscent of some species in *Clypeobarbus*, a genus recently reaffirmed as distinct from *Barbus* and *Enteromius* (Conway & Stiassny, 2008; Stiassny & Sakharova, 2016; Hayes & Armbruster, 2017). However, the new species does not fit the current diagnosis of that genus (Stiassny & Sakharova, 2016) because it lacks an occipital fontanelle and has well developed intraorbital bones with flanges that extend far beyond the sensory canal (Fig. 1.10). It also lacks the distinctive cleithral pigmentation of *Clypeobarbus* and its lateral line scales are of a similar size to those adjacent, in contrast to the enlarged midlateral scales of *Clypeobarbus*. As such, the new species best fits the current concept of *Enteromius*.

Diet

The stomach of the cleared and stained specimen (OS22152) was full of unidentifiable flocculent material, and its intestine contained more of the same flocculence plus a few chitinous fragments and three mostly-digested dark objects that might have been seeds. Though these data are very limited, they suggest that the species is omnivorous, with plant and insect material in the diet.

Etymology

The specific epithet *pinnimaculatus* refers to the multiple small dark spots on the dorsal fin, which is a rare characteristic within *Enteromius*. An adjective in the nominative singular.

Distribution and Habitat

Enteromius pinnimaculatus is currently known only from two sites (Fig. 1.2). The first collection site is a small stream that drains into the Louetsi River near the Mioki Rapids (11.60085°E; 2.09669°S), near Ndoubi village. The second is a small stream near Leyonga village in the Bissina River watershed (12.178365°E; 2.208614°S). Both sites are at moderate elevation, between 400 and 700 meters above sea level. Both streams drain primary forest (Fig. 1.14), and each was approximately 1 meter wide and about 30 cm deep with the substrate a slurry-like mud mixed with dead leaves. In the Bibaka, the banks were vertical with substantial under bank, dead wood and roots.

Figure 1.54. Collection localities for Enteromius pinnimaculatus sp. nov. in Gabon, Ngounie Province. (a) Type locality, small swampy right bank affluent of the Louetsi River, Ngounie subdrainage of the Ogowe drainage, upstream from the Chutes de Mioki. 2.09669° S, 11.60085° E. (b) Swampy lowland tributary of the Bibaka River, Bissina subdrainage of the Nyanga drainage. 2.208614° S, 12.178365° E

The sites are in two different major watersheds (Ogowe and Nyanga) but both in Ngounie province, which borders Congo-Brazzaville.

The Chaillu Massif, a mountain range that straddles the border of Gabon and Congo, dominates this region. The relief of the Chaillu Massif consists of a metamorphic formation incised by steep hills and high mountain regions. Most of the massif is covered in dense forest with interspersed savannah formations, although these are mainly confined to the eastern parts (Vicat & Gioan, 1989; Mamonekene & Stiassny, 2012). The Chaillu Massif may have served as a refugium for species from climatic changes during ancient glaciation events and the rivers of this region contain a rich diversity of fishes. Despite forming part of the Lower Guinea ichthyofaunal province, the rivers of this region contain a ichthyofaunal community that appears to share some affinity with the Congo, as evidenced by the presence of fishes like *Enteromius chiumbeensis*, which is common further south (Poll, 1967; Mamonekene & Stiassny, 2012) in the Congo drainage but unknown in more northerly areas.

Co-occurring species

Other fish species collected syntopically at the Louetsi site (Ogowe drainage) include *Aphyosemion ocellatum*, *A. primigenium*, *Microctenopoma nanum*, and *Enteromius chiumbeensis.* All these are widespread throughout the Louetsi. Other fish species collected syntopically at the Bibaka site (Nyanga drainage) include a young *Clarias* (probably *C. camerunensis*) and two rare *Aphyosemion*: *A. hofmanni* and *A. wuendschi*. *Aphyosemion hofmanni* is only known from about ten localities in the region, and *A. wuendschi* is otherwise known only from its type locality in the Louetsi watershed, where it was captured in 1985 (Radda & Pürzl, 1985).

Conservation Status

Even though the two known localities for *Enteromius pinnimaculatus* correspond to two different major watersheds (Ogowe and Nyanga), the collection sites are actually separated by only 65 km. A polygon enclosing the two localities and encompassing sites at similar altitude estimates an extent of occurrence of approximately 1,500km^2.

Even if polygon were expanded substantially, it would be hard to construe a reasonable extent of occurrence exceeding 5,000km^2.

While no information exists on the population size of the new species, its habitat appears restricted to small first or second order streams and wetlands, particularly shallow swampy areas at the confluence of streams with rivers (Fig. 1.14). Certainly, the sampling locations at which the species was not found (Fig. 1.2, purple circles) outnumber substantially those where the species was collected (Fig. 1.2, yellow star and hexagon). That apparent habitat restriction implies that its extent of occupancy is considerably less than its extent of occurrence. With only two known localities, it is impossible to estimate occupancy precisely, but it is probable that the true area of occupancy for *Enteromius pinnimaculatus* falls short of 500 km^2.

In comparing these data to the IUCN Red List criteria(International Union for Conservation of Nature, 2001), we find that the species nearly qualifies for Endangered status via criterion B (geographic distribution), because the extent of occurrence is less than 5,000 km^2 and meets subcriterion A in being known from fewer than five localities. However, there is currently no evidence for a decline or fluctuation in occupancy, occurrence or population size, meaning that the species triggers only one of two needed subcriteria for endangered status.

Enteromius pinnimaculatus does meet criterion D (very small or restricted population) of the IUCN standards for Vulnerable status, as it is known from fewer than five localities. This puts the species at substantial risk of becoming endangered due to modifications to its habitat, and recommends a formal IUCN classification at the level Vulnerable (VU).

The known collection site in the Louetsi drainage falls within the proposed Dibwangui hydroelectric dam development. If that hydropower project proceeds, it is likely that the area will be fully deforested for the purposes of construction and operation of dam infrastructure, and the critical habitat for the species might be inundated or otherwise altered. If that habitat alteration causes the decline or local extinction of the Louetsi population, only one known healthy population would remain in the Nyanga watershed, and criterion B, subcriterion B of the IUCN standards (decline in occupancy, occurrence or population size) would be triggered. It is therefore reasonable to assume that the construction of the Dibwangui dam has the potential to change the status of this species from Vulnerable (VU) to Endangered (EN).

Discussion

Enteromius pinnimaculatus, a new species of cyprinid fish from tributaries of the Louetsi (Ogowe) and Bissina (Nyanga) rivers of southern Gabon is readily distinguished from all known *Enteromius* species except *E. walkeri* by its color pattern in life and in preservative, with multiple small black spots on the dorsal fin and three to four dark spots on the flanks. As described above, numerous other differences easily separate these two species, including differences in maximum body size, meristics, morphometrics and nuances of coloration, as well as complete allopatry, with *E. walkeri* known only from coastal rivers of West Africa, most notably the Pra and Ankobra rivers of Ghana.

It is worth noting that records of *E. walkeri* from Ivory Coast are unconfirmed, and appear to refer to a single lot (MNHN a-4430) at the Muséum National d'Histoire Naturelle in Paris, collected in 1882 from an unknown location in "CI", and thus far before modern political boundaries were established. Teugels *et al.* (1988) indicate that the species inhabits the Tano River system, the mouth which lies on the border between Ivory Coast and Ghana, but also indicate that the species is "known only in the west of Ghana, never observed in Ivory Coast." One putative record of *Enteromius walkeri* from Sierra Leone (FMNH73943) is based on a set of scales, with a note in the jar indicating uncertain identification (pers. comm. C. McMahan, March 5, 2018). Otherwise, all records of this species appear to be from Ghana.

Barbel Allometry

Enteromius walkeri and *E. pinnimaculatus* share an intriguing allometry of the barbels, which are quite elongate in juveniles, but grow more slowly than other parts of the head. *Enteromius camptacanthus* and *E. chiumbeensis* show the opposite pattern, with the barbels lengthening faster than other parts of the head over ontogeny. These different allometric coefficients explain the very different slopes for each pair of species in the morphometric scatterplot of PC1 (size) versus PC2 (barbel length) (Fig. 1.8), and illustrate that barbel length can be used to separate these species if size is considered (Fig. 1.7).

The biological reason for the difference in allometry is not clear, though developmental changes in the relative importance of chemosensation may play a role. In goatfishes, (which use mental barbels to locate food) barbel length increases up to 50% after larval settlement, coinciding with the onset of benthic foraging (McCormick, 1993). It is therefore possible that different dietary or habitat shifts among these species of *Enteromius* may explain why two species have proportionately larger barbels as juveniles, while two others have longer barbels as adults. Perhaps the adults of *E. camptacanthus* and *E. chiumbeensis* spend more time foraging benthically than do adults of the other two species?

Intriguingly, the co-occurring *Enteromius pinnimaculatus* and *Enteromius chiumbeensis* differ substantially in allometric coefficients, Does the allometric difference between the syntopic species hint at underlying trophic diversification, which might in turn help them occupy different niches in their tiny stream habitats? No detailed data on microhabitat preferences or the developmental biology of these species exist, so this and any other hypothesis for the difference in barbel allometry is speculative at best. Future studies should characterize the diet of adult and juvenile specimens to test the hypotheses of ontogenetic shifts in diet, and of niche partitioning.

The similarity in fin pigmentation and allometry between the geographically distant *Enteromius walkeri* and *E. pinnimaculatus* may hint at a close evolutionary relationship, but may also arise from convergence. Because no tissue samples of *E.*

walkeri appear to exist in the world's ichthyology collections, these alternative possibilities cannot currently be tested. As more Africa's fish diversity becomes accessible to genetic investigation (e.g. Van Ginneken *et al.*, 2017), future studies should assess whether phylogenetic signal in barbel allometry exists within *Enteromius*. If so, a reconstruction of the evolutionary history of this fascinating character may help to reveal the factors that have promoted the impressive diversification of the genus.

Conclusion: perspectives on the diversity and conservation of fishes of Gabon

The discovery of this and other new species in Gabon is not surprising, because many areas of this country have not yet been inventoried. Most collections have been carried out along major highways or on major rivers, so most sampling stations occur along roads, or in the navigable sections of larger rivers such as the middle Ogowe (Fermon, 2013). Sampling in remote rivers and smaller water bodies will undoubtedly lead to the discovery of more new species, and in particular new range-restricted species and vulnerable species like *Enteromius pinnimaculatus,* or the co-occurring *Aphyosemion wuendschi,* both of which are known from only two sampling localities from small streams in primary forests within Gabon's Ngounie province.

At a time when the country is embarking on an ambitious all-out development program in line with the vision of the Gabon Emergent Strategic Plan (République Gabonaise, 2012), the discovery of this new species demonstrates that the aquatic ecosystems of Gabon have yet to deliver all their secrets. This discovery challenges scientists to continue exploring undersampled or unsampled regions, with particular attention to the small and ephemeral habitats that harbor miniature, easily missed species. Increased knowledge about this region's rich biodiversity will improve the ability to recommend effective management plans that balance conservation with the need to develop sustainable natural resources for the benefit of Gabon's people.

Comparative Material Examined

Enteromius camptacanthus. All from Gabon, Province de la Ngounie, Soungou stream near Mabanga village, small stream on the left bank of the Ngounie River, with a large waterfall between this sampling site and the confluence, 2.27860°S, 11.61192°E. OS20935, 46 specimens, (tissue vouchers GAB17-998 and GAB17-999), 2 specimens photographed but not included in morphometric or meristic analyses, 31.47 - 95.81 mm SL, collected September 1, 2017; OS 21855, 1 specimen, (tissue voucher GAB17-375), 57.21 mm SL, collected May 4, 2017; OS 21877, 1 specimen, (tissue voucher GAB17-283), 74.98 mm SL), collected with OS21855; OS 21881, 12 specimens, (tissue voucher GAB17-274), 24.44 - 79.33 mm SL, collected with OS21855.

Enteromius chiumbeensis: All from Gabon, Province de la Ngounie. OS 21285, 1 specimen, 35.02 mm SL, small swampy stream on the right bank of the Louetsi River just upstream from the Chutes de Mioki, 2.0966°S, 11.60085°E, collected September 3, 2017; OS 21879, 8 specimens (tissue voucher GAB 17-282), 21.48 - 55.12 mm SL, Soungou stream near Mabanga village, small stream on the left bank of the Ngounie river, with a large waterfall between this sampling site and the confluence, 2.27860°S, 11.61192°E, collected May 4, 2017.

Enteromius walkeri: All from Ghana. CAS-SU 62769; 15 of 43 specimens examined and measured, 32.99 - 72.90 mm SL, cascades zone of stream near Asiakwa, Akim-Abuakwa, collected January 19, 1963; UMMZ 195011, 10 of 26 specimens examined and measured, 31.65 - 84.15 mm SL, Adansu River near Kibi, collected March 20, 1971.

Chapter 2:

Title. Fish Fauna in and around the Rapids of Mboungou Badouma and Doumé Ramsar Site, Gabon

Submitted: Checklist as an annotated list of species.

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Abstract

We assessed the fish biodiversity of the Ogooué and Sébé rivers in and around the Rapids of Mboungou Badouma and Doumé Ramsar site in Gabon. The ichthyofauna of this region has not been extensively sampled in over 150 years yet encompasses one the most important type localities for fishes in Central Africa. We sampled a total of 31 sites and collected nearly 3000 fish specimens representing 97 species. Nine species appeared to be new to science, and one catalyzed the recent description of a new genus of mormyrid fishes *Cryptomyrus*.

Key words

Africa, Assemblages, Fishes, Freshwater, Ogooué, Tropics, Conservation

Introduction

Gabon‘s Ogooué River harbors at least 265 species of fish, thus forming a major component of Central Africa’s incredible diversity of freshwater fishes (Fermon et al. 2013; Brooks et al. 2011). The Ogooué is the 4th largest river in Africa by discharge (following the Congo, Niger, and Zambezi), stretches for 1,200 km and drains roughly 75% of the country of Gabon. With a rural density of 1 inhabitant/km2, the Ogooué is considered one of the world’s most pristine large tropical rivers (Braun et al. 2017). However, as Gabon develops its mining, timber and hydroelectric industries, existing and planned projects pose risks to its freshwater ecosystems and the species they support.

To protect part of the Ogooué, the Government of Gabon declared the Rapids of Mboungou Badouma and Doumé as a Ramsar site (Fig. 2.1) (Mengue Medou et al. 2002). This Ramsar site protects the mainstem Ogooué between Lastoursville and Moanda in the Ogooué-Lolo and Haut-Ogooué provinces of southeastern Gabon. The Ramsar site stretches for 140 km and extends 2 km in both directions from the Ogooué, covering a total of 59,500 ha of river and riparian habitat.

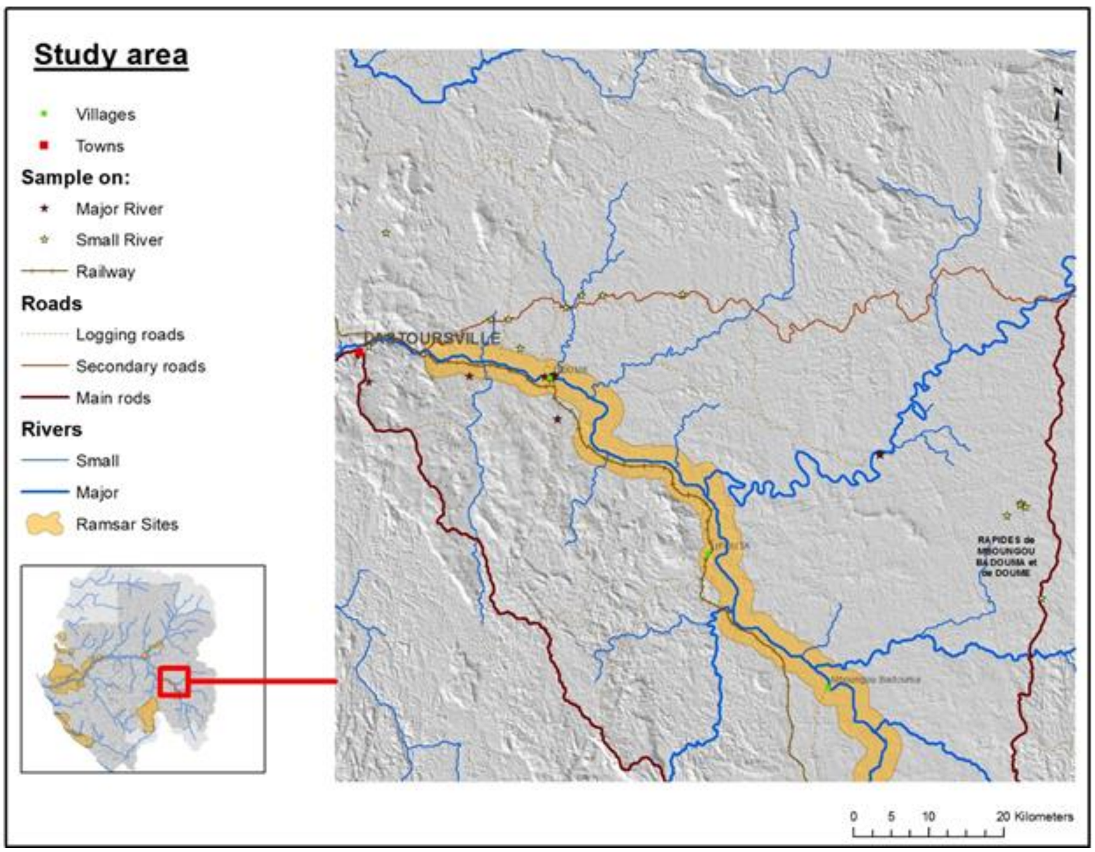

Figure 2.3. Sampling localities September 2014. The Chutes de Mboungou Badouma et de Doumé Ramsar site is highlighted in yellow. Sampling localities on small river sites appear as yellow stars, large river sites appear as black stars.

The Rapids of Mboungou-Badouma and Doumé Ramsar site has been very poorly sampled for fishes in comparison to other regions of the Ogooué basin. The

FAUNAFRI website (http://www.poissons-afrique.ird. fr/faunafri/ accessed 10/25/2018) indicates no fish collection sites on the Ogooué mainstem between Lastoursville and the Sébé River confluence apart from those conducted by Alfred Marche at Doumé in 1876–1877 and subsequently described by Henri Sauvage (Sauvage 1879, 1880). Despite limited sampling, those early collections make Doumé (0.843°S,12.96°E) arguably the most important type locality for fishes of the Ogooué. Marche's collections yielded numerous species descriptions including 10 new species of fishes from around the Chutes de Doumé, nine of which are still valid; *Mastacembelus marchei*, *Mastacembelus niger*, *Atopochilus savorgnani*, *Doumea typica*, *Clarias buthupogon*, *Labeobarbus compiniei*, *Ivindomyrus marchei*, *Paramormyrops sphekodes*, and *Petrocephalus simus*. A fourth mormyrid, *Petrocephalus afnis*, proved to be a synonym of *Stomatorhinus walkeri* (Günther 1867). Two other siluriforms, *Malapterurus oguensis* and *Parauchenoglanis balayi*, came from Marche's collection at Lopé.

We conducted a fish sampling expedition in the Rapids of Mboungou Badouma and Doumé Ramsar site in September 2014 organized and funded by The Nature Conservancy who sought to learn more about the values of this site. Team members included representatives from Gabon's Institut de Recherches Agronomiques et Forestières (IRAF) of the Gabonese Centre National de la Recherche Scientifique et Technologique (CENAREST), Oregon State University, Cornell University, the University of California Santa Cruz, the association AIMARA, and The Nature Conservancy. The expedition aimed to sample fish diversity within, and around the

Ramsar site, thereby providing a more comprehensive assessment of the site's ichthyofauna. These baseline data provide the foundation to build a framework for more effective management, conservation and development of this biologically and historically significant region.

Methods

Study Area. The list of species presented is based on collections made at 31 sites within and around the Rapids of Mboungou Badouma and Doumé Ramsar site between September 6 and 21, 2014 (Figure 2.1). We assumed fish community composition would depend upon stream size and therefore we sampled not only the mainstem Ogooué and Sébé, but also major tributaries, forest streams, creeks, and springs (Table 2.1, Figure 2.2). We sampled in two primary regions; on the Ogooué mainstem near Doumé (sites 1-21), and on the Sébé River near Lelama close to the confluence with the Ogooué (sites 22-31) (Table 2.1). This region has few roads and the best access to the river is via train, or on timber roads within forestry concessions, thus our sampling sites were partially determined by accessibility.

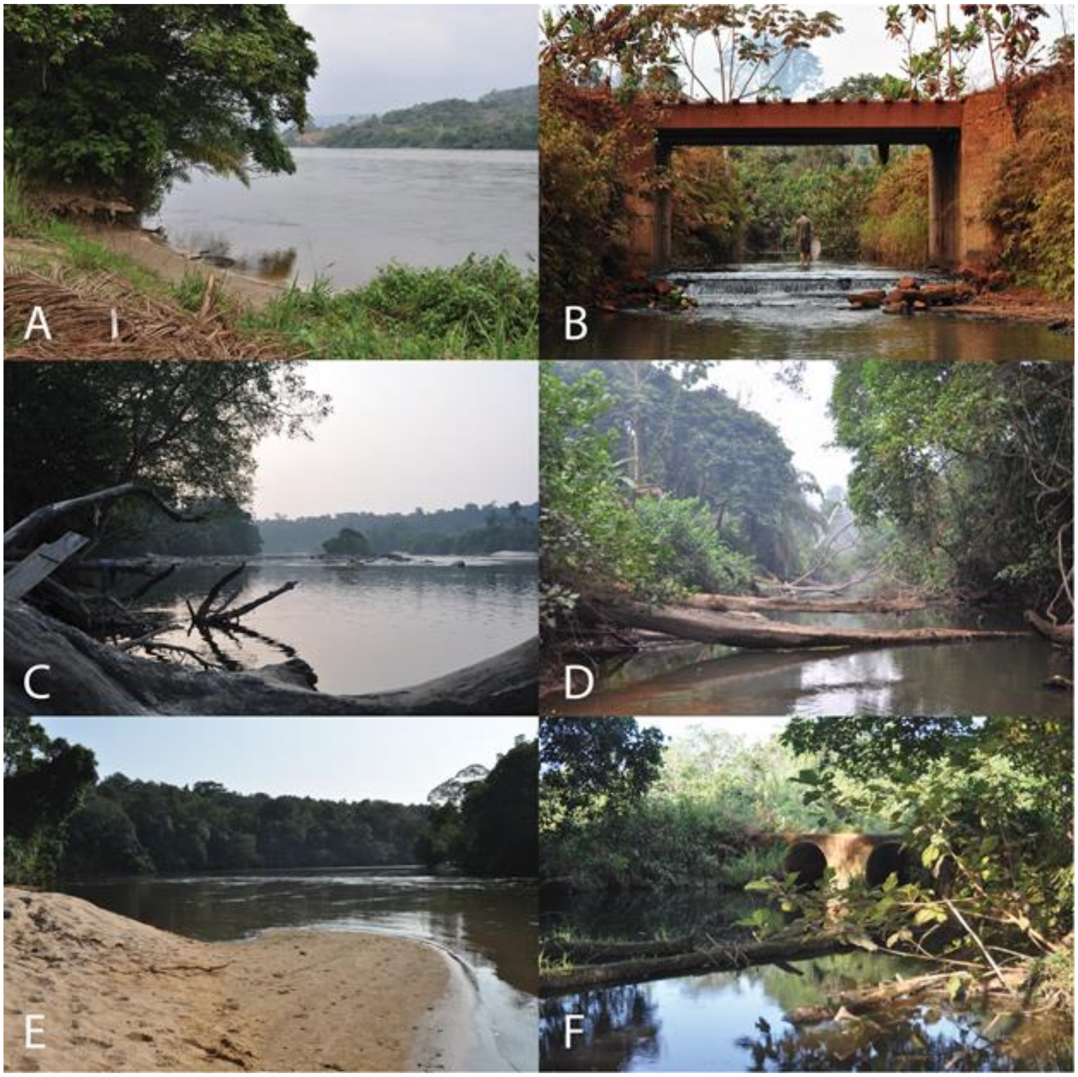

Figure 2.2. Collection Localities. A. Site 1, Ogooué River at Lastoursville. B. Site 4, Bakoussou Creek. C. Site 15, Ogooué River at Doumé. D. Site 6, Moumba Creek. E. Site 24, Sébé River. F. Site 30, Lewogo Creek.

