



First record of *Moenkhausia costae* (Steindachner 1907) in the Paraíba do Norte basin after the São Francisco River diversion

Telton Pedro Anselmo Ramos^{1*}, Silvia Yasmin Lustosa-Costa², Railla Maria Oliveira Lima¹,

José Etham de Lucena Barbosa¹ & Rosemberg Fernandes Menezes³

¹Universidade Estadual da Paraíba, Laboratório de Ecologia Aquática, Departamento de Biologia/CCBS, Campus universitário, 58109-753, Campina Grande, PB, Brasil.

²Universidade Federal do Rio Grande do Norte, Laboratório de Ictiologia Sistemática e Evolutiva/CB, Departamento de Botânica e Zoologia, Campus Central, Lagoa Nova, 59078-900, Natal, RN, Brasil.

³Universidade Federal da Paraíba, Centro de Ciências Agrárias, Departamento de Fitotecnia e Ciências Ambientais, 58397-000, Areia, PB, Brasil.

*Corresponding author: telton@gmail.com

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Abstract: Construction of water diversions in drylands is boosted by increasing demands for freshwater often due to prolonged droughts. Even though these mega-enterprises result in benefits to society, it also poses a threat to freshwater biodiversity. In Northeastern Brazil, for instance, the São Francisco River Integration Project already supplies water for millions of people, but over time it will also favor the introductions of multiple aquatic species in the river basins of the Northeastern Caatinga and Coastal Drainages ecoregion. These introductions can cause unprecedented impacts in the native ichthyofauna, such as homogenization of freshwater faunas, transmission of pathogens and loss of native species. This study compares the composition and relative frequency of fish species from Poções reservoir using data obtained by gillnetting and trawling before and after the São Francisco diversion in the dry and rainy seasons, and reports the first detection of *Moenkhausia costae* introduction in the Paraíba do Norte basin, through the São Francisco River channel. Our results show some evidences that *M. costae* may become dominant and invasive in Poções reservoir. The introduction of *M. costae* adds a new component of disruption for these freshwaters and may pose a serious threat to the endemic ichthyofauna in lentic and lotic systems from the Paraíba do Norte basin.

Keywords: drylands; reservoirs; water transfer; non-native species; water shortage.

Primeiro registro de *Moenkhausia costae* (Steindachner 1907) na bacia da Paraíba do Norte após a transposição do rio São Francisco

Resumo: Obras para transposição de rios em regiões secas do mundo têm sido impulsionadas pelo aumento da demanda por água doce, muitas vezes associadas às secas prolongadas que são intrínsecas a essas regiões. Embora tais megaempreendimentos possam trazer benefícios para a sociedade, também representam uma ameaça para a biodiversidade aquática. No Nordeste do Brasil, por exemplo, o Projeto de Integração do Rio São Francisco já fornece água para milhões de pessoas, mas com o tempo também contribuirá com a introdução de várias espécies aquáticas nas bacias hidrográficas da ecorregião Nordeste da Caatinga e Drenagem Costeira. Essas introduções podem causar impactos sem precedentes, tais como homogeneização da ictiofauna nativa, transmissão de patógenos e perda de espécies nativas. Este estudo compara a composição e frequência relativa de espécies de peixes do açude Poções usando dados coletados com redes de espera e de arrasto antes e depois da transposição do rio São Francisco, nos períodos seco e chuvoso, e relata o primeiro caso de introdução de *Moenkhausia costae* na Bacia do Rio Paraíba do Norte, através do canal do rio São Francisco. Nossos resultados mostram que *M. costae* poderá se tornar dominante e invasora no açude Poções. A introdução de *M. costae* adiciona um novo componente de perturbação para esse açude e pode representar uma séria ameaça à ictiofauna endêmica de sistemas lênticos e lóticos da bacia do rio Paraíba do Norte.

Palavras-chave: regiões secas; reservatórios; transposição; espécies exóticas; escassez de água.

