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Population dynamics of *Melanorivulus rossoi*, a restricted geographic distribution killifish species

Francisco Severo-Neto · Matheus Vieira Volcan

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Abstract Species of *Melanorivulus* present behaviour and physiological traits that allow them to live in marginal aquatic habitats. In particular, *Melanorivulus rossoi* is a small nonannual fish only known from its type locality in the Brazilian Cerrado. In this study, we aimed to characterize the distribution and temporal variation in body size, sex ratio, density, length-weight relationship (LWR) and condition factor (CF) of *M. rossoi* in its natural habitat. To accomplish this, fish samples were taken monthly for a year using sieve nets every 30 min. Body size of males and females increased throughout the year until early summer. LWR was significant, and general coefficient of determination (r^2) was 92%. Juveniles showed negative allometric growth, but adults showed positive allometric growth. Both sexes presented the same tendency of temporal variation in CF, with lower values in October and January and peaks in September and February. Fire occurred in June, but no difference in population parameters was observed after this event. A decrease in the abundance of *Melanorivulus* was related with an increase in the abundance of Erythrinidae juveniles. This might be explained by an increased predation of this species over the *M. rossoi* individuals, when the population was reduced to about 30% of that in the previous months. We report four new locations where this species was recorded; thus, similar to most Rivulidae members, *M. rossoi* has a restricted distribution area and is threatened with extinction. Therefore, our results may be useful in developing management strategies aimed at conservation of this species and its habitat in Brazil.

Keywords *Melanorivulus* · Wetlands · Rivulidae · Cerrado · Threatened species

F. Severo-Neto (✉)
Universidade Federal de Mato Grosso do Sul, Cidade Universitária, CEP 79070-700, Campo Grande, Mato Grosso do Sul, Brazil
e-mail: netosevero@hotmail.com

F. Severo-Neto
Instituto de Biociências, Letras e Ciências Exatas, Departamento de Zoologia e Botânica, Laboratório de Ictiologia, Universidade Estadual Paulista "Júlio de Mesquita Filho"(UNESP), Rua Cristóvão Colombo, 2265, Jardim Nazareth, CEP, São José do Rio Preto, SP 15054-000, Brazil

M. V. Volcan
Laboratório de Ictiologia, Instituto Pró-Pampa (IPPampa), Rua Uruguai, 1242, CEP, Pelotas, Rio Grande do Sul 96010-630, Brazil

Introduction

Rivulidae is a Neotropical fish family composed of species that inhabit an extensive range of aquatic habitats, such as pools, swamps and floodplains (Loureiro and de Sá 2015). Like the African Notobranchiidae, both included in the suborder Aplocheilodei, some species have the capacity to survive in habitats unsuitable for other fish, such as intertidal or ephemeral pools (Turko and Wright 2015). Most members of these families exhibit egg diapauses, a characteristic that favours embryo survival after dissecation (Furness 2015). However, in some Rivulidae genera, diapause is lacking, and they are considered nonseasonal species (Furness 2015). Some of those species present amphibious habits (Turko and Wright 2015) and tolerance to extreme environmental condition, allowing them to live in marginal aquatic habitats, even in low-quality waters unfit for most fish species, e.g., habits with low dissolved oxygen, low pH and high ammonia concentration (Taylor 2012).

One nonseasonal rivulid genus, *Melanorivulus*, was recently established by Costa (2011). It was defined on the basis of species formerly placed in *Rivulus*. This genus includes about 50 small species (e.g., Loureiro and de Sá 2015; Nielsen et al. 2016; Costa 2017; Volcan et al. 2017) with most species occupying the Brazilian Cerrado, in particular the upper Paraná Basin which, with its rich drainage, presents a total of 15 *Melanorivulus* species (Eschmeyer et al. 2017). In Mato Grosso do Sul State of western Brazil, eight *Melanorivulus* species have thus far been described, two to the upper Paraguay Basin and six to the upper Paraná Basin (Costa 2005; Volcan et al. 2017). Most of them have a restricted distribution, and some are only known to a single site. Such is the case for *Melanorivulus rossoi* (Costa 2005), only known for its type locality, a small tributary from Anhanduí River drainage, which flows from the right margin of the Paraná River.