Data Collection. Sampling methods included: electrofishing, trapping, gill netting, dip netting, seine netting, and cast netting (Figure 2.3). In large rivers (width >20 m) including the Ogooué and Sébé, we sampled primarily with experimental gill nets deployed in slack-water areas. We opportunistically sampled along the banks with worm-baited traps, beach seines and cast nets. In smaller rivers and streams, we sampled primarily with a backpack electroshocker (Halltech HT-2000 backpack electrofisher), but also used dip nets and seines (Table 2.1).

Figure 2.3. Sampling Equipment. A. Halltech HT-2000 backpack electroshocker and dip net. B. Bicycle wheel dip net. C. Trap. D. Seine net. E. Cast net. F. Gill net.

Table 2.1: Sampling Sites. Substrate types include G = Gravel, L = Leaf Litter, M = Mud, R = Rocks, S = Sand. Gear types include: C = Castnet, D = Dipnet, E = Backpack electroshocker, G = Gillnet, L = Trot Line, LS = Large Seine, SS = Small Seine, T = Trap.

Site #	Sampling Events	Region	Coord. (X)	Coord. (Y)	River Type*	Substrate†	Gear‡
1	1	Doumé	12.74488	-0.84800	Major River	S, M	D
2	2	Doumé	12.74448	0.80551	Small River	G, M, L	D
3	3	Doumé	12.92636	-0.80776	Small River	M, S, L	D
4	4	Doumé	12.89150	-0.77313	Small River	S, R	SS
5	5	Doumé	12.91172	-0.77253	Small River	G, S, M, L	D
6	6, 7, 10, 14, 15, 16, 18	Doumé	12.98106	-0.75878	Small River	S, L	LS, SS, T
7	8	Doumé	13.12101	-0.74257	Small River	G, M, R, L	D
8	9	Doumé	13.02508	-0.74460	Small River	G, S, R, L	D
9	11, 12, 13	Doumé	12.99941	-0.74427	Small River	S, L	D, SS, LS
10	17	Doumé	12.76561	-0.66884	Small River	S, M, L	D
11	21, 23, 25, 29, 30, 33, 36, 38,	Doumé	12.96249	-0.84245	Major River	S, R	G

12	34	Doumé	12.95582	-0.84177	Major River	S, R	LS
13	22, 24, 26, 31, 32, 35, 37	Doumé	12.96249	-0.84245	Major River	R, S	G
14	20, 27	Doumé	12.96249	-0.84245	Major River	S	LS
15	19, 39	Doumé	12.96363	-0.84189	Major River	S	LS, C
16	40	Doumé	12.96381	-0.84434	Small River	S, M	E
17	28, 44, 45	Doumé	12.86548	-0.84132	Major River	R	T, D
18	42, 47, 49	Doumé	12.96679	-0.84043	Major River	S, M	G
19	41	Doumé	12.97062	-0.89232	Major River	M, S	G
20	46, 48	Doumé	12.97062	-0.89232	Major River	S, L	G
21	43	Doumé	12.96582	-0.84146	Major River	R	C
22	51, 52, 53, 55, 56	Lelama	13.52629	-0.99385	Small River	M, S	D, G
23	50, 54	Lelama	13.52579	-0.99613	Small River	M, R	D, T
24	57, 62, 70	Lelama	13.35707	-0.934945	Major River	S	LS, SS
25	58, 63	Lelama	13.35732	-0.93568	Major River	S	G

26	59, 64, 66	Lelama	13.35707	-0.934945	Major River	S, M	G, L
27	60, 65	Lelama	13.35707	-0.934945	Major River	S, R	G
28	61, 68	Lelama	13.35707	-0.934945	Major River	R	T
29	67	Lelama	13.50984	-1.00853	Small River	M, L	E
30	69	Lelama	13.55104	-1.10777	Small River	R, S	E
31	71	Lelama	13.53217	-0.99832	Small River	M, L	E

* The small river category includes creeks and sloughs.
† Substrate Types (Listed in order of dominance): S = Sand, G = Gravel, R = Rocks M = Mud, L = Leaf Litter.

‡ Gear Types: T = fish trap baited with earthworms, LS = large seine, SS = small seine, G = gill net, C = cast net, D = dip net, E = electroshocker, L = Trot Line.

At each site, we recorded field data including GPS coordinates (WGS84), date and time, stream width and depth, pH, conductivity, dissolved oxygen, temperature, turbidity, substrate type, and general notes. We report a subset of these data herein, and complete locality records can be obtained from the Oregon State Ichthyology Collection's database at https://ichthyology.oregonstate.edu or requested from its curator (BLS).

After capture, specimens were euthanized with an overdose of the anesthetic MS-222 (tricaine methanesulfonate) in accordance with recommended guidelines for the use of fishes in research (Jenkins et al. 2014). After euthanization, tissue samples were taken from a subset of vouchered specimens and preserved in 95% ethanol, and photographs of coloration immediately post-mortem were taken in in an immersion aquarium with the specimen positioned between two panes of glass following the procedure of Sabaj Perez (2009). Electric organ discharges (EODs) of mormyrid fishes were recorded in small aquaria with water from their collection site, using an Echo 2 USB analog to digital converter sampling at 192 kHz/16 bits. Specimen were fixed in 10% formalin, and later transferred to 50% isopropanol for long-term preservation. All specimens were provisionally identified on the day of capture.

Field identifications for all specimens accessioned into the OS collection were verified in 2015 and 2016 by team members JSC, JHMB, and BLS using the keys in Stiassny et al. (2007), while taking subsequent species descriptions and revisions into account (e.g. within Hepsetus, *Notoglanidium*, *Nannopetersius* and *Labeobarbus*, (Decru et al. 2013; Geerinckx et al. 2013; Wamuini Lunkayilakio and Vreven 2008; Vreven et al. 2016). All mormyrid specimens deposited into the CUMV were verified by JPS, and EOD recordings are now archived at the Macaulay Library at Cornell https://www.macaulaylibrary.org/.

All collection and exportation of specimens occurred with the permission of the Gabonese Ministry of Scientific Research (Permit # AR0036 14/MESRS/CENAREST/CG/CST/CSAR (28 August 2014)). As required by the Gabonese government, half of each specimen series was retained in Gabon and the remainder exported. Vouchers were deposited at Oregon State University (OS, general collections) and the Cornell University Museum of Vertebrates (CUMV, mormyrids), with basic data listed in Table 2.1, and full data accessible at http://ichthyology.oregonstate.edu/home, and http://www.cumv.cornell.edu/fishes.html or at http://www.fishnet2.net. Small juvenile or damaged specimens that could not be identified to species level are not included as distinct taxa in that list, and "sp." designations represent probable undescribed species. Some specimens of killifishes and mastacebelid eels were exported J.F. Agnèse in France for molecular analyses, field identifications could not be verified for those specimens.

Taxonomic nomenclature used in this publication follows Eschmeyer's Catalogue of Fishes (Eschmeyer et al. 2018) with the exception of the genus *Paramormyrops*, within which there are several known, yet undescribed species. Identifications and nomenclature for that genus follow Sullivan et al. 2002 and 2004. Morphological diagnoses for all other species (except those potentially new to science) appear in Stiassny et al. (2007); Decru et al. (2013) and Geerinckx et al. (2013).

Results

We sampled 31 sites and collected 2,634 fishes, representing a minimum of 97 distinct species in 18 families and 9 orders (Table 2.1). The most species-rich orders of fishes were the Siluriformes (23 spp.), Characiformes (22 spp.) and Osteoglossiformes (22 spp.) followed by Cypriniformes (14 spp.). The three most numerically abundant species were all cypriniforms, *Enteromius guirali* (431 individuals), *Enteromius brazzai* (246 individuals), *Raiamas buchholzi* (148 individuals) followed by the siluriform *Chrysichthys nigrodigitatus* (128 individuals). The new genus and species *Cryptomyrus ogoouensis* Sullivan et al. 2016 (Figure 2.4E) was described from specimens collected on this expedition, as was *Paramormyrops ntotom* (Rich et al. 2017). Seven other species in the collection are potentially new to science (Figs. 4 and 5). These include three undescribed *Paramormyrops*, two species of *Plataplochilus*, an enigmatic alestid species tentatively assigned to *Phenacogrammus*, and a dwarf *Enteromius* that is either a new species or an aberrant color morph of *Enteromius jae*.

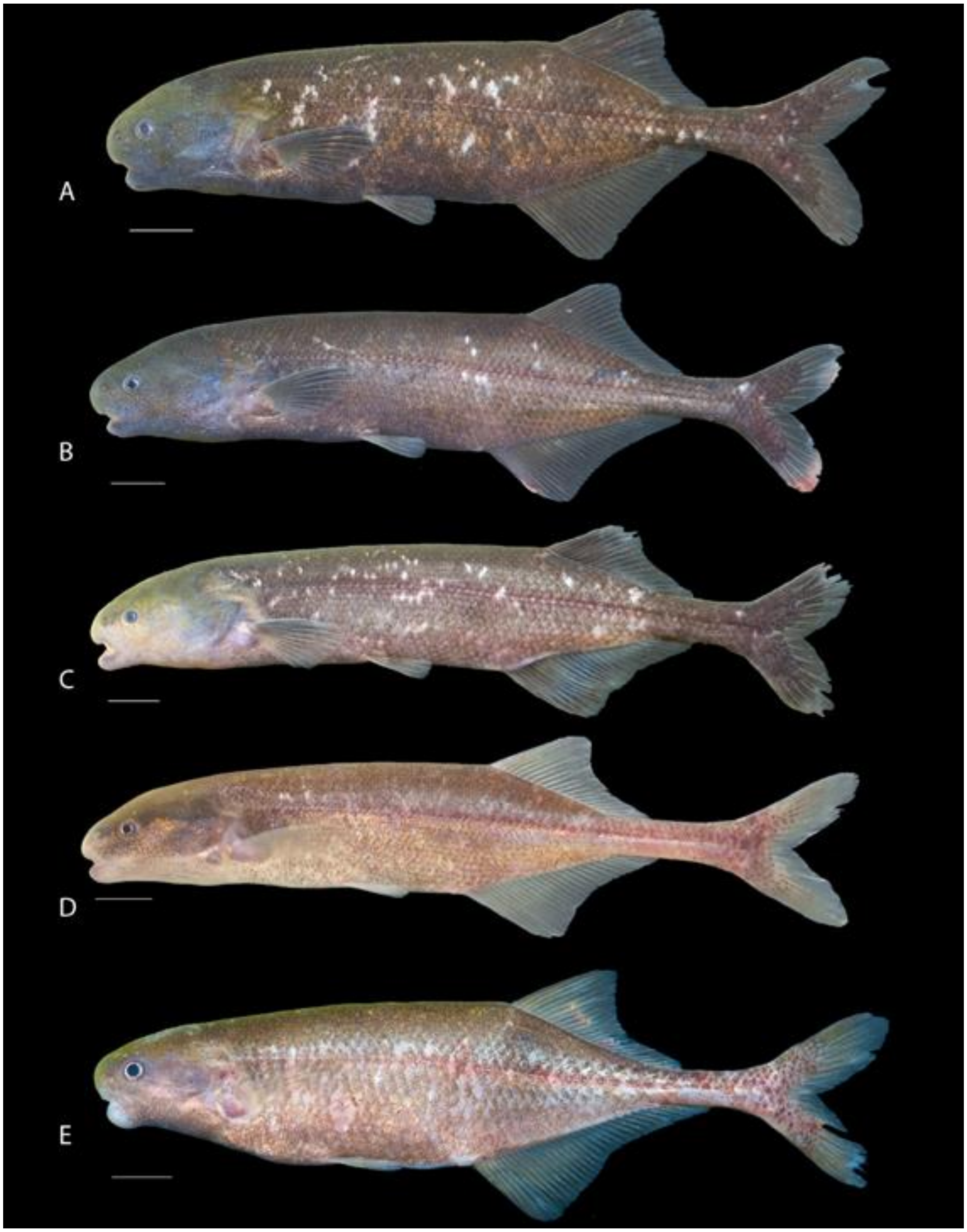

Figure 2.4. Known undescribed species of Mormyridae. A. Paramormyrops "BN2", SL = 108mm, euthanized. B. Paramormyrops "SN7", SL = 124mm, euthanized. C. Paramormyrops "MAG", SL = 133mm, euthanized. D. Paramormyrops "OFF", SL = 126mm, euthanized. E. Cryptomyrus ogoouensis, SL = 116mm, euthanized.

***Paramormyrops "BN2"* (Sullivan et al. 2002)**

Material examined: GABON; one male, 113mm; Moumba creek; -0.7587, 12.9810; 13 Sep. 2014; John P. Sullivan leg.; CUMV98120. GABON • one female, 108mm; Moumba creek; -0.7587, 12.9810; 13 Sep. 2014; John P. Sullivan leg.; CUMV98118. GABON • one female, 108mm; Moumba creek; -0.7587, 12.9810; 14 Sep. 2014; John P. Sullivan, Joseph Cutler leg.; CUMV98126. GABON • one female, 105mm; Moumba creek; -0.7587, 12.9810; 14 Sep. 2014; John P. Sullivan, Joseph S. Cutler leg.; CUMV98125. GABON • one female, 100mm; Moumba creek; -0.7587, 12.9810; 13 Sep. 2014; John P. Sullivan leg.; CUMV98119. GABON • one male, 92mm; Moumba creek; -0.7587, 12.9810; 12 Sep. 2014; John P. Sullivan leg.; CUMV98101. Figure 2.4A.

Identification. This is a blunt-snouted, smaller species of *Paramormyrops* with a maximum adult size of 110 mm SL. It has a very short EOD (less than 0.4 milliseconds) with a very small head-positive first phase, followed by a much larger head-negative second phase.

***Paramormyrops "SN7"* (Sullivan et al. 2002)**

Material examined: GABON • one male, 148mm; Moumba creek; -0.7587, 12.9810; 13 Sep. 2014; John P. Sullivan leg.; CUMV98104. GABON • one male, 143mm; Moumba creek; -0.7587, 12.9810; 12 Sep. 2014; John P. Sullivan leg.; CUMV98103. GABON • one male, 142mm; Moumba creek; -0.7587, 12.9810; 13 Sep. 2014; John P. Sullivan leg.; CUMV98108. GABON • one male, 140mm; Moumba creek; -0.7587, 12.9810; 13 Sep. 2014; John P. Sullivan leg.; CUMV98105. GABON • one male, 132mm; Moumba creek; -0.7587, 12.9810; 13 Sep. 2014; John P. Sullivan leg.; CUMV98106. GABON • one male, 127mm; Moumba creek; -0.7587, 12.9810; 14 Sep. 2014; John P. Sullivan, Joseph S. Cutler leg.; CUMV98156. GABON • one male, 126mm; Moumba creek; -0.7587, 12.9810; 14 Sep. 2014; John P. Sullivan, Joseph S. Cutler leg.; CUMV98202. GABON • one female, 124mm; Moumba creek; -0.7587, 12.9810; 14 Sep. 2014; John P. Sullivan, Joseph S. Cutler leg.; CUMV98204. GABON • one female, 124mm; Moumba creek; -0.7587, 12.9810; 13 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; CUMV98198. GABON • one female, 122mm; Moumba creek; -0.7587, 12.9810; 14 Sep. 2014; John P. Sullivan, Joseph S. Cutler leg.; CUMV98157. GABON • one male, 122mm; Moumba creek; -0.7587, 12.9810; 13 Sep. 2014; John P. Sullivan leg.; CUMV98107.GABON • one female, 114mm; Moumba creek; -0.7587, 12.9810; 12 Sep. 2014; John P. Sullivan leg.; CUMV98102. GABON • one male, 113mm; Moumba creek; -0.7587, 12.9810; 14 Sep. 2014; John P. Sullivan, Joseph S. Cutler leg.; CUMV98206. GABON • one female, 113mm; Moumba creek; -0.7587, 12.9810; 14 Sep. 2014; John P. Sullivan, Joseph S. Cutler leg.; CUMV98207. GABON • one female, 112mm; Moumba creek; -0.7587, 12.9810; 14 Sep. 2014; John P. Sullivan, Joseph S. Cutler leg.; CUMV98205. GABON • one female,110mm; Moumba creek; -0.7587, 12.9810; 13 Sep. 2014; John P. Sullivan leg.; CUMV98110. GABON • one female, 105mm; Moumba creek; -0.7587, 12.9810; 13 Sep. 2014; John P. Sullivan leg.; CUMV98109. GABON • one female, 103mm; Moumba creek; -0.7587, 12.9810; 14 Sep. 2014; John P. Sullivan, Joseph S. Cutler leg.; CUMV98203. GABON • one, 96mm; Moumba creek; -0.7587, 12.9810; 13 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; CUMV98199. Figure 2.4B.

Identification. This species has a sharp snout in dorsal view which protrudes beyond a sub-inferior mouth below. Its EOD is biphasic with a head-positive first phase approximately 1.8 ms in duration, with a smoothly concave rising slope. There is no head-negative pre-pulse. The second, head-negative phase is of lower amplitude and much shorter duration.

Paramormyrops "MAG" **(Sullivan et al. 2002)**

Material examined: GABON • one male, 150mm; Sébé River, rocky outcrop below bridge, left bank; -0.9344, 13.3577; 22 Sep. 2014; John P. Sullivan, Joseph S. Cutler, Alain Dole leg.; CUMV98178. GABON • one female, 137mm; Sébé River, rocky outcrop below bridge, left bank; -0.9344, 13.3577; 22 Sep. 2014; John P. Sullivan, Joseph S. Cutler, Alain Dole leg.; CUMV98180. GABON • one female, 136mm; Sébé River, rocky outcrop below bridge, left bank; -0.9344, 13.3577; 20 Sep. 2014; John P. Sullivan leg.; CUMV98164. GABON • one male, 133mm; Moumba Creek, under bridge within CEB concession between Ndambi and Miynza; -0.7587, 12.9810; 13 Sep. 2014; John P. Sullivan leg.; CUMV98115. GABON • one male, 133mm; Moumba Creek, under bridge within CEB concession between Ndambi and Miynza; -0.7587, 12.9810; 13 Sep. 2014; John P. Sullivan leg.; CUMV98113. GABON • one female, 126mm; Moumba Creek, under bridge within CEB concession between Ndambi and Miynza; -0.7587, 12.9810; 13 Sep. 2014; John P. Sullivan leg.;

CUMV98114. GABON • one female, 117mm; Moumba Creek, under bridge within CEB concession between Ndambi and Miynza; -0.7587, 12.9810; 13 Sep. 2014; John P. Sullivan leg.; CUMV98117. GABON • one female, 115mm; Moumba Creek, under bridge within CEB concession between Ndambi and Miynza; -0.7587, 12.9810; 14 Sep. 2014; John P. Sullivan, Joseph S. Cutler leg.; CUMV98121. GABON • one female, 114mm; Sébé River, rocky outcrop below bridge, left bank; -0.934422, 13.3577; 20 Sep. 2014; John P. Sullivan leg.; CUMV98163. GABON • one male, 109mm; Moumba Creek, under bridge within CEB concession between Ndambi and Miynza; -0.7587, 12.9810; 13 Sep. 2014; John P. Sullivan leg.; CUMV98116. GABON • one female, 94mm; Moumba Creek, under bridge within CEB concession between Ndambi and Miynza; -0.7587, 12.9810; 11 Sep. 2014; John P. Sullivan leg.; CUMV98100. GABON • one, 44mm; Mokuma Creek, small stream nearby Hotel Escale, Lastourville; -0.8055, 12.7444; 17 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville leg.; CUMV98075. Figure 2.4C.

Identification. *Paramormyrops* "MAG" is distinctive due to its very sharp snout (in dorsal view) and small eye. This is one of the few species in which different EOD types are apparent within single populations (Arnegard et al. 2005). Three EOD types have been described in adults; those in our collections correspond to Types I and III. In Type I, the negative first phase is immediately followed by a head positive pulse of near equal amplitude, followed by a small head-negative dip. The total EOD duration is about 1 millisecond. Type II EODs are longer in total duration about 1.2

milliseconds, as the first negative phase is shallower and slowly rises before onset of the head-positive second phase.

***Paramormyrops "OFF"* (Sullivan et al. 2002)**

Material examined: GABON • one male, 71mm; Ogooué River in front of Doumé Village; -0.8413, 12.9654; 17 Sep. 2014; John P. Sullivan, Brian L. Sidlauskas leg.; CUMV98149. GABON • one male, 165mm; Sébé River, rocky outcrop below bridge, left bank; -0.934422, 13.3577; 20 Sep. 2014; John P. Sullivan leg.; CUMV98168. GABON • one female, 163mm; Ogooué River in front of Doumé Village; -0.8413, 12.9654; 17 Sep. 2014; John P. Sullivan, Brian L. Sidlauskas leg.; CUMV98151. GABON • one male, 151mm; Sébé River, rocky outcrop below bridge, left bank; -0.934422, 13.3577; 20 Sep. 2014; John P. Sullivan leg.; CUMV98169. GABON • one male, 144mm; Ogooué River in front of Doumé Village; -0.8413, 12.9654; 17 Sep. 2014; John P. Sullivan, Brian L. Sidlauskas leg.; CUMV98150. GABON • one male, 134mm; Sébé River, rocky outcrop below bridge, left bank; -0.934422, 13.3577; 20 Sep. 2014; John P. Sullivan leg.; CUMV98167. GABON • one female, 134mm; Sébé River, rocky outcrop below bridge, left bank; -0.934422, 13.3577; 22 Sep. 2014; John P. Sullivan, Marie-Claire Paiz, Alain Dole leg.; CUMV98179. GABON • one male, 133mm; Sébé River, rocky outcrop below bridge, left bank; -0.934422, 13.3577; 20 Sep. 2014; John P. Sullivan leg.; CUMV98165. GABON • one female, 126mm; Sébé River, rocky outcrop below bridge, left bank; -0.934422, 13.3577; 20 Sep. 2014; John P. Sullivan leg.; CUMV98166. Figure 2.4D.

Identification. *Paramormyrops "OFF"* is a large species (reaching standard length >150 mm) It is similar to *Paramormyrops longicaudatus* of the Ivindo River of Gabon, albeit with a shorter caudal peduncle. *Paramormyrops "OFF"* have bicuspid teeth, with 5 in the upper jaw and 6 in the lower jaw. The species has a sharp snout with a somewhat conical head and no submental swelling. It has a biphasic EOD with an initial head-positive peak followed by a head-negative peak. There is no head-negative pre-pulse. The initial phase of the EOD is head-positive and follows a straight rise to an inflection point near the peak; the second negative phase of the EOD is nearly equal in amplitude but shorter than the first phase, at least in females. In males, the second phase is extended. Total EOD duration 2.7 to 3 milliseconds.

***Cryptomyrus ogoouensis* (Sullivan et al. 2016)**

Material examined: GABON • one female, 116mm; Ogooué River in front of Doumé Village; -0.8413, 12.9654; 17 Sep. 2014; John P. Sullivan, Brian L. Sidlauskas leg.; CUMV98155. Figure 2.4E.

Identification. Generally, *Cryptomyrus* have few midlateral scale (44-45 lateral line scales), and 12 circumpeduncular scales. Very few other mormyrids have so few lateral line scales (only *Marcusenius*, *Pollimyrus* and *Stomatorhinus* are similar), and *Cryptomyrus* can be distinguished from these by the shape of the chin. *Cryptomyrus* have a moderately swollen chin (much larger than that of *Pollimyrus* and *Stomatorhinus*), but it does not protrude beyond the tip of the snout (as it does in *Marcusenius*). The EOD waveform of the specimen from Doumé is triphasic and very brief, dissimilar to that of every other species recorded so far in Gabon (Sullivan et al. 2016). *Cryptomyrus ogoouensis* can be distinguished from its sole congener (*C. ona*) in that *C. ogoouensis* has 24 dorsal fin rays and 30 anal fin rays, whereas *C. ona* has 20-21 and 24-25, respectively. Furthermore in *C. ogoouensis* the anal fin is longer and begins well in advance of the dorsal fin origin. *C. ona* was described from two specimen collected in the Nyanga and Ngounié Rivers, whereas *C. ogoouensis* was only collected on the Ogooué mainstem at Doumé.