Introduction

Moenkhausia costae (Steindachner 1907) is a small omnivorous characin fish (Characiformes: Characidae), popularly known as ‘piaba’ or ‘lambari’, and in aquarium trade this species is known as ‘Tetra-fortuna’, which naturally occurs in the São Francisco and Itapicuru basins as well as in some other basins in the Northeastern Caatinga and Coastal Drainages ecoregion (Eigenmann 1917, Reis et al. 2003, Buckup et al. 2007, Lima et al. 2017, Silva et al. 2020). *Moenkhausia costae* is morphologically distinguished by a diagonal black stripe going from the beginning of the anal fin to the tip of the upper lobe of the caudal fin (Britzke 2011). It is a sedentary species that breeds multi-annually through parceled spawning preferably in lentic habitats (Godinho et al. 2010, Martins et al. 2012). Despite not being currently recognized as an invasive species, *M. costae* has already been introduced into rivers in the Paraíba do Sul basin in southeastern Brazil probably through the trade by aquarists and fish farmers (Magalhães et al. 2019).

Globalization is enhancing species introductions worldwide due to increasing international trade, tourism and transportation of raw materials among countries and continents (Jenkins 1996, Perrings et al. 2005). The introduction of species is one of the main drivers of biodiversity loss in the world (Baskin 2002, Vázquez & Aragón 2002, GISP 2005, Bellard et al. 2016). Currently, many countries have faced complex and costly issues resulting from invasive species (Bradshaw et al. 2016) and the socio-ecological damages can surpass \$100 billion dollars in countries like the United States, United Kingdom, Australia, South Africa and Brazil (CBD 2006).

Water shortage combined with rising water consumption and climate change have led worldwide governments to adopt increasingly radical solutions, such as mega-enterprises like river dammings and diversions that can affect the ecological services provided by these aquatic ecosystems (Marengo 2008). For example, in Northeastern Brazil, the São Francisco River Integration Project (SFRIP) has been developed to ease the effects of prolonged droughts (i.e. historically frequent in the region) and meet the water supply needs of part of the Brazilian semi-arid region (Lima 2005, Brazil 2004, Pittock et al. 2009, Andrade et al. 2011, Silva et al. 2020).

The SFRIP aims to divert water from the main and largest river of Northeastern Brazil (640 thousand km²) and the third largest in the country (Rosa et al. 2003) to the main river basins in the Northeastern Caatinga and Coastal Drainages (NCCD) ecoregion (Abell et al. 2018). However, this enterprise can affect the native biodiversity and speed up the process of biotic homogenization among basins (Daga et al. 2020). For instance, the SFRIP will initially supply intermittent basins of four important rivers in the Brazilian semi-arid such as Jaguaribe, Piranhas-Açu, Apodi-Mossoró and Paraíba do Norte (all from the NCCD ecoregion) (Ramos et al. 2018). However, a potential massive introduction of exotic species (e.g. parasites, invertebrates, algae and fish) can reach the NCCD ecoregion. In this context, on March 8 of 2017, the Paraíba do Norte river basin was the first to receive the waters from the São Francisco River. This paper reports the first case of *Moenkhausia costae* (Figure 1) introduction in the Paraíba do Norte basin, in Poções reservoir, through the São Francisco River East Axis channel. Moreover, this study compares the fish species assemblages before and after the São Francisco diversion into Poções reservoir, in a dry and in a rainy season, using data obtained by gillnetting and trawling, to assess the potential of *M. costae* becoming dominant and invasive in the reservoir,



Figure 1. *Moenkhausia costae* (UFPB 12069 – 50,55 mm SL).

reflecting what might happen in habitats that will indirectly receive the São Francisco waters from the Paraíba do Norte basin.

Material and Methods

1. Study Site

The study was carried out in Poções reservoir (Figure 2), located in the upper Paraíba do Norte River basin (7°53'38"S and 37°0'30"W) in the Monteiro municipality, Paraíba State, Northeastern Brazil. The reservoir has a maximum storage capacity of 29,861,562 m³ and is used for irrigation, public supply, leisure and fishing. The Paraíba do Norte River basin is the second largest in the Paraíba State, comprises 20,071.83 km², and it currently houses 52% of the state's population (AESAs 2006, PARAÍBA 2007). The climate is semi-arid (according to the Köppen-Geiger climate classification) with a dry season that can last 10 months (AESAs 2010). The annual mean temperature and annual mean precipitation in the Monteiro municipality are 23°C and 600 mm year, respectively (Fick & Hijmans, 2017). The reservoir margins are mostly vegetated by shrubs (26%) and grasslands (73%) and its littoral zones are generally vegetated by amphibian macrophytes from the genus *Polygonum* (visually dominant). In our study, the sediment in the littoral zones was mostly comprised by organic matter and clastic material (i.e., 44% of silt, 35% of sand and 19% of clay).