Most species of the Rivulidae family are threatened with extinction, and little is known about their distribution area and ecology (Rosa and Lima 2008; Volcan et al. 2017). Similarly, the occurrence area of *M. rossoi* is threatened by landscape modification for agricultural use, and basic biological information about the species is still unknown. The population dynamics and life history of these highly endemic species, as well as their density responses to seasonal and weather changes, such as pluviosity and temperature, can be understood through long-term monitoring (Douglas and Marsh 1996; Ebner and Thiem 2009; Van Haverbeke et al. 2013). However, most studies with this approach focus on species related to fisheries, and little attention has been given to the smallest species.

Therefore, in the present study, we aimed to verify the distribution and temporal variation in body size, sex ratio, density, length-weight relationships (LWR) and condition factor (CF) of *M. rossoi* in its natural habitat. Interestingly, during the course of this study, two unpredicted variables emerged: fire in the marsh during the dry season and an explosive abundance of Erytrhinidae juveniles, which are putative predators of *M. rossoi*.

Methods

Study area

The study area is located in the boundaries of Campo Grande City, Mato Grosso do Sul, western Brazil. The altitude is about 480 m, and the region is located on the right bank of the Anhanduí River, Paraná Basin, bounding the Paraguay River Basin to the West. Historically, the area used to be a large connected wetland now divided by a state highway and surrounded by fields of corn and soy bean crops periodically sprayed with pesticides. The few marshes that still exist are legal reserves of farms, fragments of native vegetation that the proprietary are required to maintain in accordance with Brazilian law. The study area is found within the Cerrado ecoregion (Morrone 2014) and follows the Aw classification of Koppen-Geiger (Peel et al. 2007), with rainy summers and dry winters.

Sampling

In order to search for new populations of *Melanorivulus rossoi*, satellite images from Google Earth (earth.google.com) were analyzed to identify potential sites for species occurrence. Fieldwork was carried out by traveling the highways and secondary unpaved roads to access potential sites. An active search for fish was performed by two researchers using sieves 45 cm in diameter with 5 mm mesh at every site recorded. When we identified even a single individual, we took it to indicate the presence of the species in the marsh, but not necessarily homeogeneous occupation.

Since access to private land was limited, we chose a single wetland (20°37′44″S, 54°45′04″W, Fig. 1) for the monthly monitoring of population dynamics. The marsh comprises an area of 53 ha, average depth of 40 cm and vegetal coverage of Poaceae.

The samples were taken monthly from April 2015 to March 2016 using the method noted above during 30 min. To avoid bias from monthly removal of individuals from the site, the specimens were anesthetized with eugenol at 0.1 mg/L. Afterwards, specimens were counted, sexed, and total (TL) and standard length (SL) were measured with a digital caliper. Between April and August, the first 60 individuals sampled were weighed on a 0.001 precision digital scale, kept in plastic