Figure 2.5. Potentially Undescribed Species. A. Plataplochilus sp. 1, SL = 24.9mm, euthanized, photographed on black background. B. Plataplochilus sp. 2, SL = 28.56mm, euthanized, photographed on white background. C. Enteromius cf. jae, SL = 22.57mm, euthanized. D. cf. Phenacogrammus, SL = 60.36mm, preserved.

***Plataplochilus* sp. 1**

Material examined: GABON • one male, 24.9mm; Ogooué River at Hotel Escale de l'Ogooué, Lastoursville; -0.8080, 12.7448; 7 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville leg.; OS19378. Figure 2.5A.

Identification. On this expedition we collected two distinct species of *Plataplochilus* that posed taxonomic difficulty. With a tubular supraorbital canal with four large pores these specimens clearly key to the genus *Plataplochilus*, but species level identification has been challenging. According to the literature there are eight recognized species, of which only *P. terveri* was known previously from the region but *P. terveri* is not a morphological match for either species we collected (Stiassny et al. 2007). The taxonomy of the genus *Plataplochilus* is poorly resolved and several new species are in the process of being described by J.F. Agnèse, L. Chirio and colleagues. Specimens collected during this expedition have been send to that lab to be included in the taxonomic revision. *Plataplochilus* sp. 1 is a medium-sized species with a pointed snout and dorsal caudal fin ray extensions. *Plataplochilus* sp. 1 can be distinguished from *P. miltotaenia*, *P. pulcher and P. mimus* because *P.* sp 1 lacks a red mid-lateral line. *Plataplochilus* sp. 1 can be distinguished from *P. terveri* because *P. terveri* lacks fin extensions. *Plataplochilus loemensis* has a D/A position of 4-6, rather than 7-9 present in *P.* sp. 1. *Plataplochilus chalcopyrus* can be distinguished from *P.* sp. 1 as its D/A is 9-10 and it has a large dark spot on caudal peduncle and base of caudal fin. The closest morphological matches for *P.* sp. 1, appear to be *P. cabindae* and *P. ngaensis*, but neither species is known to occur in the region.

Plataplochlius sp. 1 is morphologically similar to *P. cabindae* but differs in eye color (P. cabindae has an orange eye whereas *P*. sp. 1 has a white eye). *Plataplochilus* sp. 1 is also morphologically similar to *P. ngaensis* but *P. ngaensis* has two broad bands on the posterior flank absent in the specimen we collected. *Plataplochilus* sp. 1 can be distinguished from *P*. sp. 2 by its color pattern, *P*. sp. 1 has bright iridescent blue flanks, red fin tips and an uncolored eye whereas *P*. sp. 2 has moderately blue flanks, yellow fins (with minimal red tips) and a blue eye.

***Plataplochilus* sp. 2**

Material examined: GABON • one, 28.56mm; Lélama Creek at the Compagnie Equatoriale des Bois roadside; -0.9938, 13.5262; 19 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19739. GABON • one, 25.6mm; Lélama Creek at the Compagnie Equatoriale des Bois roadside; -0.9938, 13.5262; 19 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19742. GABON • one, 24.14mm; Small stream running behind forestry camp between camp and confluence with Lélama, Sébé drainage; -0.9983, 13.5321; 23 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Gervais Koudaou leg.; OS19757. GABON • one, 21.3mm; Lélama Creek at the Compagnie Equatoriale des Bois roadside; -0.9938, 13.5262; 19 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19744. GABON • one, 20.2mm; Lélama Creek at the Compagnie Equatoriale des Bois roadside; -0.9938, 13.5262; 19 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19741. GABON • one, 16.31mm; Small stream running behind forestry camp between camp and confluence with

Lélama, Sébé drainage; -0.9983, 13.5321; 23 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Gervais Koudaou leg.; OS19750. GABON • one; Small stream 2km east of Lélama, Sébé drainage; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Gervais Koudaou, Brian L. Sidlauskas leg.; OS19904. Figure 2.5B.

Identification. The specimens tentatively assigned to *Plataplochilus* sp. 2 differ from all other described species of *Plataplochilus* in the Lower Guinea ichthyofaunal province. *Plataplochilus* sp. 2 is a medium-sized species with a pointed snout and dorsal caudal fin ray extensions, moderately blue flanks, yellow fins (with minimal red tips) and a blue eye. Only *Plataplochilus terveri* is known to occur in the region, but several characteristics distinguish *P.* sp. 2 from *P. terveri* including that *P. terveri* lack fin extensions. *Plataplochilus* sp. 2 can be distinguished from *P. miltotaenia, P. pulcher and P. mimus* based on color pattern because *P.* sp 2 lacks a red mid-lateral line on the flanks. *Plataplochilus* sp. 2 can be distinguished from *P. loemensis* and *P. chalcopyrus* by relative fin position, D/A of 7-9 versus 4-6 and 9-10 (respectively). *Plataplochlius* sp. 2 is morphologically similar to *P. cabindae* but differs in eye color (P. cabindae has an orange eye whereas *P.* sp. 2 has a blue eye). *Plataplochilus* sp. 2 is also morphologically similar to *P. ngaensis* but *P. ngaensis* has two broad bands on the posterior flank absent in the specimen we collected. *Plataplochilus* sp. 2 and *P.* sp. 1 can be distinguished by color pattern, *P.* sp. 1 is much more brilliant than *P.* sp. 2, and has bright iridescent blue flanks, red fin tips and an uncolored eye. *P.* sp. 2 has moderately blue flanks, yellow fins (with minimal red tips) and a blue eye.

***Enteromius jae* (Boulenger 1903)**

Material examined: GABON • one, 24.1mm; Small stream 2km east of Lélama, Sébé drainage; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Gervais Koudaou, Brian L. Sidlauskas leg.; OS19408. GABON • one, 22.57mm; Small stream 2km east of Lélama, Sébé drainage; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Gervais Koudaou, Brian L. Sidlauskas leg.; OS19409. GABON • one, 21.92mm; Small stream 2km east of Lélama, Sébé drainage; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Gervais Koudaou, Brian L. Sidlauskas leg.; OS19410. GABON • one, 21.9mm; Small stream 2km east of Lélama, Sébé drainage; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Gervais Koudaou, Brian L. Sidlauskas leg.; OS19411. GABON • one, 20.75mm; Small stream 2km east of Lélama, Sébé drainage; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Gervais Koudaou, Brian L. Sidlauskas leg.; OS19405. GABON • two, 19.4-20.3mm; Small stream 2km east of Lélama, Sébé drainage; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Gervais Koudaou, Brian L. Sidlauskas leg.; OS19403. GABON • one, 18.97mm; Small stream 2km east of Lélama, Sébé drainage; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Gervais Koudaou, Brian L. Sidlauskas leg.; OS19404. GABON • one, 18.77mm; Small stream 2km east of Lélama, Sébé drainage; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Gervais Koudaou, Brian L. Sidlauskas leg.; OS19406. GABON • one, 18.57mm; Small stream 2km east of Lélama, Sébé drainage; -1.0085, 13.5098; 21

Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Gervais Koudaou, Brian L. Sidlauskas leg.; OS19407. Figure 2.5C and 2.12J.

Identification. This dwarf cyprinid species *Enteromius* jae can be separated from most other members of *Enteromius* by the combination of small body size (maximum TL less than 4 cm), the lack of barbels, terminal mouth, highly incomplete lateral line with no more than 6 perforated scales, a lack of spinous elements in the dorsal fin, and a color pattern with multiple black dots and bars along the flanks with another at the dorsal fin origin, and only three simple rays in the dorsal fin (the very similar *Enteromius parajae* has four). Substantial variation in the number of dark bars occurs among individuals of *Enteromius jae*, which might represent sexual dimorphism, regional variation, or the presence of multiple species; however, there are normally at least three such bars. During this investigation, we caught barred specimens clearly identifiable as *Enteromius jae* (e.g. Figure 2.12J) together with similarly sized individual lacking bars and with no trace of banded melanophores on the flanks (for example, OS19400, Fig 4C). Aside from the difference in coloration, these specimens are morphologically similar. It is unclear whether these specimens lacking dark markings are conspecific with *Enteromius jae*, or whether they represent a new species.

***Phenacogrammus* sp.**

Material examined: GABON • one, 60.36mm; Left bank of Ogooué River at Doumé above the rapids; -0.8414, 12.9658; 17 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19716. Figure 2.5D.

Identification. One alestid specimen in the collection (OS 19716) cannot be reliably identified to genus or species and appears to be intermediate between the current concepts of *Phenacogrammus* and *Brachypetersius*. It possesses an incomplete lateral line series (typically indicative of *Phenacogrammus*), but that series contains 21 pored scales (of 29 total in the series), which exceeds the maximum number in any species of that genus occurring in Lower Guinea by six (Paugy and Schaefer 2007). The number of upper transverse scales (5.5) is in the range of *Brachypetersius* (and not *Nannopetersius*), but the incomplete lateral line prevents assignation of the specimen to any known species in those genera. The specimen may represent a new species, a highly aberrant individual of a known species, or a range extension for a species not otherwise known to occur in the area. With only one specimen and no DNA sample, it is impossible to be certain.

Amphilius nigricaudatus **(Pellegrin 1909)**

Material examined. GABON • one, 53.8mm; Small stream (Lewogo) in Lékoni drainage; -1.1077, 13.5510; 20 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Brian L. Sidlauskas leg.; OS19901. GABON • seven, 33.97-53.41mm; Small stream (Lewogo) in Lékoni drainage; -1.1077, 13.5510; 22 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Brian L. Sidlauskas leg.; OS19658. GABON • one, 50.9mm; Small stream (Lewogo) in Lékoni drainage; -1.1077, 13.5510; 22 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Brian L. Sidlauskas leg.; OS19898. GABON • one, 48.56mm; Bakoussou stream at road R19 east of Lastoursville, Ogooué drainage; -0.7731, 12.891; 10 Sep. 2014; Colin Apse, Jean Hervé Mvé Beh, Brian L. Sidlauskas, Thibault Cavalier de Cuverville leg.; OS19659. GABON • one, 38.15mm; Stagnant river east of Lastoursville and south of road R19 near bridge, Ogooué drainage; -0.8077, 12.9263; 10 Sep. 2014; Colin Apse, Jean Hervé Mvé Beh, John P. Sullivan, Thibault Cavalier de Cuverville leg.; OS19661. GABON • one, 27.58mm; Stagnant river east of Lastoursville and south of road R19 near bridge, Ogooué drainage; -0.8077, 12.9263; 10 Sep. 2014; Colin Apse, Jean Hervé Mvé Beh, John P. Sullivan, Thibault Cavalier de Cuverville leg.; OS19660. Figure 2.6A.

Identification. Eyes placed posteriorly on head. Pelvic fins behind dorsal fin. Caudal fin with 6+7 principle rays Origin of dorsal fin more than one head-length behind head. Caudal fin with large central black disk.

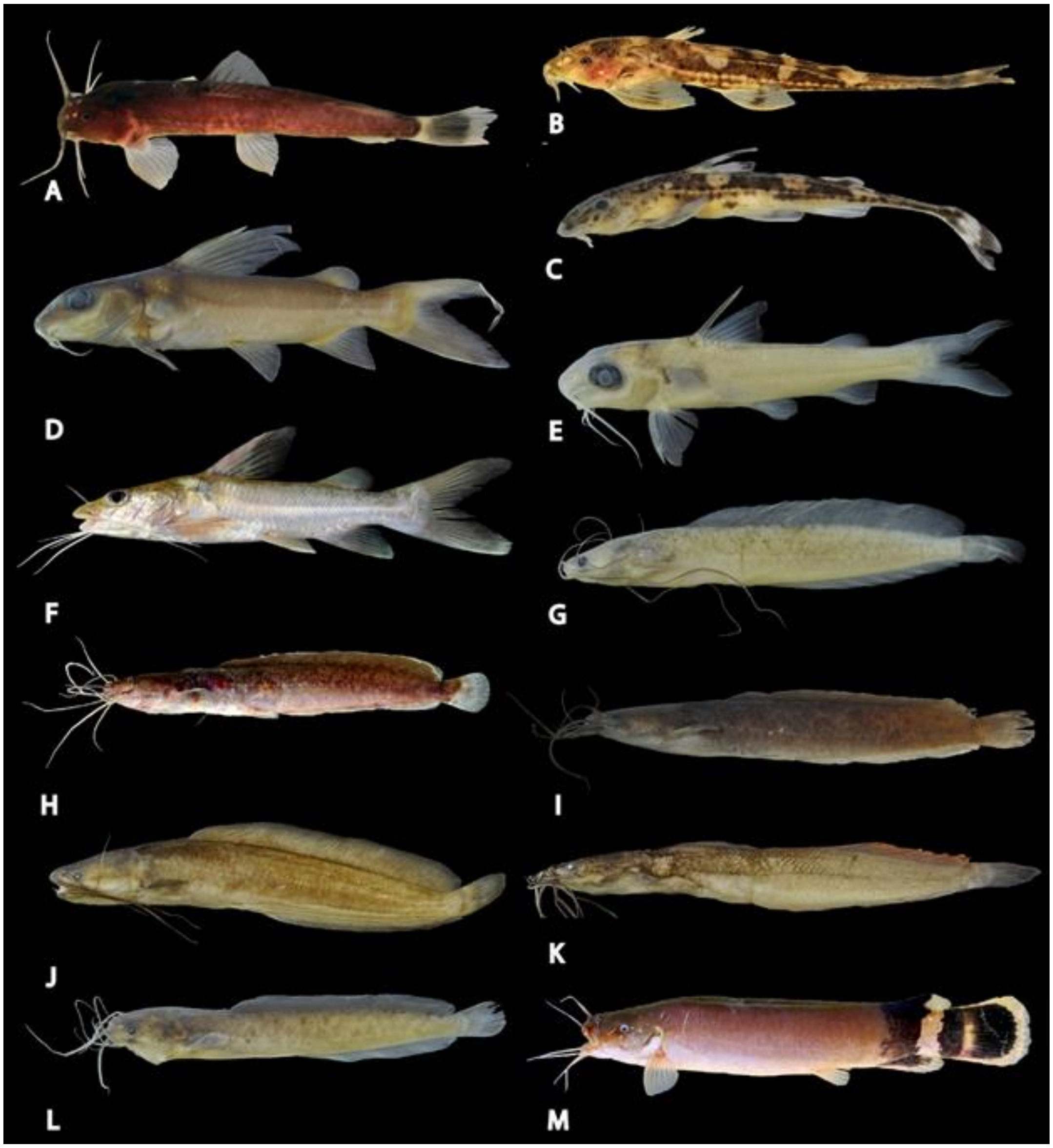

Figure 2.6. Siluriformes. A. Amphilius nigricaudatus, SL = 49mm, euthanized. B. Phractura brevicauda, SL = 45mm, euthanized. C. Phractura longicauda, SL = 41mm, preserved. D. Chrysichthys nigrodigitatus, SL = 131mm, preserved. E. Chrysichthys ogooensis, SL = 49mm, preserved. F. Chrysichthys thysi, SL = 135mm, preserved. G. Clarias buthupogon, SL = 73mm, preserved. H. Clarias camerunensis, SL = 107mm, euthanized. I. Clarias jaensis, SL = 131mm, preserved. J. Clarias

pachynema, SL = 111mm, preserved. K. Clarias platycephalus, SL = 52mm, preserved. L. Clarias submarginatus, SL = 57mm, preserved. M. Malapterurus oguensis, SL = 175mm, euthanized.

***Phractura brevicauda* (Boulenger 1911)**

Material examined. GABON • three, 45.2-50.1mm; Stagnant river east of Lastoursville and south of road R19 near bridge, Ogooué drainage; -0.8077, 12.9263; 10 Sep. 2014; Colin Apse, Jean Hervé Mvé Beh, John P. Sullivan, Thibault Cavalier de Cuverville leg.; OS19647. GABON • one, 45.1mm; Stagnant river east of Lastoursville and south of road R19 near bridge, Ogooué drainage; -0.8077, 12.9263; 10 Sep. 2014; Colin Apse, Jean Hervé Mvé Beh, John P. Sullivan, Thibault Cavalier de Cuverville leg.; OS19645. GABON • one, 29.78mm; Small stream (Lewogo) in Lékoni drainage; -1.1077, 13.5510; 22 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Brian L. Sidlauskas leg.; OS19855. GABON • one; Stagnant river east of Lastoursville and south of road R19 near bridge, Ogooué drainage; -0.8077, 12.9263; 10 Sep. 2014; Colin Apse, Jean Hervé Mvé Beh, John P. Sullivan, Thibault Cavalier de Cuverville leg.; OS19646. Figure 2.6B.

Identification. Body with visible bilateral, dorsal and ventral linear bony ridges. Caudal penduncle relatively short, 3-4.2 times in SL and slender. Length of caudal peduncle 8-16 times depth.

***Phractura longicauda* (Boulenger 1903)**

Material examined. GABON • five, 34.53-41.88mm; Small stream (Lewogo) in Lékoni drainage; -1.1077, 13.5510; 22 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Brian L. Sidlauskas leg.; OS19656. Figure 2.6C.

Identification. Body with visible bilateral, dorsal and ventral linear bony ridges. Caudal peduncle long (>33% of standard length) and extremely slender (length more than 18 times depth). Interorbit wide, width 1.5-2 times orbit diameter.

***Malapterurus oguensis* (Sauvage 1879)**

Material examined. GABON • one, 133.9mm; Small stream running behind forestry camp between camp and confluence with Lélama, Sébé drainage; -0.9983, 13.5321; 23 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Gervais Koudaou, Marie-Claire Paiz leg.; OS19903. Figure 2.6M.

Identification. Rayed dorsal fin absent, adipose fin present. Dorsal and flank unspotted, caudal saddle and bar pattern expressed intensely. Saddle continuous with anal fin pigmentation. Venter unmarked.

***Parauchenoglanis punctatus* (Boulenger 1902)**

Material examined. GABON • one, 282.17mm; Confluence of Moumba and Ogooué Rivers; -0.8923, 12.9706; 17 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19427. GABON • one, 152.1mm; Lélama Creek; -0.9961, 13.5257; 19 Sep. 2014; John P. Sullivan leg.; OS19870. GABON • one, 108.7mm; Lélama Creek; -0.9961, 13.5257; 19 Sep. 2014; John P. Sullivan leg.; OS19869. GABON • one, 84.73mm;

Small stream near Hotel Escale de l'Ogooué, Lastoursville; -0.8055, 12.7444; 8 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville leg.; OS19655. GABON • one, 44.96mm; Small stream near Hotel Escale de l'Ogooué, Lastoursville; -0.8055, 12.7444; 8 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville leg.; OS19532. Figure 2.7A.

Identification. Supraoccipital process and first nuchal plate in contact. Premaxillary tooth plate narrow (7-18% head length). Caudal peduncle short. Pectoral spine strongly serrated on anterior margin. Barbels very long, external mandibular barbel reaching beyond the tip of the pectoral spine. Typically, with 6-11 vertical rows of black dots on flanks.

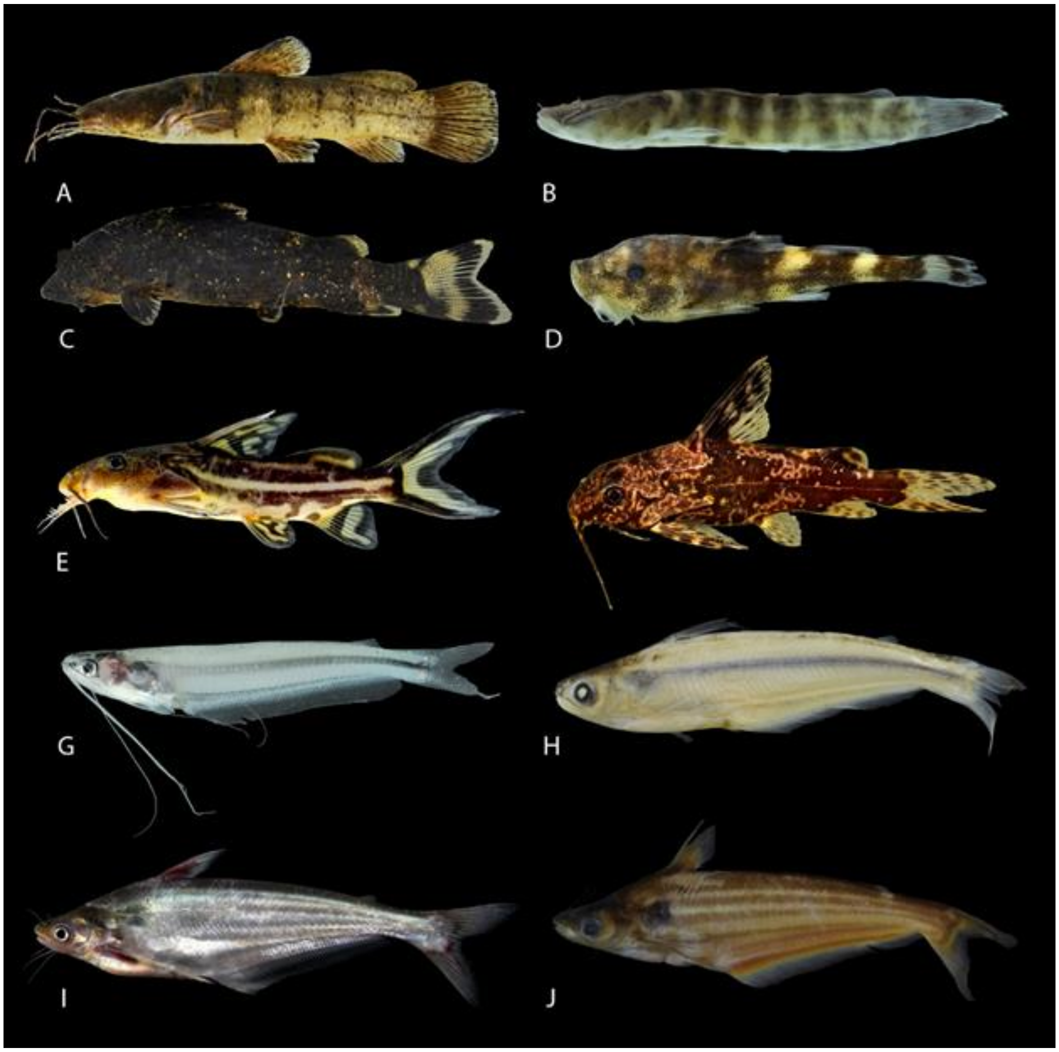

Figure 2.7. Siluriformes. A. Parauchenoglanis punctatus, SL = 282mm, euthanized. B. Notoglanidium macrostoma, SL = 33mm, preserved. C. Atopochilus savorgnani, SL = 40mm, euthanized. D. Chiloglanis cameronensis, SL = 20mm, preserved. E. Synodontis tessmanni, SL = 101mm, euthanized. F. Synodontis batesii, SL = 62mm, euthanized. G. Pareutropius debauwi, SL = 94mm, preserved. H. Parailia occidentalis, SL = 36mm, preserved. I. Schilbe grenfelli, SL = 165mm, euthanized. J. Schilbe multitaeniatus, SL = 147mm, preserved

***Notoglanidium macrostoma* (Pellegrin 1909)**

Material examined. GABON • one, 31.94mm; Small stream running behind forestry camp between camp and confluence with Lélama; -0.9983, 13.5321; 23 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Gervais Koudaou, Marie-Claire Paiz leg.; OS19853. Figure 2.7B.

Identification. Snout broad and flat. Eye covered with skin (without free border) and dorsally positioned on head. Supraoccipital process well separated from first nuchal plate. Head and body moderately depressed with a maximal body depth of 16-18% standard length. Seven dorsal fin rays and 9-13 anal fin rays.