2. Sampling and analysis

Fish samplings were performed in a dry and in a rainy season before and after the São Francisco River diversion (Figure 3). Before the river diversion, samplings were carried out in July (rainy season) and in November 2016 (dry season). After the river diversion, samplings were carried out in July 2018 (rainy season) and in January 2020 (dry season).

Fishes were captured through standardized methods, applying two different fishing gears: (i) multi mesh gillnets and (ii) trawl nets. Two sets of gillnets (30 m long and 20, 25, 40, 50, 60, 100 and 120 mm meshes), were randomly placed at the littoral zone for at least four hours. The trawl nets (10 m long and 12 mm mesh) were dragged twice in three different regions of the littoral zone. Fish trawling and gillnetting were carried out in a littoral zone near the Poções reservoir dam (Figure 3). The sampled site was chosen based on sampling reports performed before the transfer of water from the São Francisco River to Poções reservoir.

First record of *Moenkhausia costae*

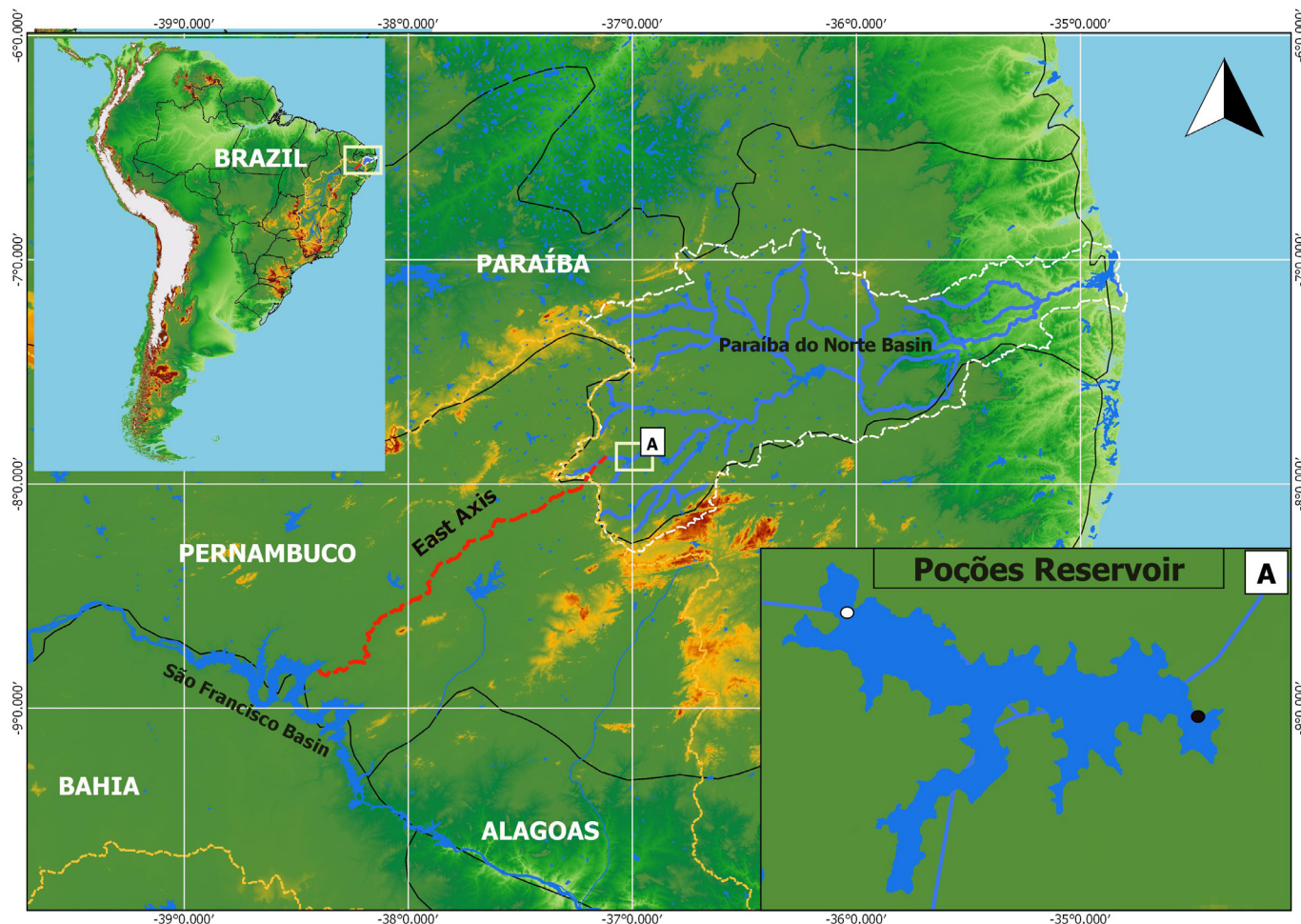