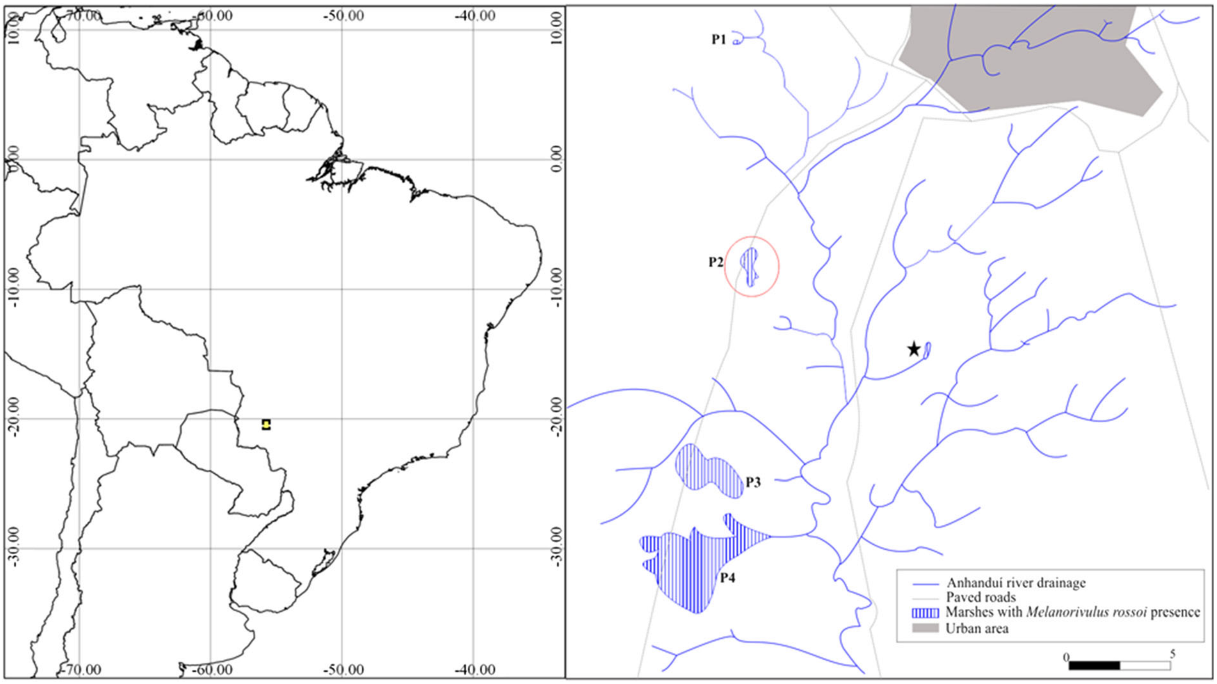

Fig. 1 Map with the distribution of *Melanorivulus rossoi* populations. Star represents the species type locality, and the red circle indicates the marsh where the monthly collections took place

receptacles to avoid resampling, and returned to the environment after recovering from the effects of eugenol. In the following months, all collected individuals were measured and weighed since abundance was low. Species was confirmed through the original description by Costa (2005). Since the original description does not include differences between sexes, females were determined through general phenotypic criteria on *Melanorivulus* species (Huber 1992), which indicate that the female presents a conspicuous ocellus near the top origin of the caudal fin, and this was confirmed later with gonadal analysis of the specimens. More specifically, *M. rossoi* females present a distinct ocellus, brownish dots below the middle of the flank, black spots/stripes on the caudal fin, and absence of red dots on the dorsal fin (Fig. 2). Individuals that could not be differentiated externally were considered juveniles. Occurrence and abundance of non-Rivulidae fish species of the marsh were recorded monthly, and identification was performed with reference to Britski et al. (2007) and Graça and Pavanelli (2007), in addition to direct analysis of specimens from the Coleção Zoológica da Universidade Federal de Mato Grosso do Sul (ZUFMS).

In order to identify which species consume *M. rossoi* individuals, the identified putative predators [*Hoplias malabaricus* (Bloch, 1794), *Hoplerythrinus unitaeniatus* (Spix & Agassiz, 1829), *Synbranchus marmoratus* (Bloch, 1795), and *Gymnotus* spp.] were fixed on formalin solution 10% and later transferred to alcohol 70%. In the laboratory, their gastric contents were analysed under stereomicroscopy. All collections were authorized by the

Fig. 2 *Melanorivulus rossoi* male above and female below. Non-preserved individuals

responsible environmental agency (ICMBio, under license N°49,242). Voucher specimens were deposited in ZUFMS.

Body size, length-weight relationship (LWR), condition factor (CF) and sex ratio

Length-weight relationships (LWR) were estimated for males, females and juveniles. To estimate LWR, a least square linear model was then fitted taking the base-10 logarithms of the allometric eq. W = aTLb (Le Cren 1951; Froese 2006) using Total Length (TL) -Weight (W) pairs. The confidence limits for b (CL 95%) were calculated to determine if the hypothetical value of isometry (3) fell between these limits (Froese 2006). Coefficient factor was calculated between males and females and across months using the eq. $CF = (W/TL^b) \times 100$ (Vazzoler 1996), where b is the slope of LWR.

Environmental variables

Data from monthly rainfall and air temperature were gathered at the Inmet website (available at http://www.inmet.gov.br/portal/index.php?r=home/page&page=rede_estacoes_auto_graf) based on the station at Campo Grande City, about 15 km from the field site. The pH and water temperature were taken monthly in loco.