***Atopochilus savorgnani* (Sauvage 1879)**

Material examined. GABON • one, 39.71mm; Bakoussou stream at road R19 east of Lastoursville; -0.7731, 12.891; 10 Sep. 2014; Brian L. Sidlauskas, Joseph S. Cutler, Thibault Cavalier de Cuverville, Jean Hervé Mvé Beh, Colin Apse leg.; OS19648. Figure 2.7C.

Identification. Lips well-developed forming a sucker disk. Mandibular barbels fused into lower lip. Eye with free border. Mandibular teeth uniformly distributed along the lower jaw in a straight row. Pectoral spine with well-developed serrations along the posterior margin.

***Chiloglanis cameronensis* (Boulenger 1904)**

Material examined. GABON • one, 20.42mm; Moumba River; -0.7587, 12.9810; 12 Sep. 2014; Joseph S. Cutler, Gervais Koudaou leg.; OS19662. Figure 2.7D.

Identification. Lips well developed, forming a round sucking disk. Pectoral spines serrations weakly developed. Mandibular teeth concentrated toward jaw symphysis. Mandibular barbels moderately long. Entire surface of sucker disk covered with papillae of similar size. Mandibular teeth 4+4 to 8+8.

Synodontis tessmanni **(Pappenheim 1911)**

Material examined. GABON • one, 100.3mm; Wooded area on left bank of Sébé River upstream from sand beach near bridge; -0.93494, 13.3570; 20 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19910. Figure 2.7E.

Identification. Lips not forming a sucker or oral disk. Mandibular barbels highly branched. Eye with a free border. Caudal fin forked. Dorsal spine not serrated along entire anterior edge. Opercle without a bony spine and smooth. Maxillary barbel bordered with broad membrane, and 0.8-2.2 times head length. Fewer than 50 mandibular teeth. Interorbital distance 58.5-86.6% of snout length. Body uniformly colored, caudal fin not spotted.

Synodontis batesii **(Boulenger 1907)**

Material examined. GABON • one, 67.3mm; Lélama Creek at the Compagnie Equatoriale des Bois roadside; -0.9938, 13.5262; 19 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh.; OS19874. GABON • one, 63.47mm; Moumba River; -0.7587, 12.9810; 12 Sep. 2014; Joseph S. Cutler, Gervais Koudaou leg.; OS19641. GABON • one, 61.88mm; Moumba River; -0.7587, 12.9810; 13 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19640. GABON • two, 54.71-60.8mm; Lélama Creek at the Compagnie Equatoriale des Bois roadside; -0.9938, 13.5262; 19 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19639. Figure 2.7F.

Identification. Lips not forming a sucker or oral disk. Mandibular barbels highly branched. Eye with a free border. Caudal fin forked. Dorsal spine fully serrated along entire anterior edge. Eye large (18-21% of head length). Body with two large clear transverse bands.

***Pareutropius debauwi* (Boulenger 1900)**

Material examined. GABON • one, 93.69mm; Right bank of Ogooué River at Doumé village; -0.8424, 12.9624; 15 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19638. GABON • one, 82.88mm; Right bank of Ogooué River at Doumé village; -0.8424, 12.9624; 15 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19636. GABON • one, 76.73mm; Wooded area on left bank of Sébé River upstream from sand beach near bridge; -0.93494, 13.3570; 20 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19635. GABON • two, 44.63-45.42mm; Moumba River; -0.7587, 12.9810; 13 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19634. GABON • one, 40.04mm; Ogooué River at Hotel Escale de l'Ogooué, Lastoursville; -0.8080, 12.7448; 7 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville leg.; OS19654. GABON • one, 39.76mm; Ogooué River at

Doumé, below the rapids; -0.8413, 12.9654; 17 Sep. 2014; Jean Hervé Mvé Beh leg.; OS19731. GABON • one, 36.54mm; Ogooué River at Doumé, below the rapids; -0.8413, 12.9654; 17 Sep. 2014; Jean Hervé Mvé Beh leg.; OS19729. GABON • 13, 23.52-70.34mm; Sébé River at sand beach near bridge; -0.93494, 13.3570; 20 Sep. 2014; Jean Hervé Mvé Beh, Gervais Koudaou, Thibault Cavalier de Cuverville leg.; OS19637. Figure 2.7G.

Identification. Rayed dorsal fin present with 3-5 branched rays. One pair of mandibular barbels. Dorsal dark band continues onto the caudal fin. No dark oblique band. no spots on the caudal lobes.30-54 branched anal fin rays.

***Parailia occidentalis* (Pellegrin 1901)**

Material examined. GABON • one, 36mm; Moumba River; -0.7587, 12.9810; 13 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19725. Figure 2.7H.

Identification. Rayed dorsal fin absent. Adipose fin present. Inner side of pectoral spine feebly serrated. Vomerine teeth absent. A dark triangular blotch at the base of the caudal fin.

***Schilbe grenfelli* (Boulenger 1900)**

Material examined. GABON • one, 187.66mm; Right bank of Ogooué River at Doumé village; -0.8424, 12.9624; 15 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19625. GABON • one, 178.7mm; Left bank of Ogooué River at Doumé village, including small side channel; -0.8424, 12.9624; 15 Sep. 2014; Joseph S.

Cutler, Jean Hervé Mvé Beh leg.; OS19622. GABON • one, 164.79mm; Left bank of Ogooué River at Doumé village, including small side channel; -0.8424, 12.9624; 15 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19624. GABON • one, 152.4mm; Wooded area on left bank of Sébé River upstream from sand beach near bridge; -0.9349, 13.3570; 20 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Brian L. Sidlauskas, Gervais Koudaou leg.; OS19995. GABON • one, 146.83mm; Right bank of Ogooué River at Doumé village; -0.8424, 12.9624; 15 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19623. GABON • one, 136.47mm; Right bank of Ogooué River at Doumé village; -0.8424, 12.9624; 15 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19551. Figure 2.7I.

Identification. Rayed dorsal present with 6 branched rays. Two pairs of mandibular barbels. Adipose fin present and fully developed. Anterior nostrils closer to each other than the posterior pair. Nasal barbel not reaching beyond the posterior border of the eye. Inner side of pectoral spine weakly serrated.

***Schilbe multitaeniatus* (Pellegrin 1913)**

Material examined. GABON • one, 148.7mm; Left bank of Sébé River, main channel near bridge; -0.9356, 13.3573; 20 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19877. GABON • one, 130.2mm; Wooded area on left bank of Sébé River upstream from sand beach near bridge; -0.9349, 13.3570; 20 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Brian L. Sidlauskas, Gervais Koudaou leg.; OS19889. GABON • one, 119.7mm; Left bank of Sébé River, main channel near bridge; -0.9356, 13.3573; 20 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19878. Figure 2.7J.

Identification. Rayed dorsal present with 6 branched rays. Two pairs of mandibular barbels. Adipose fin present and fully developed. Posterior nostrils as close to each other as the anterior pair. Inner side of pectoral spine weakly serrated. Coloration predominantly with several dark lateral streaks. Nasal barbel always reaching beyond posterior eye border.

***Hemichromis elongatus* (Guichenot 1861)**

Material examined. GABON • two, 126.0-150.83mm; Lélama Creek at the Compagnie Equatoriale des Bois roadside; -0.9938, 13.5262; 20 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Gervais Koudaou leg.; OS19573. GABON • one, 116.7mm; Lélama Creek at the Compagnie Equatoriale des Bois roadside; -0.9938, 13.5262; 19 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19867. GABON • one, 105.09mm; Left bank of Ogooué River at Doumé village, including small side channel; -0.8424, 12.9624; 15 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, leg.; OS19574. GABON • one, 78.14mm; Ogooué River at Hotel Escale de l'Ogooué, Lastoursville; -0.8080, 12.7448; 7 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville leg.; OS19580. GABON • one, 49.48mm; Moumba River; -0.7587, 12.9810; 12 Sep. 2014; Joseph S. Cutler, Gervais Koudaou leg.; OS19578. GABON • one, 40.35mm; Right bank of Ogooué River at factory near Doumé village; -0.8417, 12.9558; 17 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de

Cuverville leg.; OS19577. GABON • two, 39.05-59.31mm; Small stream (Lewogo) in Lékoni drainage; -1.1077, 13.5510; 22 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Brian L. Sidlauskas leg.; OS19579. GABON • two, 29.02-30.51mm; Ogooué River at Doumé village; -0.8424, 12.9624; 16 Sep. 2014; Yves Fermon leg.; OS19576. GABON • one, 21.95mm; Road 19 east of Compagnie Equatoriale des Bois headquarters; -0.7446, 13.0250; 12 Sep. 2014; Gervais Koudaou, Jean Hervé Mvé Beh, Thibault Cavalier de Cuverville leg.; OS19575. GABON • one, 18.72mm; Moumba River; -0.7587, 12.9810; 12 Sep. 2014; Joseph S. Cutler, Gervais Koudaou leg.; OS19582. GABON • five, 17.45-18.32mm; Moumba River; -0.7587, 12.9810; 12 Sep. 2014; Joseph S. Cutler, Gervais Koudaou leg.; OS19581. Figure 2.8E.

Identification. Teeth unicuspid, no visor-like hanging pharyngeal pad. 4-5 distinct vertical bars on flanks, a series of red dots (often forming horizontal rows along the flanks). Two rows of teeth on upper jaw.

Hemichromis stellifer **(Loiselle 1979)**

Material examined. GABON • one, 34.32mm; Small stream near Hotel Escale de l'Ogooué - Lastoursville; -0.8055, 12.7444; 8 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville leg.; OS19590. GABON • one, 31.48mm; Small stream near Hotel Escale de l'Ogooué - Lastoursville; -0.8055, 12.7444; 8 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville leg.; OS19588. GABON • one, 23.7mm; Small stream near Hotel Escale de l'Ogooué - Lastoursville; -0.8055, 12.7444; 8 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville leg.; OS19589. Figure 2.8F.

Identification. Teeth unicuspid, no visor-like hanging pharyngeal pad. One relatively large mid-lateral black spot present. Iridophores rarely present on body or unpaired fins. Single row of small teeth in upper jaw.

Figure 2.8. Perciformes. A. Chromidotilapia kingsleyae, SL = 91mm, euthanized. B. Chromidotilapia regani, SL = 152 mm, euthanized. C. Coptodon tholloni, SL = 47mm, euthanized. D. Divandu albimarginatus, SL = 112mm, euthanized. E. Hemichromis elongatus, SL = 105mm, euthanized. F. Hemichromis stellifer, SL = 31mm, euthanized. G. Oreochromis schwebischi, SL= 70mm, preserved. H. Pelmatolapia cabrae, SL = 51mm, preserved.

***Bryconalestes intermedius* (Boulenger 1903)**

Material examined: GABON • four, 20.82-69.20mm; Small stream (Lewogo) in Lékoni drainage; -1.1077, 13.5510; 22 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Brian L. Sidlauskas leg.; OS19688. Figure 2.9E.

Identification. Species of the genus *Bryconalestes* are externally differentiable from other members of Alestidae by the possession of a combination of an open fronto-parietal fontanelle, three teeth in the outer premaxillary tooth row, and a robust and almost molariform morphology of the symphyseal teeth in the second premaxillary row. Zanata and Vari (2005) list four additional synapomorphies for the clade, including a ventrally directed process of the supraorbital, sexual dimorphism of the anterior dorsal-fin rays and pelvic-fin rays, and extension of a portion of the anterior and middle anal-fin rays. Within the genus, *Bryconalestes intermedius* can be separated from all other valid species except *Bryconalestes tholloni* by the presence of an additional transverse scale row above the lateral line (6.5 versus 5.5). *Bryconalestes intermedius* is most similar to *Bryconalestes tholloni* (not captured on this trip) but can be separated by its fewer anal fin rays (19-21 versus 22-25) and lateral line scales (31-34 versus 34-38).

Figure 2.9. Alestidae. A. Bryconalestes longipinnis, SL = 61mm, euthanized. B. Brycinus opisthotaenia, SL = 81mm, euthanized. C. Brycinus macrolepidotus, SL = 125mm, euthanized. D. Brycinus kingsleyae, SL = 49mm, preserved. E. Brycinus intermedius, SL = 69mm, preserved. F. Bryconaethiops macrops, SL = 102mm, preserved. G. Bryconaethiops microstoma, SL = 112mm, preserved. H.

Nannopetersius ansorgii, SL = 51mm, preserved. I. Brycinus taeniurus, SL 81mm, preserved. J. Nannopetersius lamberti, SL = 71mm, preserved. K. Phenacogrammus aurantiacus, SL = 42mm, preserved. L. Phenacogrammus urotaenia, SL 42mm, preserved.

***Distichodus notospilus* (Günther 1867)**

Material examined. GABON • one, 104.28mm; Right bank of Ogooué River at Doumé village; -0.8424, 12.9624; 17 Sep. 2014; Joseph S. Cutler leg.; OS19544. GABON • two, 93.25-117.11mm; Left bank of Ogooué River at Doumé village, including small side channel; -0.8424, 12.9624; 15 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19529. GABON • one, 85.65mm; Left bank of Ogooué River at Doumé village, including small side channel; -0.8424, 12.9624; 15 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19543. GABON • one, 74.98mm; Lélama Creek; -0.9961, 13.5257; 19 Sep. 2014; John P. Sullivan leg.; OS19527. GABON • one, 27.44mm; Lélama Creek at the Compagnie Equatoriale des Bois roadside in Sébé drainage; -0.9938, 13.5262; 19 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19514. Figure 2.10A.

Identification. Relatively deep bodied, subterminal mouth with two rows of bicuspid teeth in each jaw. 38-43 scales in lateral line. Flanks without distinct markings other than vertically elongate spots on the flanks and a vertically elongate spot present at the base of the caudal fin.

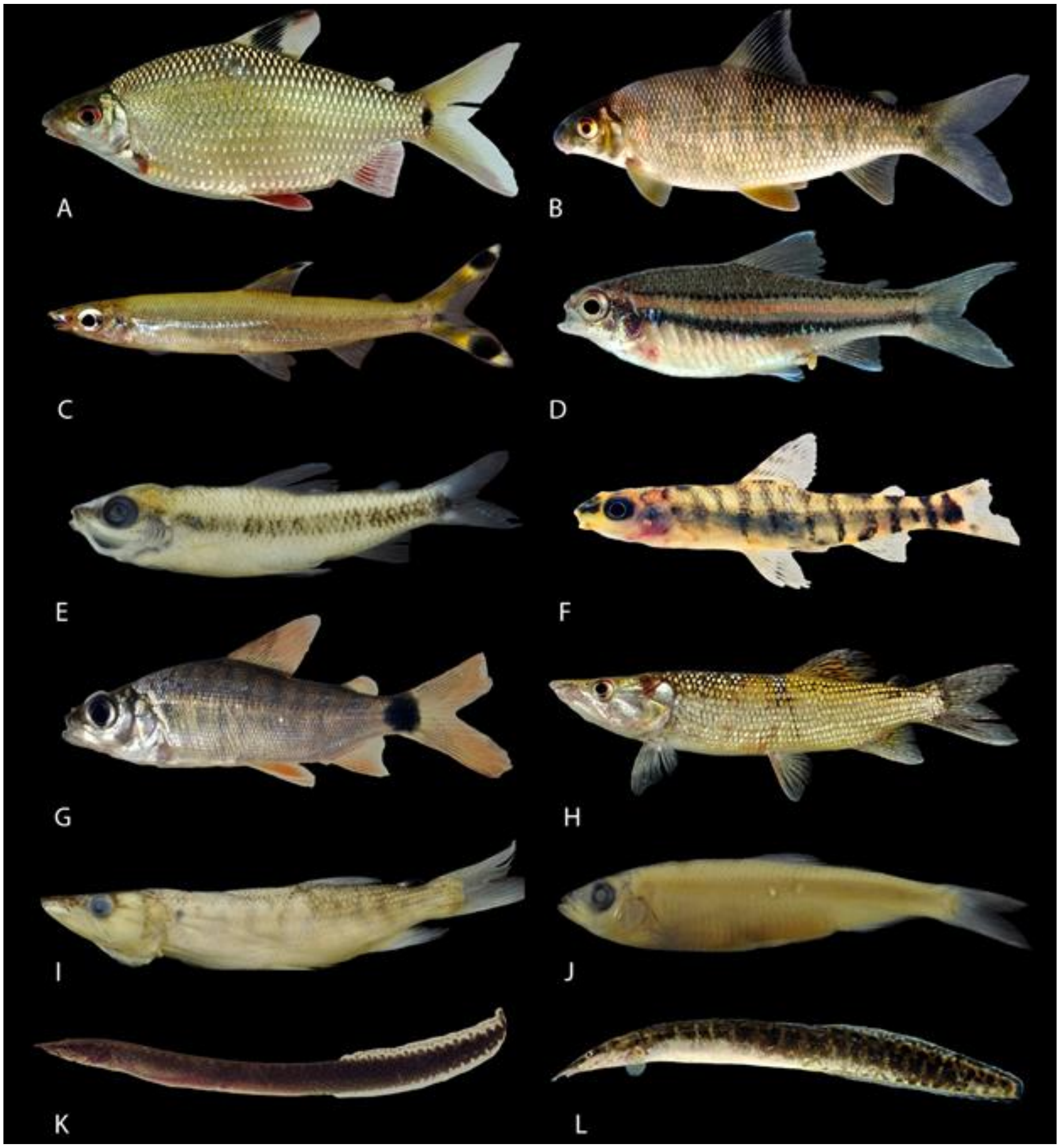

Figure 2.10. Characiformes, Clupeiformes and Synbranchiformes. A. Distichodus notospilus, SL = 104mm, euthanized. B. Distichodus hypostomatus, SL = 97mm, euthanized. C. Monistichodus elongatus, SL = 59mm, euthanized. D. Neolebias trewavasae, SL = 31mm, euthanized. E. Nannocharax parvus, SL = 26mm, preserved. F. Nannocharax intermedius, SL = 28mm, euthanized. G. Xenocharax spilurus, SL = 77mm, euthanized. H. Hepsetus lineata, SL = 219mm, euthanized. I. Hepsetus

kingsleyae, SL = 154mm, preserved. J. Pellonula vorax, SL = 91mm, preserved. K. Mastacmbelus niger, SL = 86mm, euthanized. L. Mastacembelus marchei, SL = 161mm, euthanized.

***Distichodus hypostomatus* (Pellegrin 1900)**

Material examined. GABON • one, 181.5mm; Left bank of Sébé River, main channel near bridge; -0.9356, 13.3573; 20 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19876. GABON • one, 111.68mm; Left bank of Ogooué River at Doumé above the rapids; -0.8414, 12.9658; 17 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19541. GABON • one, 97.1mm; Bakoussou stream at road R19 east of Lastoursville; -0.7731, 12.8915; 10 Sep. 2014; Brian L. Sidlauskas, Colin Apse, Thibault Cavalier de Cuverville, Jean Hervé Mvé Beh leg.; OS19542. GABON • one, 73.0mm; Bakoussou stream at road R19 east of Lastoursville; -0.7731, 12.8915; 10 Sep. 2014; Brian L. Sidlauskas, Colin Apse, Thibault Cavalier de Cuverville, Jean Hervé Mvé Beh leg.; OS19518. GABON • one, 69.95mm; Left bank of Ogooué River at Doumé above the rapids; -0.8414, 12.9658; 17 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19540. GABON • two, 59.34-67.39mm; Left bank of Ogooué River at Doumé above the rapids; -0.8414, 12.9658; 17 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19523. GABON • one, 35.52mm; Road 19 east of Compagnie Equatoriale des Bois headquarters at stream crossing; -0.7442, 12.9994; 13 Sep. 2014; Thibault Cavalier de Cuverville, Gervais Koudaou leg.; OS19526. Figure 2.10B.

Identification. Body elongate, mouth distinctly inferior with two rows of bicuspid teeth in each jaw. 53-60 scales in lateral line. Flanks with a series of distinct vertically elongate bars, caudal peduncle without dark spot.

***Aphyosemion lamberti* (Radda and Huber 1977)**

Material examined. GABON • one, 31.06mm; Moumba River; -0.7587, 12.9810; 13 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19733. GABON • one, 27.55mm; Spring behind school at Doumé village; -0.8443, 12.9638; 17 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19736. GABON • one, 22.08mm; Spring behind school at Doumé village; -0.8443, 12.9638; 17 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19734. GABON • one, 21.26mm; Wooded area on left bank of Sébé River upstream from sand beach near bridge; -0.9349, 13.3570; 20 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19735. Figure 2.11A.
Identification. Preopercular canal tubular with six pores. Dorsal fin inserted well behind fourth anal fin ray. No longitudinal dark band, red ventral bank, or red bands on flanks. No vertical bars or concentric pigmentation pattern in caudal fin. Caudal fin with interradial stripes (flamed), and acuminate, dorsally and ventrally edged with dark red. Ground color of unpaired fins red.

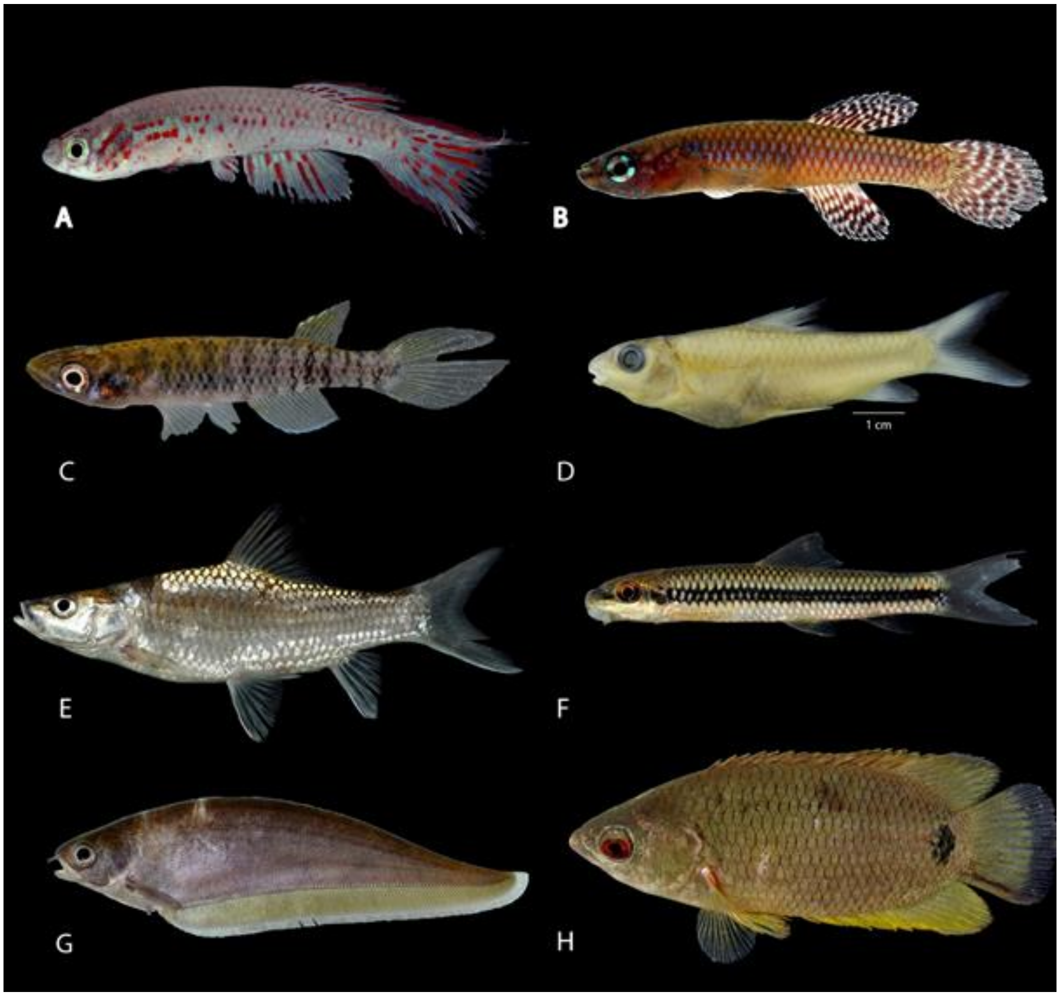

Figure 2.11. Cyprinodontiformes, Cypriniformes, Osteoglossiformes and Anabantiformes. A. Aphyosemion lamberti, SL = 31.06mm, live. B. Aphyosemion cf. cyanostictum, SL = 23.2mm, live. C. Epiplatys neumanni, SL = 21.2mm, live. D. Labeobarbus malacanthus, SL = 68.72mm, preserved. E. Labeobarbus progenys, SL = 125.8mm, euthanized. F. Labeo annectens, SL = 17.95mm, euthanized. G. Xenomystus nigri, SL = 142.4mm, euthanized. H. Ctenopoma kingsleyae, SL = 78.2mm, euthanized.