Figure 2. Map of South America highlighting the Paraíba do Norte River Basin in Northeastern Brazil, the East Axis channel from the São Francisco River (in red), and the Poções reservoir (A). The white circle in “A” indicates the entrance of East Axis channel into Poções reservoir, whereas the black circle indicates the sampling site.

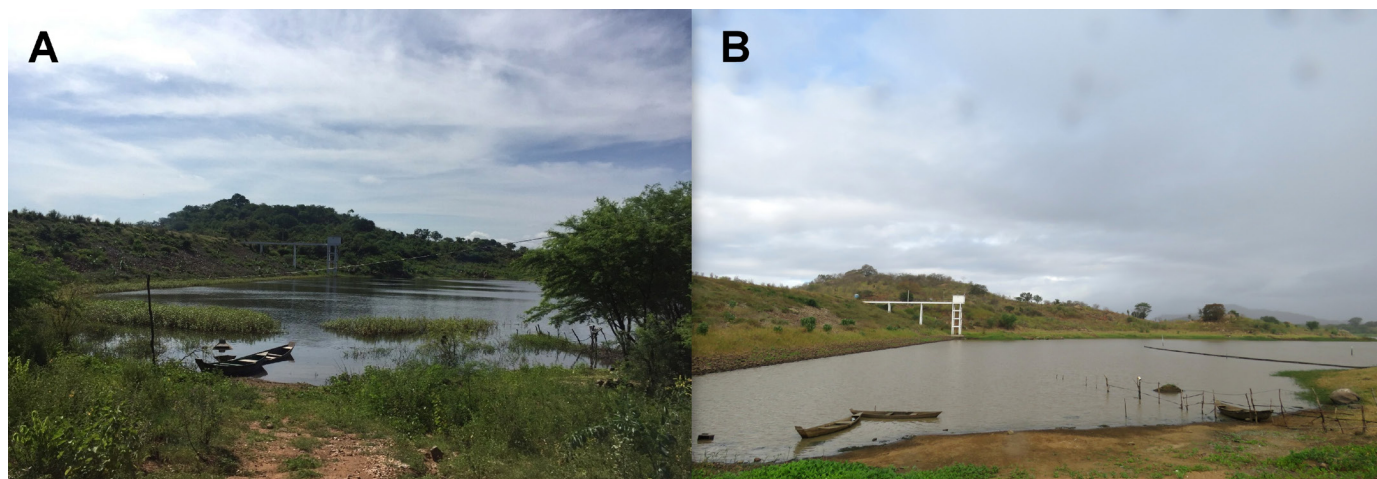


Figure 3. Sampled site in Poções reservoir in the (A) rainy and (B) dry seasons (Coordinates: 7°53’18”S and 37°59’58”W).

All specimens were anesthetized in the field with eugenol solution (Lucena et al. 2013) and then their morphological features were quantified. Next, the specimens were preserved in a 10% formaldehyde solution. At the laboratory, fishes were sorted, labeled and preserved in 75° GL alcohol according to Malabarba & Reis (1987). Specimens were taxonomically identified and were added to the Ichthyological Collection of the Department of Systematic and Ecology of Federal University of Paraíba (*Departamento de Sistemática e Ecologia, Universidade Federal da Paraíba*) (CIUFPB), Brazil. Samplings were performed under the collection permit (N°56416-4/2019) from Chico Mendes Institute for Biodiversity and Conservation/Biodiversity Authorization and Information System (*Instituto Chico Mendes de Conservação da Biodiversidade/Sistema de Autorização e Informação em Biodiversidade – ICMBio/SISBIO*).