Statistical analysis

To evaluate the variation of condition factor (CF) and total length (TL) between the sexes, we performed a mixed model. We treated time as a random factor where months were nested within the year, and sex was a fixed factor with two levels (male and female) for both CF and TL. Sex was transformed into a continuous variable where males were represented as 1, females were represented as −1, and individuals of undetermined sex were represented as 0. This modification was necessary because of the correlation between sex and age of the individuals. Young individuals whose sex was not possible to identify through external chacteristics were considered juveniles. The models were built using R language (R core team 2017) and the lme4 package to adjust the mixed models (Bates et al. 2015). The slopes of length-weight regressions were compared to three using Student's *t*-test to ascertain if species grew isosymetrically (Pauly 1984). All tests were performed under a significance level of 5%.

Results

Distribution of *Melanorivulus rossoi* was extended to four other sites (Fig. 1, Table 1), all in the Anhanduí River Basin, covering a total area of 470 km^2. These new sites presented areas from 3 to 830 ha and were 3 to 25 km apart.

During the sample period, accumulated rainfall reached 1847 mm. The mean temperature was relatively stable throughout all months (Fig. 3), with lower mean temperatures between May and July (minimum 22 and 23 °C, respectively) and higher mean temperatures between August and March (maximum 25.5 and 26.5 °C, respectively). August was the driest month (9 mm), and rain peaks occurred in September and January (215 and 361 mm, respectively). Water temperature varied from 16 in July to 25 °C in October and December (mean 21 °C), and pH ranged from 5.8 in February to 7 in June.

Overall, 1040 individuals were collected and measured. A total of 508 females, 272 males and 260 juveniles were collected. The body size of males and females generally did not differ between months, and adults were significantly larger than juveniles (Table 2, Fig. 4). Juveniles showed mean body size of 16.7 ± 2.75 SE ($9.1 \le TL \le 23.0$ mm), while adult females showed mean body size of 22.4 mm ± 3.67 SE ($13.9 \le TL \le 35.7$ mm), and males showed mean body size of 24.0 mm ±4.03 SE ($14.8 \le TL \le 35.8$ mm). Adult body size increases throughout the year, from April to November, but decreases in January of the following year, while juveniles show greater growth between April and October, with a steep reduction in body size in November (Fig. 4).

Estimated parameters of LWR are given in Table 3. The LWRs were significant in the three categories ($p < 0.001$), and general coefficient of determination (r^2) was 92%. The individual category analysis showed lower values for juveniles (77%) and higher values for

Table 1 Sites of *Melanorivulus rossoi* distribution, all belonging to the Anhanduí River Basin and Campo Grande Municipality, Brazil

Site	Longitude	Latitude	Altitude (masl)	Area (ha)
P1	20°32′14″S	54°45′19″W	507	3.22
P2	20°37′46″S	54°44′53″W	494	37
P3	20°43′04″S	54°46′25″W	483	274
P4	20°45′35″S	54°46′54″W	497	830

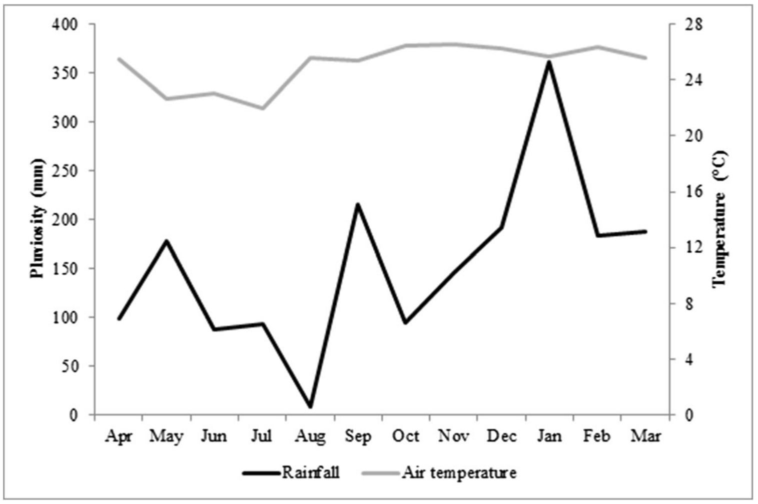

Fig. 3 Monthly accumulated rainfall and average temperature in Campo Grande City, Brazil, during the months of collection of *Melanorivulus rossoi*. Data gathered from Inmet website

males (91%). When data for juveniles, males and females were analyzed together, the population showed isometric growth (b = 3.00) (*t*-test, $P > 0.05$). However, when separated, juveniles showed negative allometric growth (b = 2.78), while adults showed positive allometric growth (Males = 3.06; Females = 3.13) (*t*-test, $P < 0.05$).