***Aphyosemion cyanostictum* (Lambert and Géry 1968)**

Material examined: GABON • one, 25.76mm; Small stream 2km east of Lélama; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Brian L. Sidlauskas, Gervais Koudaou, Jean Hervé Mvé Beh leg.; OS19854. GABON • one, 23.2mm; Small stream 2km east of Lélama; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Brian L. Sidlauskas, Gervais Koudaou, Jean Hervé Mvé Beh leg.; OS19823. GABON • one, 21.22mm; Small stream 2km east of Lélama; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Brian L. Sidlauskas, Gervais Koudaou, Jean Hervé Mvé Beh leg.; OS19803. GABON • one, 20.04mm; Small stream 2km east of Lélama; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Brian L. Sidlauskas, Gervais Koudaou, Jean Hervé Mvé Beh leg.; OS19852. Figure 2.11B.

Identification. We tentatively identified one specimen as *Aphyosemion cyanostictum*. That species is distinguished from most other *Aphyosemion* species by morphology and breeding coloration. *Aphyosemion cyanostictum* is a small-bodied species, with the origin of the dorsal fin opposite or slightly in front of the anal fin origin (Lambert and Géry 1968). *Aphyosemion cyanostictum* have a dorsal fin with 10-12 rays, and 10-12 anal fin rays. the caudal peduncle has fewer than 13 circumpeduncular scales and there are 26-27 scales in the longitudinal series. The dorsal and caudal fin in *A. cyanostictum* are not elongate, and the dorsal fin tips do not reach the base of the caudal fin. As with most killifish, male breeding coloration is critical in assigning specimens to species. Breeding males of *A. cyanostictum* are typically scarlet red, becoming red brown dorsally. The flank scales typically show a white, or light blue spot. The median fins are red with light blue spots and a thin blue margin. The anal fin has no orange marking. Females are uniformly grey-brown, becoming lighter ventrally. *A. cyanostictum* never shows two black bands on the flanks even when stressed (as do species in the genus *Chromaphyosemion*). The specimen collected on this expedition (which was a male in breeding coloration) is distinguished from all other known populations of *A. cyanostictum* in two fashions; the specimen has a distinct blue band of scales running down the midline of the fish, and the pigmentation pattern on the dorsal and anal fin is neatly banded, whereas in other populations the fins are spotted (See Figure 11B). It is noteworthy to mention that within *Aphyosemion*, small differences in color pattern often reflect significant genetic differences (Van der Zee, *pers. comm*). *Aphyosemion cyanostictum* is otherwise only known from the Ivindo drainage, thus our collection near Lastoursville represents a major extension to the range of this species or might represent a new species entirely.

***Epiplatys neumanni* (Berkenkamp 1993)**

Material examined. GABON • one, 21.2mm; Small stream 2km east of Lélama; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Brian L. Sidlauskas, Gervais Koudaou leg.; OS19822. Figure 2.11C.

Identification. Preopercular canal tubular with five pores. Anterior part of lower jaw broad. Two central neuromasts in frontal laterosensory system in one pit (closed). Mouth large. Ventral head dark, without contrasting white pattern. Thin black bars on flanks.

***Labeobarbus malacanthus* (Pappenheim 1911)**

Material examined: GABON • one, 68.72mm; Left bank of Ogooué River at Doumé above the rapids; -0.8414, 12.9658; 17 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19550. Figure 2.11D.

Identification. 9-12 branched dorsal rays, scales with numerous convergent striae. Mouth inferior. Two pairs of barbels, posterior barbel not reaching to posterior margin of eye. Last simple ray of dorsal fin as long, or longer than head. 27-30 scales in lateral line.

***Labeobarbus progenys* (Boulenger 1903)**

Material examined: GABON • one, 125.8mm; Lélama Creek at the Compagnie Equatoriale des Bois roadside; -0.9938, 13.5262; 29 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Gervais Koudaou leg.; OS19888. Figure 2.11E.

Identification. 9-12 branched dorsal rays, scales with numerous convergent striae. Mouth terminal. 4.5-5.5 scales between lateral line and mid-ventral line, three scales between lateral line and origin of pelvic fin. Last simple ray in dorsal fin 67% of head length.

***Xenomystus nigri* (Günther 1868)**

Material examined: GABON • one, 142.4mm; Right bank of Sébé River, main channel near bridge; -0.9353, 13.3576; 20 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19890. Figure 2.11G.

Identification. Pelvic and dorsal fins absent, anal fin long and confluent with caudal fin. Three branchiostegal rays, gill rakers rudimentary. Body coloration uniform brown.

***Enteromius martorelli* (Roman 1971)**

Material examined: GABON • one, 57.05mm; Left bank of Ogooué River at Doumé above the rapids; -0.8414, 12.9658; 17 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19428. GABON • one, 53.73mm; Stagnant river east of Lastoursville and south of road R19 near bridge; -0.8077, 12.9263; 10 Sep. 2014; John P. Sullivan, Thibault Cavalier de Cuverville, Jean Hervé Mvé Beh, Colin Apse leg.; OS19429. Figure 2.12A.

Identification. Two pairs barbels. 11-12 circumpeduncular scales, 20-31 scales in lateral line. Black stripe on flanks. Last simple ray of dorsal fin ossified and serrated. Black spot at base of first rays of dorsal fin.

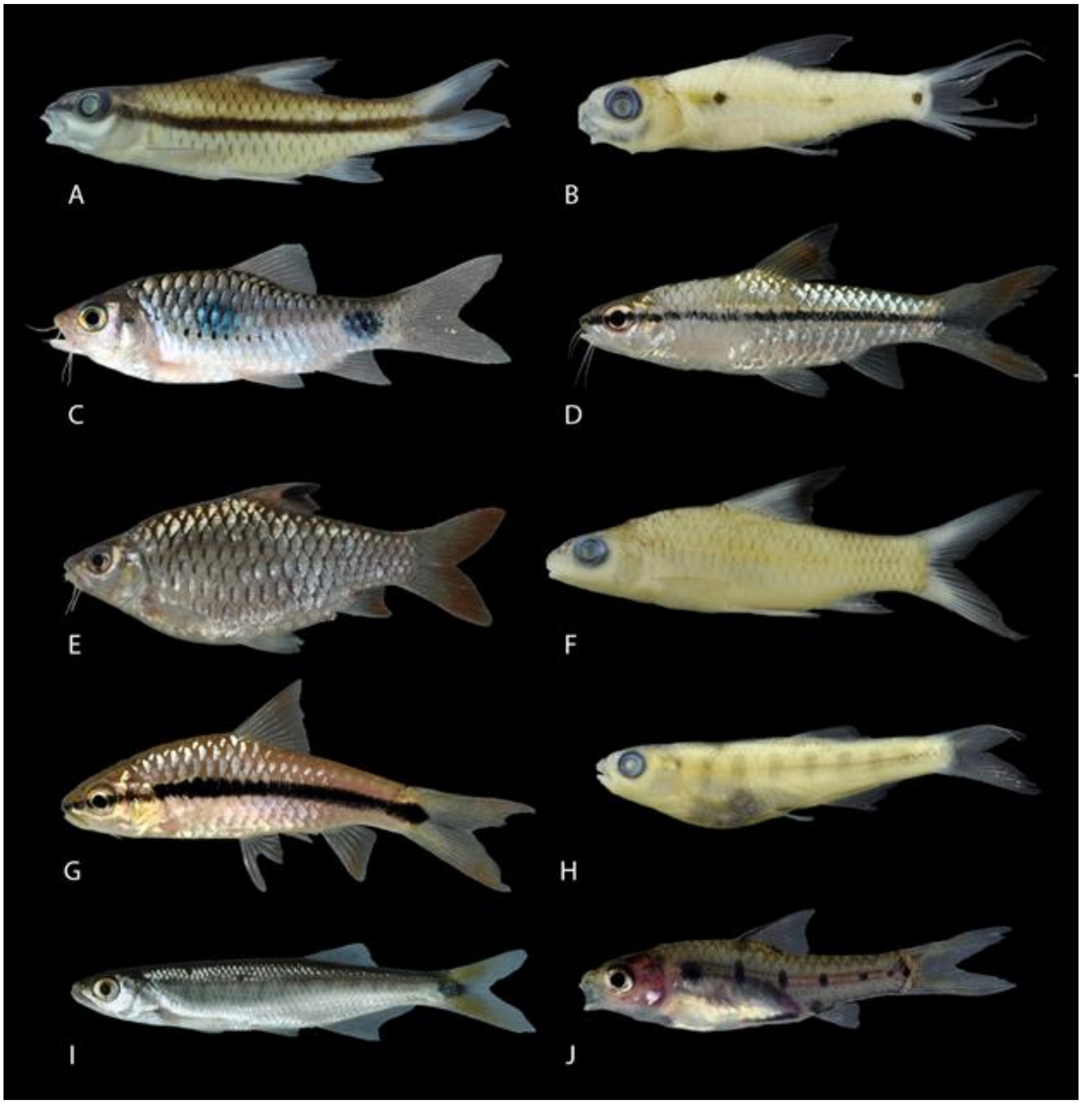

Figure 2.12. Cypriniformes. A. Enteromius martorelli, SL = 54mm, preserved, B. Enteromius trispilomimus, SL = 23mm, preserved, C. Enteromius camptacanthus, SL = 56mm, euthanized, D. Enteromius holotaenia, SL = 54mm, euthanized, E. Enteromius guirali, SL= 61mm, euthanized, F. Enteromius brazzai, SL = 62mm, preserved, G. Enteromius prionacanthus, SL= 37mm, euthanized, H. Opsaridium

ubangiense, SL = 23mm, euthanized, I. Raiamas buchholzi, SL = 74mm, euthanized, J. Enteromius jae, SL. 22mm, preserved.

***Enteromius trispilomimus* (Boulenger 1907)**

Material examined: GABON • one, 28.06mm; Sébé River at sand beach near bridge; -0.9349, 13.357; 20 Sep. 2014; Thibault Cavalier de Cuverville, Jean Hervé Mvé Beh, Gervais Koudaou leg.; OS19426. Figure 2.12B.

Identification. Barbels absent or very small. 8-10 circumpeduncular scales. Lateral line complete with 21-23 scales in lateral line. Three oval or round spots on the sides.

***Enteromius camptacanthus* (Bleeker 1863)**

Material examined: GABON • one, 86.55mm; Small stream near Hotel Escale de l'Ogooué, Lastoursville; -0.8055, 12.7444; 8 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville leg.; OS19430. GABON • one, 70.01mm; Small stream near Hotel Escale de l'Ogooué, Lastoursville; -0.8055, 12.7444; 8 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville leg.; OS19432. GABON • one, 56.5mm; Small stream 2km east of Lélama, Sébé drainage; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Brian L. Sidlauskas, Jean Hervé Mvé Beh, Gervais Koudaou leg.; OS19892. GABON • two, 55.63-58.65mm; Small stream 2km east of Lélama, Sébé drainage; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Brian L. Sidlauskas, Jean Hervé Mvé Beh, Gervais Koudaou leg.; OS19431. GABON • one, 42.2mm; Small stream 2km east of Lélama, Sébé drainage; -1.0085, 13.5098; 21 Sep. 2014; Joseph S.

Cutler, Brian L. Sidlauskas, Jean Hervé Mvé Beh, Gervais Koudaou leg.; OS19894. GABON • one, 28.37mm; Road 19 east of Compagnie Equatoriale des Bois headquarters; -0.7446, 13.0250; 12 Sep. 2014; Jean Hervé Mvé Beh, Gervais Koudaou, Thibault Cavalier de Cuverville leg.; OS19433. Figure 2.12C.

Identification. Two pairs barbels. 11-12 circumpeduncular scales, 21-25 scales in lateral line. Two large black spots on the sides. Dorsal fin 0.8-0.9 times in head length.

Enteromius holotaenia **(Boulenger 1904)**

Material examined: GABON • one, 117.71mm; Left bank of Ogooué River at Doumé village, including small side channel; -0.8424, 12.9624; 16 Sep. 2014; Jean Hervé Mvé Beh leg.; OS19434. GABON • one, 54.13mm; Left bank of Ogooué River at Doumé village, including small side channel; -0.8424, 12.9624; 17 Sep. 2014; Joseph S. Cutler leg.; OS19436. GABON • one, 38.56mm; Ogooué River at Doumé village; -0.8424, 12.9624; 16 Sep. 2014; Yves Fermon leg.; OS19437. GABON • one, 35.73mm; Left bank of Ogooué River at Doumé above the rapids; -0.8414, 12.9658; 17 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19435. GABON • one, 27.05mm; Ogooué River at Doumé, below the rapids; -0.8413, 12.9654; 17 Sep. 2014; Jean Hervé Mvé Beh leg.; OS19732. GABON • one, 26.29mm; Ogooué River at Doumé, below the rapids; -0.8413, 12.9654; 17 Sep. 2014; Jean Hervé Mvé Beh leg.; OS19726. Figure 2.12D.

Identification. Two pairs barbels. 11-12 circumpeduncular scales, 20-31 scales in lateral line. Last simple ray of dorsal fin ossified and serrated. Large dark stripe on flanks. Dorsal fin with black markings, but no dark spot at base of first dorsal fin rays. Pectoral fins not reaching origin of pelvic fins.

***Enteromius guirali* (Thominot 1886)**

Material examined: GABON • one, 106.63mm; Lélama Creek at the Compagnie Equatoriale des Bois roadside; -0.9938, 13.5262; 20 Sep. 2014; Joseph S. Cutler, Gervais Koudaou, Jean Hervé Mvé Beh leg.; OS19563. GABON • one, 106.5mm; Lélama Creek at the Compagnie Equatoriale des Bois roadside; -0.9938, 13.5262; 20 Sep. 2014; Joseph S. Cutler, Gervais Koudaou, Jean Hervé Mvé Beh leg.; OS19866. GABON • one, 97.5mm; Lélama Creek at the Compagnie Equatoriale des Bois roadside; -0.9938, 13.5262; 20 Sep. 2014; Joseph S. Cutler, Gervais Koudaou, Jean Hervé Mvé Beh leg.; OS19865. GABON • three, 90.29-109.06mm; Lélama Creek at the Compagnie Equatoriale des Bois roadside; -0.9938, 13.5262; 19 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19553. GABON • three, 82.12-113.77mm; Lélama Creek at the Compagnie Equatoriale des Bois roadside; -0.9938, 13.5262; 20 Sep. 2014; Joseph S. Cutler, Gervais Koudaou, Jean Hervé Mvé Beh leg.; OS19549. GABON • one, 71.3mm; Lélama Creek; -0.9961, 13.5257; 19 Sep. 2014; John P. Sullivan leg.; OS19873. GABON • three, 67.27-83.80mm; Left bank of Sébé River, main channel near bridge; -0.9356, 13.3573; 20 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19556. GABON • one, 66.4mm; Lélama Creek;

-0.9961, 13.5257; 19 Sep. 2014; John P. Sullivan leg.; OS19872. GABON • one, 64.32mm; Small stream near Hotel Escale de l'Ogooué, Lastoursville; -0.8055, 12.7444; 8 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville leg.; OS19583. GABON • three, 64.17-88.40mm; Rock outcrop on left bank of Sébé River just downstream from bridge; -0.9344, 13.3577; 20 Sep. 2014; John P. Sullivan leg.; OS19564. GABON • one, 63.76mm; Left bank of Ogooué River at Doumé village, including small side channel; -0.8424, 12.9624; 15 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19620. GABON • two, 52.32-61.95mm; Left bank of Ogooué River at Doumé village, including small side channel; -0.8424, 12.9624; 15 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19555. GABON • one, 52.09mm; Wooded area on left bank of Sébé River upstream from sand beach near bridge; -0.9349, 13.3570; 20 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19570. GABON • one, 45.30mm; Road R19 between Lastoursville and Compagnie Equatoriale des Bois headquarters; -0.7725, 12.9117; 11 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville, Gervais Koudaou leg.; OS19571. GABON • one, 35.8mm; Small stream 2km east of Lélama; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Brian L. Sidlauskas, Gervais Koudaou leg.; OS19896. GABON • one, 31.62mm; Road 19 east of Compagnie Equatoriale des Bois headquarters at stream crossing; -0.7442, 12.9994; 13 Sep. 2014; Gervais Koudaou, Thibault Cavalier de Cuverville leg.; OS19561. GABON • one, 29.43mm; Road 19 east of Compagnie Equatoriale des Bois headquarters at stream crossing; -0.7442, 12.9994; 13 Sep. 2014; Gervais Koudaou, Thibault Cavalier de Cuverville leg.; OS19560. GABON • 14, 27.51-40.27mm; Sand bank on left bank of Ogooué River at Doumé village; -0.8418, 12.9636; 15 Sep. 2014; Joseph S. Cutler, Brian L. Sidlauskas, Jean Hervé Mvé Beh leg.; OS19565. GABON • one, 26.29mm; Ogooué River at Doumé, below the rapids; -0.8413, 12.9654; 17 Sep. 2014; Jean Hervé Mvé Beh leg.; OS19730. GABON • 51, 26.21-97.11mm; Small stream (Lewogo) in Lékoni drainage; -1.1077, 13.5510; 22 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Brian L. Sidlauskas leg.; OS19554. GABON • one, 25.68mm; Road 19 east of Compagnie Equatoriale des Bois headquarters; -0.7446, 13.0250; 12 Sep. 2014; Jean Hervé Mvé Beh, Gervais Koudaou, Thibault Cavalier de Cuverville leg.; OS19558. GABON • 20, 24.10-32.81mm; Sébé River at sand beach near bridge; -0.9349, 13.3570; 20 Sep. 2014; John P. Sullivan, Brian L. Sidlauskas, Gervais Koudaou leg.; OS19568. GABON • two, 23.79-24.63mm; Ogooué River at Doumé village; -0.8424, 12.9624; 16 Sep. 2014; Yves Fermon leg.; OS19566. GABON • one, 23.4mm; Ogooué River at Doumé, below the rapids; -0.8413, 12.9654; 17 Sep. 2014; Jean Hervé Mvé Beh leg.; OS19728. GABON • seven, 23.31-60.88mm; Ogooué River at Doumé village; -0.8424, 12.9624; 16 Sep. 2014; Yves Fermon leg.; OS19567. GABON • 15, 21.75-27.70mm; Moumba River; -0.7587, 12.9810; 12 Sep. 2014; Joseph S. Cutler, Gervais Koudaou leg.; OS19569. GABON • one, 20.96mm; Small stream 2km east of Lélama; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Brian L. Sidlauskas, Gervais Koudaou, Jean Hervé Mvé Beh leg.; OS19802. GABON • 36, 20.86-32.33mm; Sébé River at sand beach near bridge; -0.9349, 13.3570; 20 Sep. 2014; Thibault Cavalier de Cuverville, Gervais Koudaou, Jean Hervé Mvé Beh leg.;

OS19552. GABON • seven, 20.35-60.41mm; Small stream near Hotel Escale de l'Ogooué, Lastoursville; -0.8055, 12.7444; 8 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville leg.; OS19562. GABON • three, 18.36-24.13mm; Lélama Creek at the Compagnie Equatoriale des Bois roadside; -0.9938, 13.5262; 19 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19557. Figure 2.12E.

Identification. Two pairs barbels. 11-12 circumpeduncular scales, 20-31 scales in lateral line. No trace of any striping or spotting on sides. Last simple ray of dorsal fin heavily ossified and serrated.

Enteromius brazzai **(Pellegrin 1901)**

Material examined: GABON • one, 88.1mm; Left bank of Ogooué River at Doumé above the rapids; -0.8414, 12.9658; 17 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19538. GABON • two, 62.2-64.26mm; Left bank of Ogooué River at Doumé village, including small side channel; -0.8424, 12.9624; 16 Sep. 2014; Jean Hervé Mvé Beh leg.; OS19537. GABON • two, 44.01-45.24mm; Small stream near Hotel Escale de l'Ogooué - Lastoursville; -0.8055, 12.7444; 8 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville leg.; OS19534. GABON • 13, 36.53-71.43mm; Sand bank on left bank of Ogooué River at Doumé village; -0.8418, 12.9636; 13 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Brian L. Sidlauskas leg.; OS19536. GABON • 33, 34.47-63.55mm; Ogooué River at Doumé village; -0.8424, 12.9624; 15 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Brian L. Sidlauskas leg.; OS19539. GABON • 36, 29.16-74.12mm; Ogooué River at Doumé village; -0.8424, 12.9624; 16 Sep. 2014; Yves Fermon leg.; OS19533. GABON • 35, 26.0-56.2mm; Sébé River at sand beach near bridge; -0.9349, 13.3570; 20 Sep. 2014; Jean Hervé Mvé Beh, Gervais Koudaou, Thibault Cavalier de Cuverville leg.; OS19535. GABON • one, 21.11mm; Small stream 2km east of Lélama; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Brian L. Sidlauskas, Gervais Koudaou leg.; OS19798. GABON • one, 18.74mm; Small stream 2km east of Lélama; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Brian L. Sidlauskas, Gervais Koudaou leg.; OS19800. Figure 2.12F.

Identification. Barbels absent or very small. Mouth inferior or subinferoir. 12 circumpeduncular scales. Lateral line complete. No spots on the sides, 24-28 scales in lateral line. Tip of dorsal fin black.

***Enteromius prionacanthus* (Mahnert and Géry 1982)**

Material examined: GABON • one, 125.18mm; Lélama Creek at the Compagnie Equatoriale des Bois roadside; -0.9938, 13.5262; 20 Sep. 2014; Joseph S. Cutler, Gervais Koudaou, Jean Hervé Mvé Beh leg.; OS19438. GABON • one, 78.86mm; Wooded area on left bank of Sébé River upstream from sand beach near bridge; -0.9349, 13.3570; 20 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19390. GABON • one, 64.27mm; Road R19 between Lastoursville and Compagnie Equatoriale des Bois headquarters; -0.7725, 12.9117; 11 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville, Gervais Koudaou leg.; OS19444. GABON • two, 60.45-79.36mm; Small stream near Hotel Escale de l'Ogooué, Lastoursville; -0.8055, 12.7444; 8 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville leg.; OS19442. GABON • one, 36.8mm; Stagnant river east of Lastoursville and south of road R19 near bridge; -0.8077, 12.9263; 10 Sep. 2014; John P. Sullivan, Thibault Cavalier de Cuverville, Jean Hervé Mvé Beh, Colin Apse, Gervais Koudaou leg.; OS19441. GABON • one, 28.77mm; Right bank of Ogooué River at factory near Doumé village; -0.8417, 12.9558; 17 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville leg.; OS19443. GABON • three, 26.41-36.46mm; Road R19 between Lastoursville and Compagnie Equatoriale des Bois headquarters; -0.7725, 12.9117; 11 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville, Gervais Koudaou leg.; OS19440. GABON • 13, 26.12-50.61mm; Sébé River at sand beach near bridge; -0.9349, 13.3570; 20 Sep. 2014; Thibault Cavalier de Cuverville, Gervais Koudaou, Jean Hervé Mvé Beh leg.; OS19439. GABON • one, 21.04mm; Small stream 2km east of Lélama; -1.0085, 13.5098; 21 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh, Brian L. Sidlauskas, Gervais Koudaou leg.; OS19799. Figure 2.12G.

Identification. Two pairs barbels. 11-12 circumpeduncular scales, 20-31 scales in lateral line. Last simple ray of dorsal fin heavily ossified and serrated. Large dark stripe on flank. Dorsal fin colorless; 25-29 scales in lateral line.