Meristic and morphometric data were gathered according to Hubbs & Lagler (2006), using caliper rule and stereomicroscope. Specimens were taxonomically identified following Ramos et al. (2018). *Moenkhausia costae* was identified according to Britzki (2011) genus key.

The relative frequency of species were calculated by using the following formula:

$$\%Spi = n \left(\frac{100}{N} \right)$$

Where %*Spi* is the relative frequency of the species, N is the total number of individuals of the species, and *n* is the total number of individuals of all species sampled. The calculations were separately performed for gillnets and trawl nets.

Results

1. Fish community structure before the river diversion

A total of 905 individuals and 15 species were caught before the river diversion in Poçoões reservoir. Of these, 805 individuals were caught by trawl

nets and 100 individuals by gillnets. Five species were caught by trawl nets alone and two species, *Crenicichla brasiliensis* and *Poecilia vivipara*, were only caught by this method (Figure 4). Eight species were captured by gillnets and five species, *Astyanax bimaculatus*, *Hypostomus pusanum*, *Plagioscion squamosissimus*, *Coptodon rendalli* and *Cichlasoma orientale* were only caught by this method. Three non-native species, *P. squamosissimus*, *Oreochromis niloticus* and *C. rendalli*, were captured. However, only *O. niloticus* was captured by both trawl and gill nets (Figure 4).

Species composition was slightly different between seasons, but the differences observed were driven by three low abundant species, *Leporinus piau*, *Cichlasoma orientale* and *Crenicichla brasiliensis*, that were only captured in the dry period (Figure 4). When comparing the catches by gillnets and trawl nets, *O. niloticus*, *A. bimaculatus*, *P. vivipara*, *P. squamosissimus* and *H. pusanum* were the most common species in the reservoir and together they comprised more than 85% of the catches by numbers (Figure 4; Tables 1 and 2). *Oreochromis niloticus* was the first most common species captured by trawl nets in both dry and rainy periods and comprised more than 75% of all individuals captured. In the rainy season, *O. niloticus* was also the first most common species captured by gillnets, but in the dry season *A. bimaculatus* was the first most common species caught by the same method and comprised about 30% of all individuals (Figure 4).

2. Fish community structure after the river diversion

A total of 231 individuals and 11 species were caught after the river diversion in Poçoões reservoir. Of these, 138 individuals were caught by trawling and 93 individuals by gillnetting. Nine species were caught by trawl nets alone and two species (*P. vivipara* and *Hemigrammus cf. marginatus*) were only captured by this method (Figure 4). Nine species were also caught by gillnets and *Prochilodus brevis* and *C. brasiliensis* were only captured by this method. Two non-native species, *O. niloticus* and *M. costae*, were captured and both caught by trawl and gill nets, but only *O. niloticus* was captured before the river diversion

Species dominance changed substantially after the river diversion and between seasons. When comparing the catches by gillnets and trawl nets, *Steindachnerina cf. notonota*, *A. bimaculatus*, *M. costae* and *P. brevis* were the most common species in the reservoir and together they comprised more than 90% of the catches by numbers (Figure 4; Tables 1