Males presented higher CF than females, and a significant difference was observed between the CF of both sexes during the year (Table 4). Both sexes presented the same tendency of temporal variation in CF, with lower values in October and January and peaks in September and February (Fig. 5).

From April to March, 260 juvenile individuals were collected. The positive peak of abundance of juveniles occurred in May, and the least abundance was registered during September–October when the dry season ended (Fig. 6). No males were collected in November. Sex ratio was biased to females, and sex ratio varied between 0.28 to 0.9.

Syntopic species were Characiformes: *Characidium* sp., *Hoplerythrinus unitaeniatus* (Spix & Agassiz, 1829), *Hoplias malabaricus* (Bloch, 1794), *Hyphessobrycon eques* (Steindachner, 1882), *Moenkhausia oligolepis* (Günther, 1864), *Pyrrhulina australis* (Eigenmann & Kennedy, 1903) and *Serrapinnus kriegi* (Schindler, 1937); the Gymnotiformes *Brachyhypomus* sp. and *Gymnotus* sp. and the Synbranchiformes *Synbranchus marmoratus* (Bloch, 1795).

At the end of the dry season in September, a peak abundance of *Hoplias malabaricus* ($n = 68$) and *Hoplerythrinus unitaeniatus* ($n = 30$) juveniles emerged, and 98 juveniles from both species were collected (Fig. 7). The length of these species ranged from 33 to 46 mm, and all of them presented one or two *Melanorivulus* in their guts. After this event, successful capture of *M. rossoi* was reduced to about 30% of that in previous months. *Synbranchus marmoratus* ($N = 8$) and *Gymnotus* sp. ($N = 11$) did not present any fish in their guts.

Discussion

Brazil harbours over 100 species of Rivulidae (Costa 2008), but little is known about the biology and

Table 2 Results of the mixed model testing variation of total length of *Melanorivulus rossoi* over a year, as explained by sex and age

Coefficient	Estimate	SE	*T*	*P.Z*
Intercept	23.9646547	0.5069231	47.274733	0.000000e + 00
Sex	0.7126668	0.1674186	4.256795	2.073787e-05
Juvenile	−6.7009465	0.3593222	−18.648852	0.000000e + 00

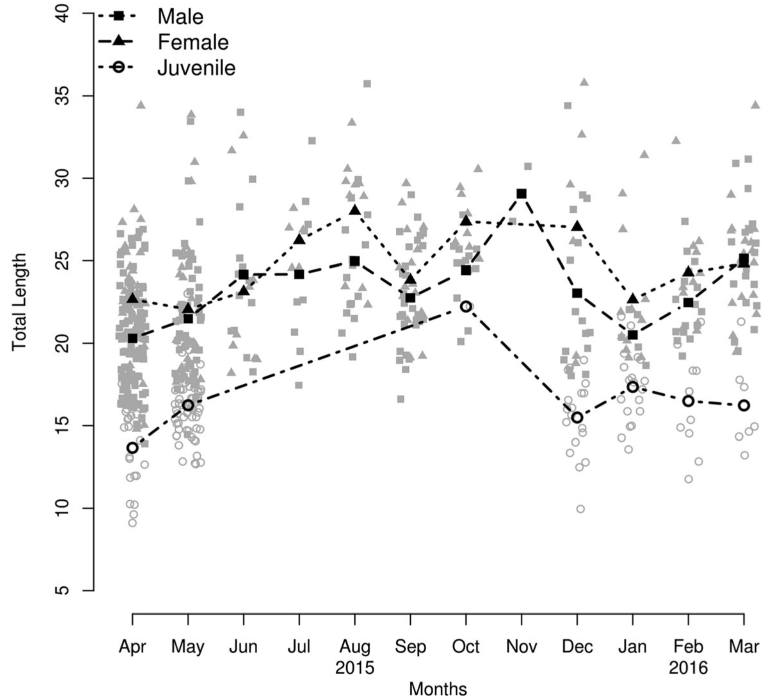

Fig. 4 Temporal variation of body size (mean ± SE of total length) of *Melanorivulus rossoi* from April 2015 to March 2016 at Campo Grande (20°37′44″S, 54°45′04″ W). In September, no juveniles were collected, and in November no males were collected

population dynamics of these species. After its description, *Melanorivulus rossoi* was only known from its type locality, and no further information about its biology has since been available. In this work, we provide information about its population dynamics and responses to environmental and interspecific variables. Since its conservation is classified as Data Deficient (ICMBIO 2014), these data support the expansion of its area of occurrence and provide information that may guide future evaluations toward the conservation of this restricted range species.