Opsaridium ubangiense **(Pellegrin 1901)**

Material examined: GABON • three, 37.39-53.82mm; Road 19 east of Compagnie Equatoriale des Bois headquarters at stream crossing; -0.7442, 12.9994; 13 Sep.

2014; Thibault Cavalier de Cuverville, Gervais Koudaou leg.; OS19448. GABON • one, 23.12mm; Moumba River; -0.7587, 12.9810; 13 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19447. Figure 2.12H.

Identification. Nine or more branched anal rays. Lateral line decurved below mid-line. Barbels absent. Flanks silvery and marked with numbers bars. Maxilla short and not generally reaching beyond center of eye. Snout rounded and, in breeding adults, studded with large granular tubercles.

***Raiamas buchholzi* (Peters 1877)**

Material examined: GABON • one, 131.91mm; Left bank of Ogooué River at Doumé village, including small side channel; -0.8424, 12.9624; 16 Sep. 2014; Jean Hervé Mvé Beh leg.; OS19384. GABON • one, 109.36mm; Left bank of Ogooué River at Doumé village, including small side channel; -0.8424, 12.9624; 15 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19385. GABON • one, 74.51mm; Left bank of Ogooué River at Doumé village, including small side channel; -0.8424, 12.9624; 16 Sep. 2014; Jean Hervé Mvé Beh leg.; OS19450. GABON • one, 73.72mm; Confluence of Moumba and Ogooué Rivers; -0.8923, 12.9706; 17 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19452. GABON • one, 73.58mm; Ogooué River at Doumé, below the rapids; -0.8413, 12.9654; 17 Sep. 2014; Jean Hervé Mvé Beh leg.; OS19386. GABON • one, 72.21mm; Road 19 east of Compagnie Equatoriale des Bois headquarters at stream crossing; -0.7442, 12.9994; 13 Sep. 2014; Gervais Koudaou, Thibault Cavalier de Cuverville leg.; OS19387.

GABON • three, 68.58-76.07mm; Sand bank on left bank of Ogooué River at Doumé village; -0.8418, 12.9636; 15 Sep. 2014; Joseph S. Cutler, Brian L. Sidlauskas, Jean Hervé Mvé Beh leg.; OS19381. GABON • four, 62.77-116.61mm; Small stream near Hotel Escale de l'Ogooué, Lastoursville; -0.8055, 12.7444; 8 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville leg.; OS19379. GABON • one, 35.78mm; Moumba River; -0.7587, 12.9810; 12 Sep. 2014; Joseph S. Cutler, Gervais Koudaou leg.; OS19456. GABON • one, 34.86mm; Ogooué River at Doumé, below the rapids; -0.8413, 12.9654; 17 Sep. 2014; Jean Hervé Mvé Beh leg.; OS19727. GABON • three, 30.21-115.27mm; Road 19 east of Compagnie Equatoriale des Bois headquarters at stream crossing; -0.7442, 12.9994; 13 Sep. 2014; Gervais Koudaou, Thibault Cavalier de Cuverville leg.; OS19449. GABON • two, 29.02-29.04mm; Road 19 east of Compagnie Equatoriale des Bois headquarters at stream crossing; -0.7442, 12.9994; 13 Sep. 2014; Gervais Koudaou, Thibault Cavalier de Cuverville leg.; OS19454. GABON • eight, 28.94-67.26mm; Sébé River at sand beach near bridge; -0.9349, 13.3570; 20 Sep. 2014; Gervais Koudaou, Thibault Cavalier de Cuverville, Jean Hervé Mvé Beh leg.; OS19380. GABON • one, 28.87mm; Road 19 east of Compagnie Equatoriale des Bois headquarters at stream crossing; -0.7442, 12.9994; 13 Sep. 2014; Gervais Koudaou, Thibault Cavalier de Cuverville leg.; OS19453. GABON • one, 26.53mm; Small stream near Hotel Escale de l'Ogooué, Lastoursville; -0.8055, 12.7444; 7 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville leg.; OS19451. GABON • two, 23.36-27.64mm; Small stream near Hotel Escale de l'Ogooué, Lastoursville; -0.8055, 12.7444; 8 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville leg.; OS19458. GABON • six, 21.68-27.16mm; Moumba River; -0.7587, 12.9810; 12 Sep. 2014; Joseph S. Cutler, Gervais Koudaou leg.; OS19457. Figure 2.12I.

Identification. Nine or more branched anal rays. Lateral line decurved below mid-line. Barbels absent. Flanks silvery and marked with numbers bars. Maxilla long and usually reaching well beyond center of eye, snout acute. 13-16 circumpeduncular scales, 46-52 scales in lateral line, 8.5-11.5 scales between lateral line and dorsal fin origin. Elongated spot on caudal peduncle.

***Brienomyrus brachyistius* (Gill 1863)**

Material examined: GABON • one male, 138mm; Moumba Creek, under bridge within CEB concession between Ndambi and Miynza; -0.7587, 12.9810; 11 Sep. 2014; John P. Sullivan leg.; CUMV98082. GABON • one female, 135mm; Moumba Creek, under bridge within CEB concession between Ndambi and Miynza; -0.7587, 12.9810; 13 Sep. 2014; John P. Sullivan leg.; CUMV98111. GABON • one female, 120mm; Moumba Creek, under bridge within CEB concession between Ndambi and Miynza; -0.7587, 12.9810; 13 Sep. 2014; John P. Sullivan leg.; CUMV98112. Figure 2.13A.

Identification. Nostrils separated from each other and from the eye. Teeth only in the middle of each jaw. Body moderately elongate. Anal fin extends beyond the end of dorsal. Distal tips of last anal and dorsal fin rays offset. Dorsal fin base 0.41-0.68 times as long as anal fin base. 25-31 anal fin rays; 47-66 lateral line scales.

Figure 2.13. Mormyridae. A. Brienomyrus brachyistius, SL = 120mm, euthanized. B. Ivindomyrus marchei, SL = 135mm, euthanized. C. Marcusenius moori, SL = 112mm, euthanized. D. Mormyrops nigricans, SL= 228mm, euthanized. E. Mormyrops zanclirostris, SL = 167mm, euthanized. F. Petrocephalus microphthalmus, SL = 66.87mm, euthanized. G. Petrocephalus simus, SL = 92.08mm, preserved. H. Petrocephalus sullivani, SL = 77mm, euthanized. I. Stomatorhinus walkeri, SL =

40.0mm, preserved. J. Paramormyrops sphekodes, SL = 119mm, euthanized. K. Paramormyrops batesii, SL = 103mm, euthanized. L. Paramormyrops ntotom, SL = 147mm, euthanized

***Ivindomyrus marchei* (Sauvage 1879)**

Material examined: GABON • one male, 203mm; Sébé River, left bank rocks below bridge; -0.9344, 13.3577; 20 Sep. 2014; John P. Sullivan leg.; CUMV98176. GABON • one male, 180mm; Sébé River, left bank rocks below bridge; -0.9344, 13.3577; 20 Sep. 2014; John P. Sullivan leg.; CUMV98174. GABON • one male, 165mm; Sébé River, left bank rocks below bridge; -0.9344, 13.3577; 20 Sep. 2014; John P. Sullivan leg.; CUMV98175. GABON • one male, 137mm; Sébé River, left bank rocks below bridge; -0.9344, 13.3577; 20 Sep. 2014; John P. Sullivan leg.; CUMV98173. GABON • one male, 135mm; Sébé River, left bank rocks below bridge; -0.9344, 13.3577; 20 Sep. 2014; John P. Sullivan leg.; CUMV98171. GABON • one female, 135mm; Sébé River, left bank rocks below bridge; -0.9344, 13.3577; 20 Sep. 2014; John P. Sullivan leg.; CUMV98172. Figure 2.13B.

Identification. Nostrils close to one another, mid-way between eye and end of snout. Body moderately deep and laterally compressed. Caudal peduncle distinct, slender and elongate. Mouth subterminal, globular swelling under chin present. Five teeth in upper jaw, six in lower. Frontal profile straight or slightly convex. EOD peak P1 greater than 40% of peak-to-peak height, peak P3 less than 0.2% of peak-to-peak height.

***Marcusenius moorii* (Günther 1867)**

Material examined: GABON • one male, 144mm; Sébé River, left bank rocks below bridge; -0.9344, 13.3577; 20 Sep. 2014; John P. Sullivan leg.; CUMV98170. GABON • one male, 133mm; Sébé River, left bank rocks below bridge; -0.9344, 13.3577; 22 Sep. 2014; John P. Sullivan, Marie-Claire Paiz, Alain Dole leg.; CUMV98183. GABON • one female, 122mm; Doumé rapids, left bank of Ogooué River; -0.8413, 12.9654; 17 Sep. 2014; Brian L. Sidlauskas, John P. Sullivan leg.; CUMV98145. GABON • four, 119.5-139.69mm; Sébé River, left bank rocks below bridge; -0.9344, 13.3577; 20 Sep. 2014; John P. Sullivan leg.; OS19370. GABON • one male, 118mm; Sébé River, left bank rocks below bridge; -0.9344, 13.3577; 22 Sep. 2014; John P. Sullivan, Marie-Claire Paiz, Gervais Koudaou leg.; CUMV98184. GABON • one female, 112mm; Doumé rapids, left bank of Ogooué River; -0.8413, 12.9654; 17 Sep. 2014; Brian L. Sidlauskas, John P. Sullivan leg.; CUMV98146. GABON • one female, 111mm; Moumba Creek, under bridge within CEB concession between Ndambi and Miynza; -0.7587, 12.9810; 11 Sep. 2014; John P. Sullivan leg.; CUMV98085. GABON • one female, 106mm; Doumé rapids, left bank of Ogooué River; -0.8413, 12.9654; 17 Sep. 2014; Brian L. Sidlauskas, John P. Sullivan leg.; CUMV98147. GABON • one female, 105mm; Moumba Creek, under bridge within CEB concession between Ndambi and Miynza; -0.7587, 12.9810; 14 Sep. 2014; Joseph S. Cutler, John P. Sullivan leg.; CUMV98124. GABON • two, 103.75-109.52mm; Ogooué River at Doumé village; -0.8424, 12.9624; 15 Sep. 2014; Joseph

S. Cutler, Brian L. Sidlauskas, Jean Hervé Mvé Beh leg.; OS19373. GABON • one, 68.4mm; Lélama Creek; -0.9961, 13.5257; 19 Sep. 2014 John P. Sullivan leg.; OS19374. GABON • two, 68.26-84.31mm; Moumba River; -0.7587, 12.9810; 11 Sep. 2014; John P. Sullivan leg.; OS19372. Figure 2.13C.

Identification. Nostrils separated from each other and from the eye. Body depth 26.6-32.8% standard length, head length 24.1-29.0% standard length. Snout blunt, mouth terminal, submental swelling prominent and forward-projecting. Eight circumpeduncular scales, 37-42 lateral line scales, 17-26 dorsal rays, and 24-33 anal fin rays. Dark vertical band between dorsal and anal fins.

***Mormyrops nigricans* (Boulenger 1899)**

Material examined: GABON • one male, 228mm; Doumé rapids, left bank of Ogooué River; -0.8413, 12.9654; 17 Sep. 2014; John P. Sullivan, Brian L. Sidlauskas leg.; CUMV98148. Figure 2.13D.

Identification. Nostrils separated from each other and from the eye. Teeth extending along the entire edge of both jaws, mouth terminal. Body moderately elongate, body depth more than 16% standard length. 10-12 circumpeduncular scales, fewer than 58 lateral line scales. Color dark grey to black with darker longitudinal lines, especially ventrally.

***Mormyrops zanclirostris* (Günther 1867)**

Material examined: GABON • one female, 212mm; Sébé River: rocky outcrop below bridge, left bank; -0.9344, 13.3577; 22 Sep. 2014; John P. Sullivan, Marie-Claire Paiz, Alain Dole leg.; CUMV98182. GABON • one female, 167mm; Sébé River: rocky outcrop below bridge, left bank; -0.9344, 13.3577; 22 Sep. 2014; John P. Sullivan, Marie-Claire Paiz, Alain Dole leg.; CUMV98181. GABON • one, 94mm; Small stream on route CEB; -0.7725, 12.9117; 11 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville, Gervais Koudaou leg.; CUMV98096. Figure 2.13E.

Identification. Nostrils separated from each other and from the eye. Teeth extending along the entire edge of both jaws, mouth terminal. Snout long, tubular and trumpet-like. Snout length more than 70% of post-orbital length of head.

Petrocephalus microphthalmus **(Pellegrin 1908)**

Material examined: GABON • one, 80.78mm; Right bank of Sébé River, main channel near bridge -0.9353, 13.3576; 20 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19375. GABON • one male, 70mm; Sandy Beach near bridge on Sébé River; -0.9349, 13.3570; 20 Sep. 2014; John P. Sullivan, Brian L. Sidlauskas, Gervais Koudaou leg.; CUMV98158. GABON • one, 66.87mm; Wooded area on left bank of Sébé River upstream from sand beach near bridge; -0.9349, 13.3570; 20 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19371. GABON • one, 43mm; Moumba Creek, under bridge within CEB concession between Ndambi and Miynza; -0.7587, 12.9810; 13 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; CUMV98200. Figure 2.13F.

Identification. Nostrils close to one another and to the eye; mouth inferior; body short and rather deep. No spot near base of dorsal fin. Dorsal fin with 15-18 segmented rays. 8-10 scale rows between the origin of the anal fin and the lateral line. Eye small 21-24% of head length.

***Petrocephalus simus* (Sauvage 1879)**

Material examined: GABON • one, 92.08mm; Left bank of Ogooué River at Doumé village, including small side channel; -0.8424, 12.9624; 15 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; OS19388. Figure 2.13G.

Identification. Nostrils close to one another and to the eye; mouth inferior; body short and rather deep. No spot near base of dorsal fin. Dorsal fin with 19 or more segmented rays. 11 or more scale rows between the origin of the anal fin and the lateral line. Mouth inferior. EOD with two peaks.

***Stomatorhinus walkeri* (Günther 1867)**

Material examined: GABON • one male, 78mm; Moumba Creek, under bridge within CEB concession between Ndambi and Miynza; -0.7587, 12.9810; 11 Sep. 2014; John P. Sullivan leg.; CUMV98083. GABON • one female, 71mm; Moumba Creek, under bridge within CEB concession between Ndambi and Miynza; -0.7587, 12.9810; 14 Sep. 2014; Joseph S. Cutler, John P. Sullivan leg.; CUMV98122. GABON • one, 56mm; Moumba Creek, under bridge within CEB concession between Ndambi and Miynza; -0.7587, 12.9810; 14 Sep. 2014; Joseph S. Cutler, John P.

Sullivan leg.; CUMV98123. GABON • one, 38mm; Small stream on route CEB; -0.7725, 12.9117; 11 Sep. 2014; Joseph S. Cutler, Gervais Koudaou, Thibault Cavalier de Cuverville leg.; CUMV98076. GABON • two, 36.01-40.0mm; Road R19 between Lastoursville and Compagnie Equatoriale des Bois headquarters; -0.7725, 12.9117; 11 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville, Gervais Koudaou leg; OS19376. GABON • three, 32.23-41.82mm; Road R19 between Lastoursville and Compagnie Equatoriale des Bois headquarters; -0.7725, 12.9117; 11 Sep. 2014; Joseph S. Cutler, Thibault Cavalier de Cuverville, Gervais Koudaou leg; OS19377. GABON • one male; Moumba Creek, under bridge within CEB concession between Ndambi and Miynza; -0.7587, 12.9810; 11 Sep. 2014; John P. Sullivan leg.; CUMV98084. Figure 2.13I.

Identification. Nostrils separated from each other and from the eye, posterior nostril close to the border of the mouth. Pectoral rays 10-12, dorsal rays 18-20, pored scales of lateral line reach caudal peduncle. Body depth 25-29% standard length. 46-53 lateral line scales, 12-14 circumpeduncular scales.

Paramormyrops sphekodes **(Sauvage 1879)**

Material examined: GABON • one male, 139mm; Sébé River, left bank rocks below bridge; -0.9344, 13.3577; 20 Sep. 2014; John P. Sullivan leg.; CUMV98162. GABON • one male, 122mm; Sébé River, left bank rocks below bridge; -0.9344, 13.3577; 22 Sep. 2014; John P. Sullivan, Marie-Claire Paiz, Alain Dole leg.; CUMV98177. GABON • one female, 118mm; Sébé River, left bank rocks below bridge; -0.9344, 13.3577; 20 Sep. 2014; John P. Sullivan leg.; CUMV98161. GABON • one male, 118mm; Sébé River, left bank rocks below bridge; -0.9344, 13.3577; 20 Sep. 2014; John P. Sullivan leg.; CUMV98159. GABON • one female, 112mm; Doumé rapids, left bank of Ogooué River; -0.8413, 12.9654; 17 Sep. 2014; John P. Sullivan, Brian L. Sidlauskas leg.; CUMV98154. GABON • one female, 115mm; Left bank Ogooué river, just above rapids at Doumé; -0.8414, 12.9658; 17 Sep. 2014; Joseph S. Cutler, Jean Hervé Mvé Beh leg.; CUMV98152. GABON • one male, 111mm; Sébé River, left bank rocks below bridge; -0.9344, 13.3577; 20 Sep. 2014; John P. Sullivan leg.; CUMV98160. GABON • one female, 97mm; Doumé rapids, left bank of Ogooué River; -0.8413, 12.9654; 17 Sep. 2014; John P. Sullivan, Brian L. Sidlauskas leg.; CUMV98153. Figure 2.13J.

Identification. Nostrils separated from each other and from the eye. Five teeth in upper jaw, six in lower. Fewer than 16 scales (typically 12) around the caudal peduncle. Head profile V-shaped when viewed from above. Upper profile of head rounded, mouth inferior. Head length 22.2% of standard length of less.

***Paramormyrops batesii* (Boulenger 1906)**

Material examined: GABON • one male, 113mm; Small stream tributary to Lelama Creek; -0.9983, 13.5321; 23 Sep. 2014; Joseph S. Cutler, Marie-Claire Paiz, Gervais Koudaou leg.; CUMV98185. GABON • one male, 103mm; Small stream tributary to Lelama Creek; -0.9983, 13.5321; 23 Sep. 2014; Joseph S. Cutler, Marie-Claire Paiz, Gervais Koudaou leg.; CUMV98186. GABON • one male, 99mm; Moumba Creek, under bridge within CEB concession between Ndambi and Miynza; -0.7587, 12.9810; 11 Sep. 2014; John P. Sullivan leg.; CUMV98093. GABON • one male, 87mm; Small stream tributary to Lelama Creek; -0.9983, 13.5321; 23 Sep. 2014; Joseph S. Cutler, Marie-Claire Paiz, Gervais Koudaou leg.; CUMV98187. GABON • one male, 86mm; Small stream tributary to Lelama Creek; -0.9983, 13.5321; 23 Sep. 2014; Joseph S. Cutler, Marie-Claire Paiz, Gervais Koudaou leg.; CUMV98189. GABON • one male, 86mm; Small stream tributary to Lelama Creek; -0.9983, 13.5321; 23 Sep. 2014; Joseph S. Cutler, Marie-Claire Paiz, Gervais Koudaou leg.; CUMV98188. GABON • one male, 78mm; Small stream tributary to Lelama Creek; -0.9983, 13.5321; 23 Sep. 2014; Joseph S. Cutler, Marie-Claire Paiz, Gervais Koudaou leg.; CUMV98190. GABON • one female, 77mm; Small stream tributary to Lelama Creek; -0.9983, 13.5321; 23 Sep. 2014; Joseph S. Cutler, Marie-Claire Paiz, Gervais Koudaou leg.; CUMV98192. GABON • one female, 73mm; Small stream tributary to Lelama Creek; -0.9983, 13.5321; 23 Sep. 2014; Joseph S. Cutler, Marie-Claire Paiz, Gervais Koudaou leg.; CUMV98191. GABON • one, 67mm; Small stream tributary to Lelama Creek; -0.9983, 13.5321; 23 Sep. 2014; Joseph S. Cutler, Marie-Claire Paiz, Gervais Koudaou leg.; CUMV98196. GABON • one, 64mm; Small stream on route CEB; -0.7725, 12.9117; 11 Sep. 2014; Joseph Cutler, Thibault Cavalier, Gervais Koudaou leg.; CUMV98098. GABON • one, 61mm; Small stream tributary to Lelama Creek; -0.9983, 13.5321; 23 Sep. 2014; Joseph S. Cutler, Marie-Claire Paiz, Gervais Koudaou leg.; CUMV98193. GABON • one, 56mm; Small stream tributary to Lelama Creek; -0.9983, 13.5321; 23 Sep. 2014; Joseph S. Cutler, Marie-

Claire Paiz, Gervais Koudaou leg.; CUMV98194. GABON • one, 52mm; Small stream on route CEB; -0.7725, 12.9117; 11 Sep. 2014; Joseph Cutler, Thibault Cavalier, Gervais Koudaou leg.; CUMV98094. GABON • one, 50mm; Small stream tributary to Lelama Creek; -0.9983, 13.5321; 23 Sep. 2014; Joseph S. Cutler, Marie-Claire Paiz, Gervais Koudaou leg.; CUMV98197. GABON • one, 48mm; Small stream on route CEB; -0.7725, 12.9117; 11 Sep. 2014; Joseph Cutler, Thibault Cavalier, Gervais Koudaou leg.; CUMV98099. GABON • one, 42mm; Small stream on route CEB; -0.7725, 12.9117; 11 Sep. 2014; Joseph Cutler, Thibault Cavalier, Gervais Koudaou leg.; CUMV98095. GABON • one, 41mm; Small stream on route CEB; -0.7725, 12.9117; 11 Sep. 2014; Joseph Cutler, Thibault Cavalier, Gervais Koudaou leg.; CUMV98097. GABON • one, 35mm; Small stream tributary to Lelama Creek; -0.9983, 13.5321; 23 Sep. 2014; Joseph S. Cutler, Marie-Claire Paiz, Gervais Koudaou leg.; CUMV98195. Figure 2.13K.

Identification. Nostrils separated from each other and from the eye. Five teeth in upper jaw, six in lower. 16 or more scales around caudal peduncle. Caudal peduncle less than 24.5% standard length. More than 72 lateral line scales.

Discussion

Previous to this expedition, Alfred Marche conducted the only extensive sampling in this zone in 1876-7, when he collected a total of 42 species belonging to ten families (Sauvage 1879, 1880). The 97 species of fish collected on this expedition contribute significantly to the known ichthyofauna of the Rapids of Mboungou Badouma and

Doumé Ramsar site and fill a major hole in our knowledge of the Ogooué basin's fish diversity. While some of those species including: *Enteromius camptacanthus, Raiamas buchholzi*, and *Marcusenius moori*, are widely distributed in the upper and lower Ogooué (Stiassny et al. 2007) and were already suspected to be present in the Ramsar site, others are entirely new to science, are already described species but with widely extended ranges, or were the subjects of longstanding taxonomic conundrums that we have helped clarify (eg. *Paramormyrops sphekodes* (Rich et al. 2017)). These discoveries, including the description of the novel genus *Cryptomyrus* (Sullivan et al. 2016), exemplify the region's underexplored nature, and highlight the need for further collections and revisionary taxonomic study. Such data in turn help catalog the biodiversity of newly formed protected areas and serve as baselines for environmental monitoring.

Of the 12 species Sauvage (1879) reported from Marche's Doumé collection, we recovered only two (*Paramormyrops sphekodes* and *Petrocephalus simus*) at Doumé proper, though although all but *Labeobarbus compiniei* were recovered at other sites during the expedition. Neither Sauvage nor Marche specified if all Marche's species had come from the Ogooué itself, or whether some could have been from nearby tributaries. The absence of some of Sauvage's species from our collections at Doumé suggest that these early specimen series may include material from a variety of locations around the village, including nearby small rivers.

Conservation Implications

The government of Gabon has shown a high degree of interest in conservation by designating thirteen national parks and nine Ramsar sites to date. This does not mean, however, that Gabon's freshwater ecosystems are well protected. Gabon's nine Ramsar sites, including the Rapides de Mboungou-Badouma et de Doumé, have no clear management restrictions or funding. Freshwater ecosystems in this region and globally, face considerable threats that fall into four major categories; 1) overexploitation, 2) introduced species, 3) habitat destruction, and 4) pollution (modified from Diamond 1984).