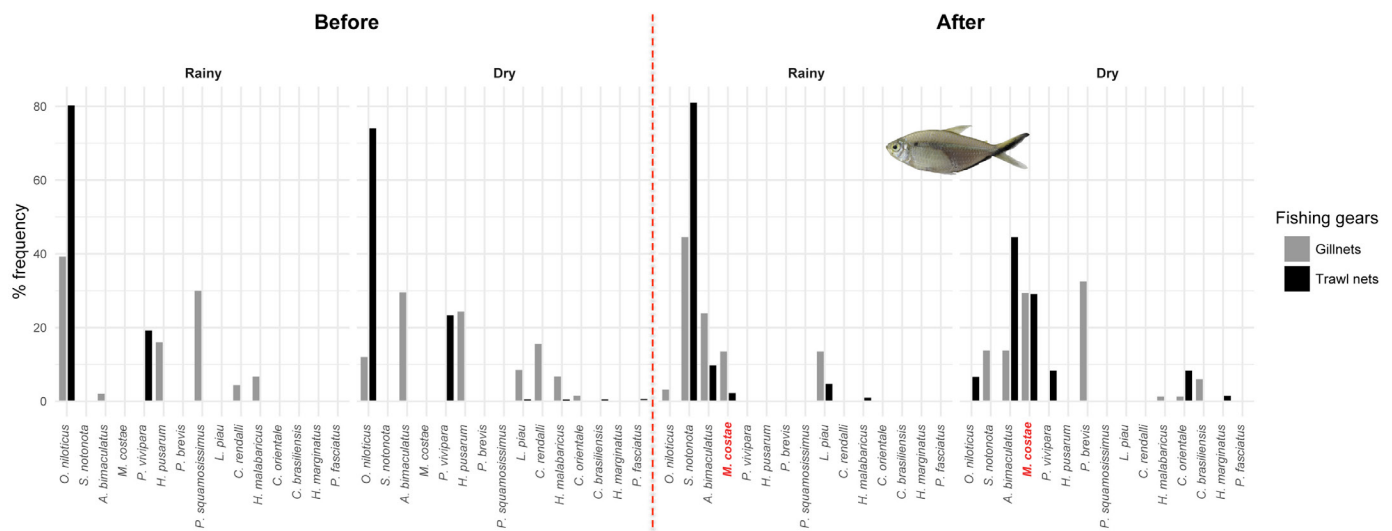


Figure 4. Frequency distribution of the fish species found in Poçoões reservoir sampled with gill and trawl nets before and after the São Francisco River diversion. The non-native species *Moenkhausia costae* is highlighted in red bold italic.

Table 1. List of fish species found in Poções reservoir in the rainy and dry seasons, before (A) and after (B) the São Francisco River diversion, and sampled with gill nets. For each species it is shown the numbers of specimens captured (N) and its relative abundance (RA). The asterisk before the species names denotes they are non-native.

	(A) Before				(B) After			
	Rainy		Dry		Rainy		Dry	
	N	RA(%)	N	RA(%)	N	RA(%)	N	RA(%)
CHARACIFORMES								
Family Characidae								
<i>Astyanax bimaculatus</i> (Linnaeus, 1758)	0	0	0	0	8	10	26	45
<i>Psalidodon fasciatus</i> (Cuvier, 1819)	0	0	3	1	0	0	0	0
<i>Hemigrammus cf. marginatus</i> (Ellis, 1911)	0	0	0	0	0	0	1	1
* <i>Moenkhausia costae</i> (Steindachner, 1907)	0	0	0	0	2	3	17	29
<i>Leporinus piau</i> Fowler, 1941	0	0	5	9	4	14	0	0
Family Erythrinidae								
<i>Hoplias malabaricus</i> (Bloch, 1794)	3	7	4	7	0	0	1	1
CICHLIFORMES								
Family Cichlidae								
<i>Cichlasoma orientale</i> Kullander, 1983	0	0	1	1	0	0	1	1
<i>Crenicichla brasiliensis</i> (Ploeg, 1991)	0	0	0	0	0	0	4	6
* <i>Oreochromis niloticus</i> (Linnaeus, 1758)	17	40	7	12	1	3	0	0
* <i>Coptodon rendalli</i> (Boulenger, 1897)	2	5	9	16	0	0	0	0
SILURIFORMES								
Family Loricariidae								
<i>Hypostomus pusearum</i> (Starks, 1913)	7	16	14	25	0	0	0	0
PERCIFORMES								
Family Sciaenidae								
* <i>Plagioscion squamosissimus</i> (Heckel, 1840)	13	30	0	0	0	0	0	0
TOTAL	43		57		29		64	

and 2). In the rainy season, *S. cf. notonota* (45%), *A. bimaculatus* (24%) and *M. costae* (14%) were the three most common species captured by gillnets. A similar pattern was observed for trawl nets, but *M. costae* (3%) was the fourth most common species caught (Figure 4; Tables 1 and 2). In the dry period, *P. brevis* (21%) and *M. costae* (19%) were the most common species captured by gillnets. For trawl nets, however, *A. bimaculatus* and *M. costae* were the most common species and together they comprised 74% of all individuals caught (Figure 4; Tables 1 and 2). *Prochilodus brevis*, *C. orientale*, *C. brasiliensis* and *Hemigrammus cf. marginatus* were only captured in the dry period and their relative frequencies were very low (Figure 4). Despite the non-native *M. costae* was only captured after the river diversion, it was interestingly among the top three dominant species in Poções reservoir irrespective of the sampling method used (Figure 4).