While the region encompassing the Rapides de Mboungou-Badouma et de Doumé Ramsar site is largely uninhabited, it is bounded upstream and downstream by small cities (Mouana and Lastoursville) and there are three fishing communities (Mboungou-Badouma, Lifouta and Doumé) located within the Ramsar site. Overexploitation of fisheries resources, particularly large migratory members of Siluriformes and Cypriniformes, poses a threat to certain freshwater species in the region. Most fisheries in this region are small-scale artisanal fisheries and most of the fish is consumed locally, so the likelihood of local fisheries overexploitation is minimal.

Our team collected no invasive fish species on this expedition, but invasive fish species (including *Oreochromis niloticus*, *Heterotis niloticus*, and *Clarias gariepinus*) are widespread throughout Gabon. The Doumé area is particularly at risk for introduced species as the two largest aquaculture facilities in Gabon, SODEPARL (Societe d'exploitation du Parc de la Lekedi) and CEB (Compagnie Equatoriale des

Bois/Precious Wood) are near Doumé. Fish farming efforts have often been linked to accidental species introductions and once invasive species become established, they threaten native species through predation, trophic cascades, competitive exclusion and, in some cases, hybridization (Stiassny et al. 2011).

The most visible threat to biodiversity in this region is habitat destruction and pollution associated with mining, dams, and timber extraction. Immediately upstream of the Rapides de Mboungou-Badouma et de Doumé Ramsar site, mines in Franceville, Mounana and Moanda and the Grand Poubara Dam drastically alter the Ogooué watershed and threaten biodiversity and ecosystem function. Mining—especially large, open mines—generates pollution and erosion and is detrimental to river health. The government of Gabon plans to develop new mines in the region including mines near Franceville and Okonja. Active forestry concessions border the Ogooué on both the North and South of the Ramsar site. Industrial extraction of timber has been known to modify patterns of sediment run-off and transport, ultimately affecting ecosystem functioning and biodiversity (Gerbersdorf et al. 2007). Effectively protecting the Rapides de Mboungou-Badouma et de Doumé Ramsar site will require management of both the immediate site and the watershed.

During the expedition we collected several species that appear to be entirely new to science and these discoveries exemplify the region's underexplored nature and highlights the need for further collections and taxonomic study. This article is not an exhaustive species list for the Ramsar site Rapides de Mboungou-Badouma et de Doumé, but it does greatly expand the known biodiversity of the region and serves as a foundation for the development of resource management plans in the area. I encourage others to explore, investigate and protect the Rapids of Mboungou-Badouma and Doumé region.

Authors' Contributions

JSC, YF, JPS, JHMB and BLS collected the data and identified the specimens. JSC, JPS, JHMB and BLS took photographs of recently euthanized or preserved specimens. JSC wrote the text with significant contributions from JPS, JHMB, and BLS.

Chapter 3:

Title: Evaluating the Distribution of Freshwater Fish Diversity using a Multispecies Habitat Suitability Model to Assess Impacts of Proposed Dam Development in Gabon, Africa

Submitted to Conservation Science and Policy

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Abstract

Few impact assessments have targeted the 39 proposed hydroelectric dams located in the central African nation of Gabon. This scarcity of data impedes a comprehensive assessment of potential impacts of these dams on Gabon's rich freshwater diversity. Here, we present a multiple-species MaxEnt distribution modeling approach to assess species richness for freshwater fishes at the landscape level and demonstrate its utility in identifying proposed dam sites in Gabon that fall in highly diverse areas. We modeled habitat suitability for 202 of Gabon's fresh and brackish water fish species based on georeferenced presence data from museum specimens and a set of ecologically meaningful environmental conditions. We removed poor performing species and compiled the distributions of 114 well-performing species to generate a new metric, species pseudorichness (*p*R), defined as the cumulative number of species that are highly suited to the habitat in a given segment of river. We used *p*R as a proxy for true species richness and use this metric evaluate the distribution of freshwater fish diversity relative to the proposed dam development in Gabon. We found that more than 80% of the proposed dams in Gabon overlap with areas of high *p*R, implying that planned hydroelectric development in Gabon may disproportionately impact high diversity areas. These dams deserve more focused baseline assessments and conservation action. This approach provides a rapid way to initiate a landscape-scale assessment of freshwater fish diversity to inform conservation decisions in areas that are species rich, but data poor.

Introduction

In North America and Europe, few new dams are being constructed and more dams are being removed than built because the best sites have already been developed, the dams are too expensive, and the overwhelming environmental and social costs of new construction outweigh the benefits (O'Connor et al. 2015). De-emphasis on hydropower in the developed world contrasts with energy strategies in developing countries where an estimated 3,700 large dams (>1MW) are planned or under construction, including dams on the world's largest and most diverse river systems, the Amazon, Congo, Mekong and the Ogooué (Zarfl et al. 2014; Winemiller et al. 2016). Developing countries need renewable and affordable energy resources to ensure long-term energy independence, but hydropower development poses threats to local animal populations, ecosystems and human communities.

Hydropower dams dramatically alter the ecosystem, are often much costlier than expected and have long-lasting socioeconomic and ecological impacts (Rex et al. 2014). Most large dams are designed to serve growing industries and urban populations and decision-makers often underestimate or overlook their impacts (Scott et al. 2011). Large dam development can displace rural communities, cause loss of livelihood, change food availability and degrade water quality (Tilt et al. 2009). Large dams change a river's ecology and can result in negative consequences including; habitat fragmentation (Fearnside 2014), fisheries collapse (McCarthy et al. 2008), changes to sedimentation regimes (Lingon et al. 1995), large releases of greenhouse gases (Fearnside & Pueyo 2012), and loss of aquatic and terrestrial biodiversity (Rosenberg 2000). The impacts of hydropower development can be long-lasting or permanent, but hydropower dams have a finite lifespan and those in the tropics tend to have a shorter lifespan due to higher sedimentation rates (Vauchel et al. 2017). Unfortunately, assessing the impacts of dam development in high biodiversity, data-poor regions including Central Africa, can be challenging as conservationists and decision-makers often suffer from a lack of baseline data.

Gabon has four existing large dams; Kinguélé (57.6MW), Tchimbélé (68.4MW), Bongolo (5.5MW) and Grand Poubara (157MW). Only one of them (Grand Poubara) lies on Gabon's greatest river, the Ogooué, which is the fourth largest by discharge in Africa and home to over 350 fish species. Because most of the Ogooué system is undammed and the watershed is sparsely populated (<5 people/km^2), the Ogooué represents one of the most pristine large tropical rivers in Africa. However, Gabon aims to develop the capacity to produce 1,200MW of hydropower energy, and is considering 39 potential hydropower dams across the country – including 28 in the Ogooué watershed (African Development Bank 2011; AECOM 2017).

The impacts of these proposed dams on biodiversity and ecosystem function have not been fully evaluated. Our understanding of Gabon's freshwater biogeography is built upon an incomplete sampling record limited to the reach of Gabon's road network. In order to identify proposed dam sites that will disproportionately affect fish biodiversity, we need to know how biodiversity is distributed across the landscape and at potential dam sites. Unfortunately, neither the time nor funding exists to conduct exhaustive baseline biodiversity assessments at every potential dam site. Therefore, we used a synthesis of distributional data from historical surveys and vouchered museum specimens paired with high-resolution environmental layers to map the distribution of suitable habitat for approximately one-third of Gabon's freshwater fish species. By stacking these distributions, we generate a new metric, species pseudorichness index (*p*R) to predict the distribution of fish diversity at the landscape level and at each of the 39 proposed dam sites in Gabon. Our approach is rapid, cost-effective, open-source and transferable to other areas of the world with limited biogeographic information and can help identify and mitigate negative impacts on freshwater ecosystems.

Methods

Data sources:

Presence records for Gabon's fresh and brackish water fishes were compiled from three open-source databases; The Global Biodiversity Information Facility, FAUNAFRI and Oregon State University's Specify database. These sources provide data on expertly identified museum specimens and any specimen with uncertain identifications or low precision locality data were excluded from the data set. Our final dataset included 314 fish species and 6,061 distinct point occurrences.

We collected relevant environmental data to characterize the riverscape and ran geoprocessing routines in ArcGIS Pro 2.6 to delineate a high-resolution drainage network segmented in 100-meter reaches and obtain local channel gradient, mean annual discharge, valley confinement, elevation and distance to the ocean. By using a 12.5-meter resolution L-Band Digital Elevation Model (ALOS PALSAR, Japan Aerospace Exploration Agency and University of Alaska, Fairbanks), we incorporated the most accurate space-borne topographic data for hydrological modeling (Shawky et al. 2019). Lastly, we generated 100-meters riparian buffers and computed zonal statistics of other potentially influential environmental predictors including land-cover (CCI, ESA), tree canopy percent (USGS, U. of Maryland), erodibility (TNC), temperature and precipitation (WorldClim 2).

Model construction:

Our species-level habitat assessment modeling took a Maximum Entropy approach (Maxent; Phillips et al. 2005). MaxEnt is a machine-learning algorithm that builds relationships between presence-only records and a set of environmental variables to estimate a target probability distribution of maximum entropy (the most uniform distribution) (Merow et al. 2013). To ensure that we were working with enough data to construct effective models, we excluded any species collected at fewer than five distinct sampling localities, developed models for the remaining species, and tested the model performance for each species. All the species with lower performing models (AUC<0.75) were excluded from the final dataset. Of the 351 fish species known to occur in Gabon's freshwater ecosystems, a total of 114 species and 62 genera were included in the final version of the multispecies model (Supporting Information). Species included in this analysis span many ecological guilds (sensu Welcomme et al. 2006). and include range restricted and migratory species that are expected to be adversely affected by dam development.

For model optimization, we used the R package 'MaxentVariableSelection'. This package identifies the most influential and uncorrelated environmental variables and finds an optimal regularization multiplier to avoid building overcomplex or overfitted models. It varies parameters among stepwise MaxEnt runs and assesses performance with the Area Under the receiver operating Characteristic (AUC) (Jueterbock et al. 2016). Due to the processing constraints of optimizing the model for all species, we grouped them by habitat-type guilds (Welcomme et al. 2006). Final parameters were set by harmonizing the models with the highest AUC and lowest Akaike Information Criterion (AIC) values. During model optimization, the mean annual temperature was dropped from the analysis because of collinearity with elevation ($r^2 = 0.95$), and land cover and tree cover percent were dropped because of their small contribution to predictions (< 5%). To test the model's sensitivity to range-restricted species, we removed all medium and highly range-restricted fish species from the data set and re-ran the analyses. When all range-restricted species are removed from the analysis model performance decreases, but the general conclusions remain unchanged. We therefore retained all 114 fish species for the final model presented here.

We developed a species pseudorichness (*p*R) index defined as the cumulative number of species that are highly suited to the habitat in a given segment of river. To generate the *p*R index, we used a conservative occurrence probability threshold (mean plus standard deviation) for extracting only areas with high probability of occurrence for each species. We then stacked the outputs from the 114 species distribution models and tallied the number of species expected to occur at each point to quantify *p*R and assess habitat suitability for freshwater fishes at the landscape level (Fig. 3.1). The average *p*R for Gabon's freshwater ecosystems was 21 and we used a standard-deviation classification method to create four pseudorichness classes; low (*p*R < 4), medium-low (5< *p*R <21), medium-high (22 < *p*R < 39) and high (*p*R >39) (Supporting Information).

Results

We developed a multiple-species MaxEnt model to predict freshwater fish species richness using more than one hundred of Gabon's fish species (Fig. 3.1). We identified potential biodiversity hotspots and assess the siting of prospective dams in Gabon. Highly suitable habitats (*p*R >39) identified using this method lie in every coastal watershed, the Nyanga drainage, and throughout the Ogooué system, including its major tributaries the Ivindo and Ngounie. The *p*R appears elevated near the coast and in main river channels but reduced in smaller streams and the high elevation areas in central Gabon. Model performance at the species level was good to very good, with a mean test AUC of 0.85 (min. 0.75, max., 0.98).

To validate the *p*R metric we ran a Spearman Rank Correlation between observed richness and *p*R using data from fifteen well-sampled localities of Gabon, showing to be duly correlated ($r_s = 0.68$, *p-value* = 0.005). The influence of different environmental variables in the distribution modeling varied among fish guilds, although topography-based conditions were the most important in training accurate models. In order, elevation, distance to the ocean, valley-confinement, discharge and channel gradient were the most important in the overall pseudorichness model. When we ran analyses without range-restricted species the results were unchanged as all dam sites fall within the same quadrant as in Fig. 3.2. Moreover, when all range-restricted species are removed from the analysis model performance decreases, especially in headwaters and tributaries, and particularly in the coastal regions and the Ivindo drainage.

In order to assess potential overlaps of proposed hydropower dams and places with high fish diversity, we compared *p*R at Gabon's 39 proposed dam sites (Fig. 3.1, Table 3.1). Of the 39 proposed dam sites in Gabon, 32 overlapped with areas of high species pseudorichness (*p*R >39) and dam development in those regions will likely affect more fish species than those dams proposed in less diverse regions (Fig. 3.1).

The following proposed dams fall in areas of high *p*R: Akieni, Angouma, Chutes Booué, the Chutes de l'Imperatrice, the Derivation Ogooué-Lolo, Dibwangui, Fe II, Guietsou, Ibola, Iboundji, Igotchi, Iroungou, Kinguele amont, Kinguele aval, Kongue, Kouta-Mango, Lebombi, Liboka, Lifoula, Mafoula Matato, Makongonio, Mingouli, Moulengui-Bindza, Nemguembani, Ndindi, Ngoulmendjim, Omvan aval, Ovan, Sindara, Souka-Minimal, Tchimbele aval, and Tsengue-Leledi (Supporting information). Moreover, 27 potential dams producing < 200MW are sited in areas of high *p*R (upper left quadrant of Fig. 3.2) and no dams have an ideal combination of low habitat suitability and high potential hydropower production (lower right quadrant of Fig. 3.2).

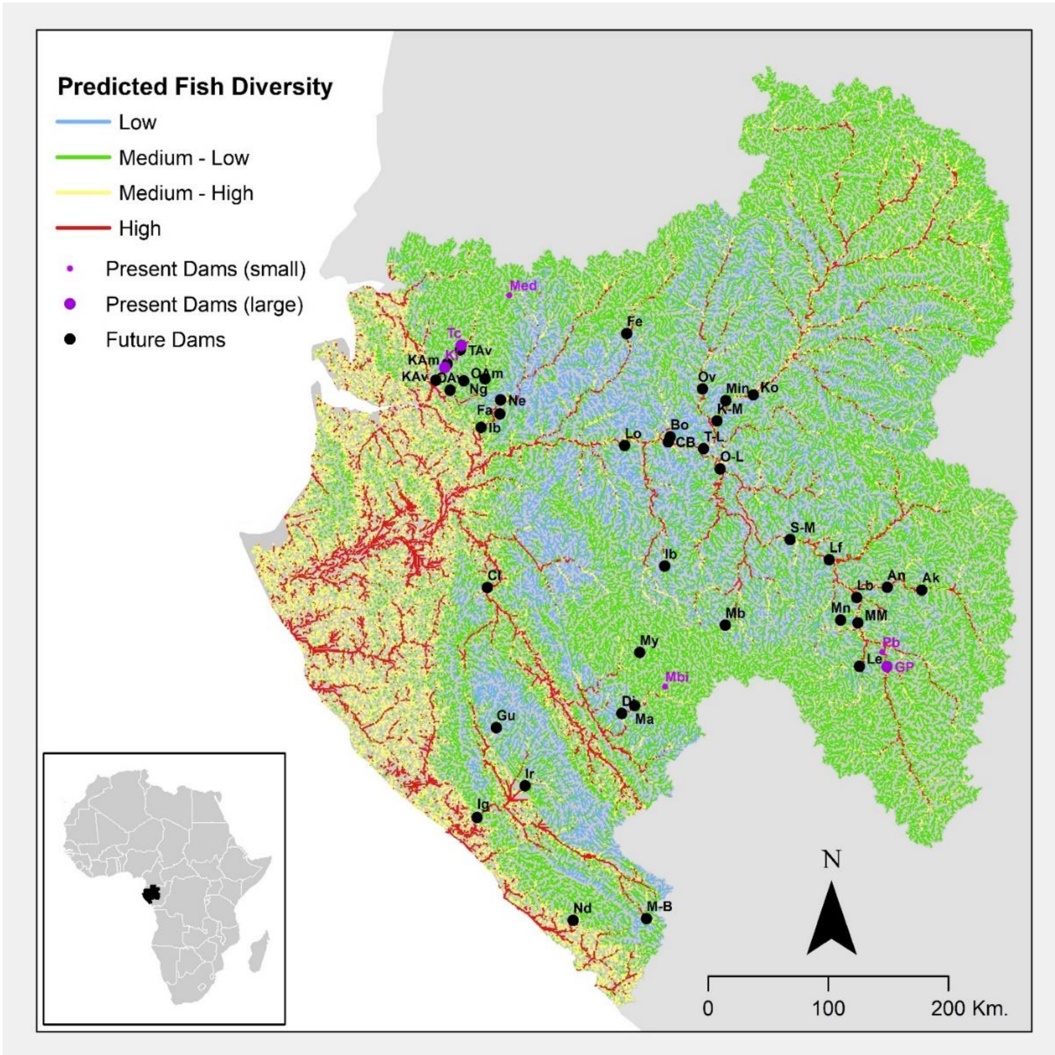

Figure 3.1: Map showing the predicted distribution for Gabon's fish diversity and proposed hydropower dams. Blue colors depict areas of low species pseudorichness (pR < 4), yellow to medium-low (< pR <21), orange to medium-high (22 < pR < 39) and red to areas of high species pseudorichness (pR >39). Existing dams appear as purple dots and proposed dam sites appear as black dots.

*Table 3.1. Proposed and existing dam sites in Gabon. * indicates existing dam.*

Dam Name	Code	River	Expected Production (MW)	Species Pseudorichness (pR)	Diversity Ranking
Kinguele aval	KAv	Mbei	60	74	High

Igotchi	Ig	Nyanga	5	74	High
Mingouli	Min	Ivindo	460	68	High
Lifoula	Lf	Ogooué	135	68	High
Kouata-Mango	K-M	Ivindo	445	67	High
Souka-Minimal	S-M	Ogooué	85	67	High
Chutes Booue	CB	Ogooué	1000	67	High
Ibola	Ib	Abanga	61	66	High
Kongue	Ko	Ivindo	435	66	High
Ndindi	Nd	Lagune Banio	0.1	66	High
Liboka	Lb	Ogooué	121	65	High
Tsengue-Leledi	T-L	Ivindo-Ogooué	565	64	High
Angouma	An	Lekoni	85	64	High
Ovan	Ov	M'voun g	3.5	61	High
Mafoula Matato	MM	Ogooué	88	61	High
Iroungou	Ir	Mougala ba	2	60	High
Akieni	Ak	Akieni	76	58	High
Moulengui-Bindza	M-B	Douli	0.1	56	High
Chutes de l'Imperatrice	CI	Ngounie	84	55	High
Derivation Ogooue-Lolo	O-L	Ogooué	550	54	High
Lebombi	Le	Lebomb i	42	54	High
Nemguembani	Ne	Abanga	74	53	High
Fe II	Fe	Okano	35	52	High
Kinguele amont	KAm	Mbei	41	48	High
Dibwangui	Di	Louetsi	10	45	High
Iboundji	Ib	Woubou	0.4	45	High
Tchimbele aval	TAv	Komo	55	44	High
Omvan amont	OAm	Mbei	35	44	High
Ngoulmendjim	Ng	Komo	100	44	High
Omvan aval	OAv	Mbei	25	43	High
Makongonio	Ma	Louetsi	5	43	High
Guietsou	Gu	Moussa	0.1	41	High

Lope	Lo	Ogooué	0.05	33	Medium-High
Mouyanama	My	Ngounie	0.2	23	Medium-High
Faga	Fa	Abanga	37	19	Medium-Low
Mboungou	Mb	Lolo	0.3	13	Medium-Low
Mounana	Mn	Ogooué	5	12	Medium-Low
Booue	Bo	Ogooué	2	6	Medium-Low

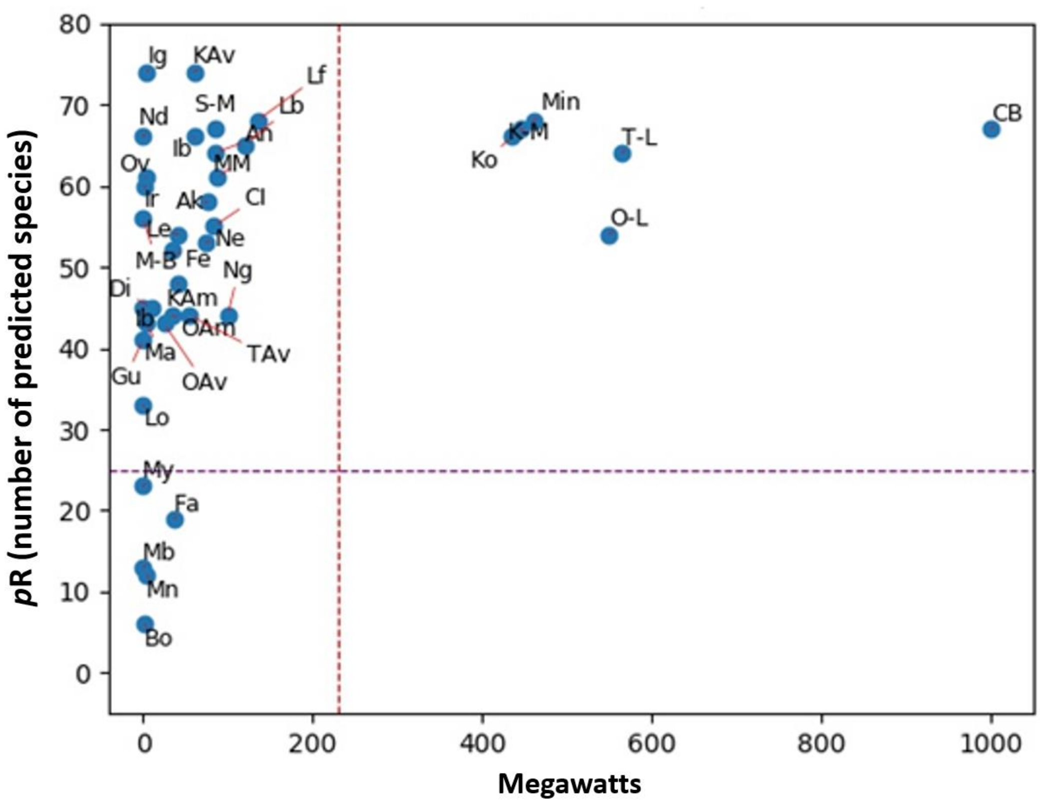

Figure 3.2: Scatterplot showing species pseudorichness and hydropower potential. Dotted lines delineate quadrants discussed in the text. Many minor dams, in the upper left quadrant of the figure, are situated in areas of high pseudorichness. No dams fall in the lower right quadrant. Dams coded as follows: Kinguele Aval (KAv), Kinguele Amont (KAm) Tchimbele aval (TAv), Omvan aval (OAv), Omvan amont (OAm), Nemguembani (Ne), Faga (Fa), Ibola (Ib), Mingouli (Min), Kongue (Ko), Kouata-Mango (K-M), Tsengue-Leledi (T-L), Derivation Ogooué-Lolo (O-L), Lebombi (Le),

Dibwangui (Di), Ovan (Ov), Souka-Minimal (S-M), Lifoula (Lf), Liboka (Lb), Mafoula Matato (MM), Angouma (An), Lope (Lo), Booué (Bo), Iboundji (Ib), Mboungou (Mb), Mouyanama (My), Mounana (Mn), Akieni (Ak), Makongonio (Ma), Guietsou (Gu), Iroungou (Ir), Igotchi (Ig), Ndindi (Nd), Moulengui-Bindza (M-B), Fe II (Fe), Chutes de l'Imperatrice (CI), Chutes Booue (CB), Ngoulmendjim (Ng).