Discussion

This study reports the first detection of *Moenkhausia costae* in the Paraíba do Norte basin after the São Francisco River diversion. Furthermore, our results show evidence that this species might become dominant and with potential of dominance and invasiveness in other river basins from the Northeastern Caatinga and Coastal Drainages

(NCCD) ecoregion. Moreover, we also showed that a single method used to capture fish species does not provide a representative of the whole-lake assemblage, as both gillnetting and trawling might miss important species that other methods capture.

Before the São Francisco River diversion, Ramos et al. (2018) investigated the ichthyofauna in the Paraíba do Norte River and reported 47 fish species corresponding to 38 genera, 20 families and six orders. The authors aimed to gather data before the river diversion to allow later detections of putative fish introductions from the São Francisco basin. Following this line, Costa et al. (2017) surveyed the ichthyofauna of two reservoirs from the same river basin. The authors registered 17 fish species, corresponding to 16 genera, 10 families and three orders. Conversely, *M. costae* was not found in none of the previous studies. However, one year later, the São Francisco waters reached Poções reservoirs and *M. costae* was already established. *Moenkhausia costae* and *M. intermedia* (Eigenman 1908) have already been reported in the NCCD ecoregion in the Apodi-Mossoró, Choró and Jaguaribe Rivers basins (Lima et al. 2017, Berbel-Filho et al. 2018). However, no individual from this genus had ever been registered in the Paraíba do Norte River basin before the São Francisco River diversion (Costa et al. 2017, Ramos et al. 2018).

Table 2. List of fish species found in Poções reservoir in the rainy and dry seasons, before (A) and after (B) the São Francisco River diversion, and sampled with trawl nets. For each species, it is shown the numbers of specimens captured (N) and its relative abundance (RA). The asterisk before the species names denotes they are non-native.

	(A) Before				(B) After			
	Rainy		Dry		Rainy		Dry	
	N	RA(%)	N	RA(%)	N	RA(%)	N	RA(%)
CHARACIFORMES								
Family Characidae								
<i>Astyanax bimaculatus</i> (Linnaeus, 1758)	0	0	0	0	8	10	26	45
<i>Psalidodon fasciatus</i> (Cuvier, 1819)	0	0	3	1	0	0	0	0
<i>Hemigrammus cf. marginatus</i> (Ellis, 1911)	0	0	0	0	0	0	1	1
* <i>Moenkhausia costae</i> (Steindachner, 1907)	0	0	0	0	2	3	17	29
Family Curimatidae								
<i>Steindachnerina cf. notonota</i> (Miranda Ribeiro, 1937)	0	0	0	0	65	81	0	0
Family Anostomidae								
<i>Leporinus piau</i> Fowler, 1941	0	0	5	1	4	5	0	0
Family Erythrinidae								
<i>Hoplias malabaricus</i> (Bloch, 1794)	0	0	4	1	1	1	0	0
CICHLIFORMES								
Family Cichlidae								
<i>Cichlasoma orientale</i> Kullander, 1983	0	0	0	0	0	0	5	9
<i>Crenicichla brasiliensis</i> (Ploeg, 1991)	0	0	1	0	0	0	0	0
* <i>Oreochromis niloticus</i> (Linnaeus, 1758)	153	81	457	73	0	0	4	7
CYPRINODONTIFORMES								
Family Poeciliidae								
<i>Poecilia vivipara</i> Bloch & Schneider 1801	37	19	145	24	0	0	5	9
TOTAL	190		615		80		58	

Environmental disturbances driven by hydrological changes may affect the structure of ecological systems and alter species composition and dominance (Daga et al. 2020, Yang et al. 2020). For instance, *Astyanax bimaculatus* is an endemic species in Central and South America that is usually very abundant both in brackish and freshwaters (Lima et al. 2003, Buckup et al. 2007). Costa et al. (2017) reported that *A. bimaculatus* was dominant in Acauã e Boqueirão reservoirs, both inserted in the Paraíba do Norte basin. In our study, conversely, *O. niloticus* and *P. vivipara* were two of the three most abundant species before the São Francisco diversion, both in the dry and the rainy seasons. Their abundances dropped drastically after the river diversion, but this pattern was stronger for *O. niloticus* (Figure 4). This drastic reduction in *O. niloticus* abundances may be related to the fact that all aquaculture tanks for tilapia farming were removed from Poções reservoir just before the river diversion. Moreover, the number of individuals of *A. bimaculatus* captured in our study was lower than that of *M. costae* (Figure 4 and Table 1). Da Luz & Okada (1999) draw the attention to the fact that *Moenkhausia* and *Astyanax* species usually share resources and coexist, since they both have the same feeding strategy (omnivores with a tendency to insectivory). A similar pattern of coexistence between