Discussion

Our objective was to assess the distribution of freshwater diversity at the landscape level to serve as a baseline to assess potential impacts of potential dam development on freshwater biodiversity. We develop an index of species pseudorichness (pR) that provide a quantitative evaluation of the distribution of fish diversity across Gabon and at 39 potential hydropower dam sites. We identify that more than 80% of the proposed dams will be overlapping areas with high species pseudorichness. These sites deserve extra attention from scientists and conservationists.

It is important to note some limitations of our approach. First, our model does not account for watershed boundaries and this may result in an overestimation of species ranges, particularly species that are range restricted. Moreover, our model does not capture other critical aspects of biodiversity, such as the presence and/or absence of endangered species at proposed dam sites. A full impact assessment and conservation strategy will need to incorporate this and other dimensions of biodiversity, ecosystem health and ecosystem services.

Our approach is inexpensive, rapid, and easily applicable in areas with little data on biodiversity and biogeography and is a valuable first step in assessing potential impacts at the landscape level. We encourage that dams are not sited in high biodiversity areas, areas with threatened or endemic species, or migratory corridors

(Thieme et al. 2007; Winemiller et al. 2016), that thorough environmental impact assessments (EIAs) and social impact assessments (SIAs) are conducted in advance of dam construction by independent parties (Moran et al. 2018), and EIA's and SIA's assessments have the capacity to stop dam construction if deemed necessary (Égré & Senécal 2003).

Chapter 4:

Title: Predicting the distribution of Marine-Associated fishes in Gabon's Freshwater Ecosystems

Submitted to Ecological Applications

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Abstract

The construction of up to 39 potential hydropower dams may threaten the more than 350 fish species inhabiting freshwater ecosystems in the megadiverse African country of Gabon. Many of Gabon's most culturally and economically important fish species are marine-associated and move between fresh and salt or brackish waters, but we know little about their life histories or movement patterns. Therefore, assessing the potential impacts of dam development on biodiversity and fisheries in Gabon is challenging. Here, we apply MaxEnt distribution modelling to predict the distribution of marine-associated fishes in Gabon's freshwater ecosystems. The model predicts such fishes to have a high likelihood of occurring in every coastal watershed, throughout the undammed Nyanga drainage, and to extend approximately 400 km into Gabon's Ogooué River and its tributaries the Ngounie and the Abanga. If all 39 potential dams are constructed, marine-associated fish species will lose nearly 7,400 km (17%) of potentially accessible habitats, and over 460 km (7%) of highly suitable habitat will become inaccessible to marine-associated species. Thus, proposed hydropower dam development poses substantial threats to Gabon's fishes, and the free-flowing rivers they require.

Introduction

Freshwater ecosystems cover less than 0.01% of Earth's surface but are home to approximately 40% percent of the world's fish biodiversity (Dudgeon et al. 2006). Much of this diversity is concentrated in large tropical rivers, including the Amazon (961 freshwater fish species), Mekong (309 species), Congo (375 species) and the Ogooué River in Gabon (308 species) (Winemiller et al. 2016; Mbega 2004). Yet, freshwater ecosystems are among the most threatened in the world and 36% of freshwater fishes that have been evaluated by the IUCN qualify as endangered. Human development, particularly dam construction, has changed the morphology, hydrology, and functioning of many freshwater ecosystems which has in turn influenced the structure and dynamics of biological communities (Petts 1996; Bunn & Arthington 2002; Poff et al. 2007; Poff & Schmidt 2016).

Large free-flowing rivers with intact natural connectivity now persist in only a few regions including remote parts of the Arctic, the Amazon and, to a lesser degree, in central Africa (Grill et al. 2019). There are three large (> 500 km) free-flowing rivers in the central African nation of Gabon: the Ivindo, which flows uninterrupted for 1,063 km, the Nyanga, which is undammed along its 559 km length, and the Ogooué, which (downstream of the dam at Poubara) maintains unimpeded flow for 557 km of its 1,200km total length (Grill et al. 2019). Large dams and their reservoirs impede movement of freshwater fauna and thus fragment these systems (Dudgeon et al. 2006; Anderson et al. 2018). Migratory fishes, including marine-associated fishes that rely on several distinct habitat types, are particularly susceptible to changes associated with hydropower dam construction (Stanford and Ward 2001, Stone 2011, Flitcroft et al 2019). Few studies have incorporated the entire range of habitats required by marine-associated fish species, especially in tropical river systems, and developing large-scale freshwater conservation strategies requires an understanding of patterns of connectivity between marine, estuarine and freshwater ecosystems (Flitcroft et al 2019).

In Gabon, proposals have been put forward to develop 39 potential hydropower dams, including 28 in the Ogooué watershed. These dams and their reservoirs will increase Gabon's energy production, but they also have the potential to fragment and alter several relatively pristine river systems. Many of Gabon's most culturally and economically important freshwater fish species are also marine-associated; moving between freshwater and marine or brackish ecosystems, including the Giant African Threadfin (*Polydactylus quadrifilis*), snappers (*Lutjanus* sp.), croakers (*Pseudotolithus* sp.), sardines (*Ethmalosa fimbriata*), mullets (*Neochelon* sp.), Atlantic Tarpon (*Megalops atlanticus*), and tongue soles (*Cynoglossus* sp.). Proposed hydropower development may threaten these fishes and the fisheries that depend on them, but most of the 39 potential dam sites have never been scientifically surveyed, and no formal studies of fish movement within Gabon's freshwater ecosystems have been conducted. Therefore, it is difficult to assess possible impacts of dam development on biodiversity and fisheries. In view of the threats associated with proposed hydropower development in Gabon, here we present a rapid appraisal of the potential impact of dam development on marine-associated fish in Gabon using MaxEnt modelling. This technique facilitates an assessment of the potential distribution of marine-associated fish guilds within Gabon's freshwater ecosystems where data are limited and helps determine which proposed dams will block access to suitable habitat for marine-associated fish species and have impacts on biodiversity, fisheries and local economies.

Methods

Distributional data

We compiled presence records for fresh and brackish water fishes of Gabon and Equatorial Guinea from three databases: The Global Biodiversity Information Facility (GBIF), FAUNAFRI and Oregon State University's Specify database. These sources provide data on expertly identified museum specimens. Data with uncertain species identifications or lacking coordinates were excluded from the initial database. We applied filters to exclude records with low precision in their geographic location (less than two decimal points) and points outlying the hydrography dataset (> 300 meters). In total we included 314 species and 6,060 unique point occurrences.

We classified each fish species present in the study region to one of the thirteen habitat-use guilds modified from Welcomme et al. (2006). Each guild includes fish species that share similar ecological niches, tend to inhabit waters with similar physicochemical and hydrological properties, and are predicted to respond similarly to changes in river hydrographs and to modification of geomorphology, habitat structure and ecological functions of river ecosystems (Welcomme et al. 2006). Four guilds present in Gabon have some reliance on marine or brackish ecosystems but move into freshwaters these include; opportunistic marine (marine species that breed in the ocean and occasionally enter freshwater), catadromous (migratory species with an oceanic phase and a freshwater phase), brackish water estuarine (euryhaline species that can tolerate fresh and saltwater), and freshwater estuarine (stenohaline, freshwater species that inhabit the lower reaches of rivers, and may move between fresh and brackish waters). Freshwater estuarine fishes are more tightly linked to freshwaters and do not require saltly or brackish water ecosystems and were therefore excluded from this analysis. The remaining three guilds are considered marine-associated guilds and are the focus of this study. In total, 30 marine-associated fish species were included in the final model, for a total of 135 unique occurrences at 47 distinct surveying localities. Once consolidated, we compiled a list of which fish guilds were present in each 100-meter river reach throughout Gabon's freshwater ecosystems. We removed duplicate guild records lying within each reach.

Environmental data

For a biologically meaningful characterization of the riverscape, we ran geoprocessing algorithms in ArcGIS Pro 2.6 to obtain local channel gradient, maximum gradient downstream, mean annual discharge, valley confinement, and distance to the ocean, based on a 12.5-meter resolution Digital Elevation Model (DEM) generated from an L-Band Synthetic Aperture Radar (ALOS PALSAR, Japan Aerospace Exploration Agency) and was radiometrically terrain-corrected (RTC, University of Alaska, Fairbanks). We also computed zonal statistics of other potentially useful environmental predictors: land-cover (CCI, ESA), tree canopy percent (USGS, U. of Maryland), erodibility, temperature and precipitation (WorldClim 2). We modeled two connectivity scenarios for Gabon's hydrological network: one based on knickpoints in the topographic relief data and existing dams (present connectivity), and a second scenario including the prospective dams.

MaxEnt model

We used a Maximum Entropy (MaxEnt) approach for species distribution modeling (Phillips 2005, Phillips et al. 2008, 2017). MaxEnt is a machine-learning algorithm that builds relationships between presence-only records and a set of environmental variables to estimate a target probability distribution of maximum entropy (the most uniform distribution).

Guilds were initially grouped into lotic, lentic, eurytopic, marine-associated habitat-types according to Welcomme et al. (2006). Parameters were set separately according to guild-specific traits and prevalence. Poorly performing guilds were set aside, and parameters individually tuned. Using a Jenks natural breaks classification that detects natural classes in the distribution of the data, we ranked every reach in one of five categories of guild habitat suitability: (1) zero, (2) low, (3) mid-low, (4) mid-high and (5) high suitability to produce the maps in Figure 4.1.

In order to assess the current state of the habitat complementation between Gabon's marine and freshwater environments for species dependent on both, we trained a model to detect threshold relationships between the presence of marine-associated guilds and downstream gradients. The threshold-based model showed a very-low likelihood of marine-associated guilds occurring upstream of reaches with more than 40% gradient, areas likely to have waterfalls or steep changes in elevation that act as natural barriers for fish dispersal. Thus, we classified stream sections exceeding that threshold as disconnected from upstream movement. As none of the existing dams in Gabon are equipped with fish passages, we classified the few systems currently blocked by flow control structures as disconnected (e.g., on the Mbei and the Upper Ogooué).

For model optimization, we used the R package 'MaxentVariableSelection'. This package helps to identify the most influential and uncorrelated environmental variables and uses an optimal regularization multiplier to avoid building overcomplex or overfitted models. This script varies parameters among stepwise MaxEnt runs and assesses performance with the Area Under the receiver operating Characteristic (AUC) and the Akaike Information Criterion (AIC) (Jueterbock et al. 2016). Final parameters were set by harmonizing the models with the highest AUC and lowest AIC values. During model optimization, the mean annual temperature was dropped from the analysis because of collinearity with elevation ($r^2 = 0.95$), and land cover and tree cover percent were dropped because of their small contribution to predictions (< 5%). Since there is a considerable fish survey bias towards Gabon's road system, we randomly selected 10,000 background samples (or pseudoabsences) restricted to accessible reaches through main roads, existing sampling locations, and adjacent reaches.

Results

We developed a MaxEnt model to predict occupancy for marine-associated fishes across Gabon's freshwater ecosystems (Fig. 4.1). Model performance was very good (AUC=0.93), and the most influential environmental variables in determining the distribution of marine-associated fishes were distance to the ocean, mean annual discharge, and valley confinement. We found that marine-associated fish species have a high likelihood of traveling 400km upstream, and that proposed dam development could result in loss of nearly 600 km of highly suitable habitat for marine-associated fishes.

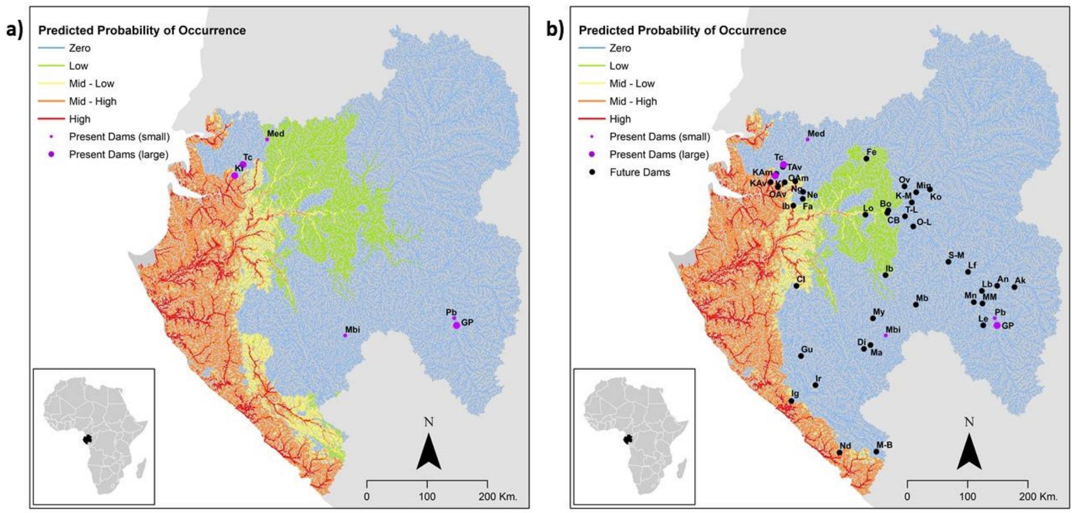

Figure 4.1. Heat map showing the predicted distribution of marine-associated fish guilds with a) existing, and b) proposed hydropower dams in Gabon. Dams coded as follows: Existing Dams; Grand Poubara (GP), Poubara (Pb), Kinguele (Ki), Tchimbele (Tc),

The model predicts marine-associated fishes to have a high likelihood of occurrence throughout the coastal watersheds, including the Noya, Komo, Remboué, N'komi, Rembo Ngové, Rembo Ndogo, Loutsiéni, and Louzibi. Marine-associated fishes are predicted to have a high likelihood of occupying the mainstem Nyanga and its major tributaries. Marine-associated fishes are also predicted to have a high likelihood of occupying the entire lower Ogooué and the mainstem Ogooué from its mouth to around Lopé, approximately 400 km upstream. In addition, we also found high likelihood of occurrence in most of the Ogooué's major tributaries including the Ngounie River to around the Chutes de l'Imperatrice and the Abanga River to around Nemguembani. Our model predicts that marine-associated fishes have a low likelihood of occurring throughout the upper Ogooué River, the upper Lolo River (near Koulamoutou), and most of the Mvoung River drainage of the Ivindo River watershed. Large waterfalls (Chutes de Booué, the Chutes de l'Imperatrice and Nemguembani) seem to form natural biogeographical barriers on the Ogooué, Ngounie, and Abanga rivers by blocking upstream movement of marine-associated fishes. Most existing hydropower dams in Gabon are sited high in watersheds and thus not expected to directly affect marine-associated fishes, with the notable exception of the dam at Kinguele on the Mbei River. This dam blocks potential upstream movement of marine-associated fishes that would otherwise have a high likelihood of occurring upstream from the proposed dam site.

Currently, marine-associated species have potential access ($p>0.1$) to 44,336 km of river kilometers, but an overlay of the 39 proposed hydropower dams over the marine-associated guild occupancy model revealed that if all dams were constructed, 17% or 7,391 stream kilometers of previously accessible habitat, would be lost (Table 4.1). Of those accessible areas, 6,522 stream kilometers are currently predicted to have a high likelihood of occurrence ($p>0.6$) for marine-associated fishes, but dam development could result in a loss of 466 highly suitable stream km (7%). These losses are particularly dramatic in the Nyanga, Ogooué, Abanga, Mvoung, Lolo, Komo-Mbei and Okano rivers (Figure 4.1b). On the Nyanga, there are currently 679 km of highly suitable habitats, but if the proposed dam at Igotchi is constructed, 392 km (or 57.7%) will be lost. In the Komo-Mbei drainage, dam construction will result in the loss of 53 km of highly suitable habitat from a total of 248 km (21.4 %). The whole Ogooué doesn't lose any highly suitable habitat, but 58 km of moderate-highly suitable habitat are lost from a total of 5,074 km (1.14 %), and 1,945 km of usable habitat are lost from a total of 12,970 km (15 %).

Table 4.1. Habitat suitability for marine-associated fishes in Gabon's freshwater ecosystems. Scenario refers to level of dam construction with existing and 39 proposed dams. Occurrence index derived from MaxEnt model. Accessible habitats have an occurrence index of 0-0.10, usable habitats are 0.11-0.43, moderately-highly suitable habitats are 0.44-0.60, and highly suitable habitats have an occurrence index >0.61. Calculations for moderate-highly and usable habitat, are cumulative with the stream miles of the higher categories.

	Occurrence index	Kilometers	Percent Loss
Accessible habitat			
Present	Non-zero	78433.49	50.68
Future	Non-zero	38686.20	
	Habitat Loss	39747.19	
Usable Habitat			
Present	> 0.1	44336.10	16.67
Future	> 0.1	36944.30	
	Habitat Loss	7391.80	
Moderately-Highly Suitable Habitat			
Present	> 0.43	22450.92	5.13
Future	> 0.43	21298.27	
	Habitat Loss	1152.66	
Highly Suitable Habitat			
Present	> 0.6	6522.02	7.15
Future	> 0.6	6055.73	
	Habitat Loss	466.29	

Discussion

Central Africa is important as a region that is relatively pristine, highly diverse and highly threatened. Gabon, in particular, has some of the world's most pristine unimpeded river systems and high freshwater biodiversity. Inaccessibility and lack of scientific effort has limited our ability to understand distribution patterns of freshwater fish across these important watersheds. Many of Gabon's most culturally and economically important fish species move between marine or brackish ecosystems and freshwaters and rely on free-flowing rivers. We demonstrate a novel application of MaxEnt to predict the distribution of marine-associated fishes in Gabon's freshwater ecosystems.

We found that marine-associated fishes have a high likelihood of occupying every coastal watershed, including the Bas Ogooué. Moreover, marine-associated fishes are predicted to occur as far inland as around Lopé on the Ogooué mainstem (approximately 400 km from the coast). This corroborates reports from local fishermen and the experience of the authors, including JSC who collected a Guinea Snapper (*Lutjanus endecacanthus*) at Lopé National Park in 2018.

With this model, we were also able to examine where proposed dams will potentially block their passage. Proposed dam construction in Gabon threatens to disrupt movement of marine-associated fishes and may reduce fish populations or impact local fisheries. Proposed dams close to the coast on highly connected river systems, particularly on the Nyanga and Komo-Mbei systems, will have the most deleterious effects on marine-associated fishes. Therefore, we conclude that proposed dam development on the Nyanga, the Komo, the Abanga, the Ogooué downstream of the Chutes de Booué, and on the Ngounie downstream of the Chutes de l'Imperatrice would result in habitat loss for marine-associated fishes and could impact local fisheries and economies. Dam construction upstream of these sites also threatens fish populations, particularly through changes in flow, sedimentation and fragmentation (Agostinho et al. 2004; Caudill et al. 2007; Anderson et al. 2018).

In summary, marine-associated fishes are predicted to occupy all coastal river systems in Gabon and could travel long distances (> 400 km) upstream to either breed, feed, or rear their young, but these species are threatened by habitat loss and fragmentation due to proposed hydropower dam development. We recommend conducting baseline assessments at each proposed dam site and that dams are not constructed in areas that may affect dispersion of marine-associated fishes. We also recommend that existing dams, particularly on the Mbei at Kinguele, are outfitted with fish passages appropriate to migratory species in the area and operated to ensure minimum environmental flows that mimic natural conditions to minimize effects on fish biodiversity (Ferguson et al. 2011; Murphy et al. 2019).

Conclusion

Gabon's freshwater ecosystems harbor at least 308 freshwater fish species and over 350 fish species in total, thus forming a major component of Central Africa's incredible diversity of freshwater species. Gabon's great river, the Ogooué, stretches for 1,200 km, drains roughly 75% of the country of Gabon, and is the 4th largest river in Africa by discharge. With only one dam in the watershed and a rural density of <5 inhabitant/km^2, the Ogooué is considered one of the world's most pristine large tropical rivers. However, as Gabon develops its mining, timber and hydroelectric industries, existing and planned projects on the Ogooué and other river systems in Gabon pose threats to freshwater ecosystems and the species they support.

Over the course of graduate career, I have had the opportunity to survey fishes in several regions of Gabon including portions of the Ogooué, Ivindo, Sébé, Komo, Mbei, Ngounie and Louetsi Rivers. In total, my team and I have collected over 15,000 fish specimen, identified and accessioned these into museum collections and made them available through online databases. On every expedition we have encountered and collected undescribed fish species, which highlights the richness and remoteness of these regions. Most of these species remain undescribed, but several have been formally described including *Cryptomyrus ogoouensis*, *Paramormyrops ntomtom*, and *Enteromius pinnimaculatus* (Chapter 1). Our sampling has been focused primarily in and around nascent protect areas, regions threatened by excessive logging, and areas where potential hydropower dams have been sited. Our goal has been to provide ecological baseline data and identify critical habitats and species that should be protected. Our survey of the Chutes de Mboungou Badouma et de Doume Ramsar Site provided the first account of the ichthyofauna of the region in over 150 years (Chapter 2). We surveyed 31 sites in and around the Ramsar site on the Ogooué and its tributaries and collected 97 species of fish including nine that were undescribed. This baseline assessment of biodiversity in the Ramsar site serves as a reference point for future studies in the area, especially impact assessments. We have collected extensively in three other regions with several proposed dam sites during 2017 and collected a total of at least 162 fish species. There are several publications that will come from that work, but my colleagues and I await further taxonomic analyses before publishing these data.

Given that Gabon has identified a total of 39 potential hydropower dam sites across the country and we have neither the time nor funding to survey each potential site before development begins, my colleagues and I developed a novel methodology to predict patterns of habitat suitability within Gabon's freshwater ecosystems and assess the relative impacts of proposed dams (Chapter 3). We began by collecting distributional data for all fresh and brackish water fishes in Gabon and relevant environmental, ecological and geospatial information. Any species occurring at fewer than 5 distinct localities were excluded from the dataset. Then, using a MaxEnt modeling approach, we developed habitat suitability models for each species. Any species with a poor performing model (AUC<.75) were removed from the database. In the end, we included 113 species, or about one-third of Gabon's fish species, in the final multi-species model. We stacked the 113 species distribution models and tallied the number of species expected to occur in a given stretch of river. We defined a new metric, species pseudorichness index (*p*R), as the cumulative number of species that are highly suited to the habitat in a given segment of river. Using *p*R, we were able to assess habitat suitability for 113 fish species across Gabon's riverscapes and at the 39 potential hydropower dam sites. Of the 39 potential dams, 32 are sited in areas of high *p*R and are expected to have disproportionately adverse effects on fish biodiversity.

Not all fish species are equally affected by dam development and species richness is just one metric of ecosystem health that should be considered when siting potential hydropower dams. Range-restricted, endangered, economically important and migratory fishes are likely the most threatened by potential changes to Gabon's freshwater ecosystems. Many of the most culturally and economically important fish species in Gabon move between freshwater and salt or brackish water ecosystems. Therefore, my colleagues and I used predictive occupancy modeling to assess the distribution of marine-associated fishes in Gabon's freshwater ecosystems (Chapter 4). Essentially, we predicted the inland range of a guild of marine-associated fishes using a combination of data from museum collections and spatial analyses. We found that marine-associated fishes are expected to extend at least 400 km into Gabon's freshwater ecosystems and that proposed dams are sited in areas that would block fish passage. This is a novel application of maxent occupancy modeling and can be used to assess fish movement without collections, tagging or fieldwork. Our approach can be applied in scenarios where threats to the ecosystem are approaching and baseline data is minimal.

In conclusion, my thesis seeks to document and describe Gabon's freshwater biodiversity, assess patterns of freshwater biogeography, and address critical conservation concerns including the effects of proposed dam development. Through extensive fieldwork, lab work and modeling we have found that Gabon's freshwater ecosystems represent a relatively intact biodiversity hotspot that is threatened by proposed development. To continue exploring Gabon's freshwater ecosystems, I am planning an expedition in 2020 to conduct a 1000km transect of the Ogooué river to document freshwater biodiversity, ecosystem health, and the reliance of local peoples on the river and the resources it provides. This project is partially funded by National Geographic and supported locally by Gabon's Agence National des Parques Nationaux (ANPN). My goal is to put the Ogooué river on the map, and in the minds of the public, and to initiate a campaign to protect this wild river.

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