these two species was observed in our study, but further studies are needed to assess how these species interact in freshwater ecosystems.

Our first sampling in Poções reservoir, after the river diversion, resulted in relatively low abundances of *M. costae*, with only six specimens captured representing 5.1% of the samples. After one and half year, *M. costae* had already become the top three most abundant species recorded in the reservoir and overcame *O. niloticus* and *P. vivipara* reaching about 19% and 29% of the total number of individuals captured by gill and trawl nets, respectively. These results show that *M. costae* has managed to establish in the new habitat, which suggests that this species can become invasive with potential to affect other systems from the NCCD ecoregion that will also receive the waters from the São Francisco River. Furthermore, among the three cascading reservoirs (Poções > Camalaú > Boqueirão) that received the waters from the São Francisco River, *M. costae* was only reported so far in Poções reservoir. Camalaú and Boqueirão reservoirs are inserted in the Paraíba do Norte basin and are located downstream the East Axis channel, so they are the most likely routes of dispersion of *M. costae* within this basin.

In the Paraíba do Norte basin, *Apareiodon davisii* Fowler 1941 and *Parotocinclus spilosoma* (Fowler 1941) might be the main native species affected by limnological changes and by the introduction of

non-native species such as *M. costae*. *Apareiodon davisi* is endemic to the NCCD ecoregion and is classified as endangered according to the Official National List of Threatened Faunistic Species - Fishes and Aquatic Invertebrates (Brasil 2014) and *Parotocinclus spilosoma* is endemic to the Paraíba do Norte River basin (Ramos et al. 2018). Despite the lack of studies on life history and behaviour of these two species, it is important to draw attention to them given the degree of threat they have been historically facing in the basin and now with the São Francisco River diversion. Thus, these threatened species are under the risk of having their populations reduced or even eliminated due to the presence of non-native species coming from the São Francisco River and continuous environmental changes in the basin.

Most ecoregions involved in the São Francisco River Integration Project are located in the Caatinga biome. The freshwater ecosystems from this biome have been suffering with multiple and chronic impacts mostly driven by anthropogenic activities, such as riparian deforestation, erosion, eutrophication, introduction of exotic species, salinization, water abstraction and rainfall reduction (Jeppesen et al. 2015, Menezes et al. 2018) and this biome is currently estimated to be 50% degraded (Leal et al. 2005, Lima et al. 2017). This scenario is commonly seen in a large number of river basins in the Caatinga biome, so the introduction of *M. costae* adds a new component of disruption for these freshwaters and poses a threat to the native ichthyofauna in the Paraíba do Norte River basin. Furthermore, the natural condition of low biodiversity and high degree of endemism of Caatinga, highlight the need for attention to the freshwater ichthyofauna and a better system of monitoring and control of the aquatic species that may establish in the Northeastern Caatinga and Coastal Drainages ecoregion.

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Author Contributions

Telton Pedro Anselmo Ramos: substantial contribution in the concept and design of the study; contribution to data analysis and interpretation; data collection contribution to manuscript preparation;

Silvia Yasmin Lustosa Costa: Substantial contribution in the concept and design of the study; data collection; contribution to critical revision.

Railla Maria Oliveira Lima: Contribution to data analysis and interpretation; data collection

José Etham de Lucena Barbosa: Contribution to data analysis and interpretation; substantial contribution in the design of the study;

Rosemberg Fernandes de Menezes: Contribution to data analysis and interpretation; substantial contribution in the design of the study; manuscript preparation; data collection; contribution to critical revision, adding intellectual content.

Conflicts of interest

The authors declare that they have no conflict of interest related to the publication of this manuscript.

Ethics

We were complied with the guidelines established by the ethics committees.

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