Isometric growth of the population (b = 3) indicates that small specimens have the same shape as large specimens (Froese 2006). However, this conclusion was biased by opposing values at different stages, i.e., negative allometric growth of juveniles (b < 3), but positive allometric growth of adults (b > 3). In other words, juveniles grow more in length than weight, while in adults, just the opposite occurred, likely a result of increased gonadal development (Froese 2006). Although LWR can yield substantial information about fish biology, LWR in nonannual Rivulidae species is still insufficient for further comparisons, as pointed out by Lanés et al. (2012).

Mean standard length of the studied population increased from April to November and started to decrease in early summer (December) and then resumed growth in February. Similar results were found for the southern Brazilian rivulid *Atlantirivulus riograndensis* (Costa & Lanés, 2009) by Lanés et al. (2012) who observed that

Table 3 Descriptive statistics and estimated parameters of length-weight relationships of *Melanorivulus rossoi*, western Brazil

		Length (mm)		Weight (g)		Regression parameters				
		Min	Max	Min	Max	A	b	95% CI of a	95% CI of b	2
Total (J + M + F)	04	9.1	35.8	0.005	0.398	−5.1332	3.0023	−5.225 to −5.041	2.932 to 3.072	.92
Juveniles	39	9.1	23.01	0.005	0.100	−4.8596	2.7782	−5.159 to −4.560	2.528 to 3.028	.77
Males	60	14.8	35.8	0.023	0.388	−5.2094	3.0610	−5.412 to −5.007	2.914 to 3.208	.91
Females	05	13.9	35.7	0.015	0.398	−5.3149	3.1338	−5.486 to −5.144	3.006 to 3.261	.88

Table 4 Results of the mixed model testing variation of condition factor of *Melanorivulus rossoi* over a year being, as explained by sex and time, using the months of collection as a random effect

	Estimate	SE	*T*	*p*
Female	0.6928	0.022	31.5281	<0.001
Male	0.0382	0.010	3.8015	<0.001

the body size of this species tends to show growth throughout the year, with a decrease at the beginning of summer, similar to that observed in the present study for *M. rossoi*. These authors attribute this change as a response to biological and ecological factors, such as senescence, higher temperature and lower pluviosity in the summer. For *M. rossoi*, rainfall may have a greater influence on the reduction of body size since the period of greatest rainfall coincided with the reduction of adult body size. We hypothesized that this may have resulted from an increasing rise in the level of the water, favouring the dispersion of larger individuals and resulting in the reduction of the mean body size. On the other hand, we also reasoned that the reduced body size of juveniles in November could have been related to the higher reproductive activity of the species in the period before, in turn resulting in a higher proportion of new juveniles with smaller body size.

The tendency of larger body size in males and female-biased abundance in the *Melanorivulus rossoi* population is consistent with other observations in this family and reinforces this sexual characteristic as a pattern common to Rivulidae species (Costa 2003; Lanés et al. 2012). However, the condition factor between males and females, as determined in the present study, is different from that found for a population of *A. riograndensis* (Lanés et al. 2012) that showed no statistical difference between sexes. Low condition factor values could be attributed to the spawning season (Froese 2006) in that the lowest CF values in our study occurred in October and January. In October, this result might have resulted from the abundance of predators during the months of August and September (Fig. 7), which would have correspondingly inhibited the reproduction of *M. rossoi* during these months. *Anablepsoides hartii* (Boulenger, 1890) populations from Trinidad exhibited a reduction up to 50% of egg production in response to the predatory threat of *H. malabaricus* (Fraser and Gilliam 1992), the same main predator we found in this study. After the decrease of CF coefficients in January, we found no increase of juveniles in the following months. This fact may be attributed to the

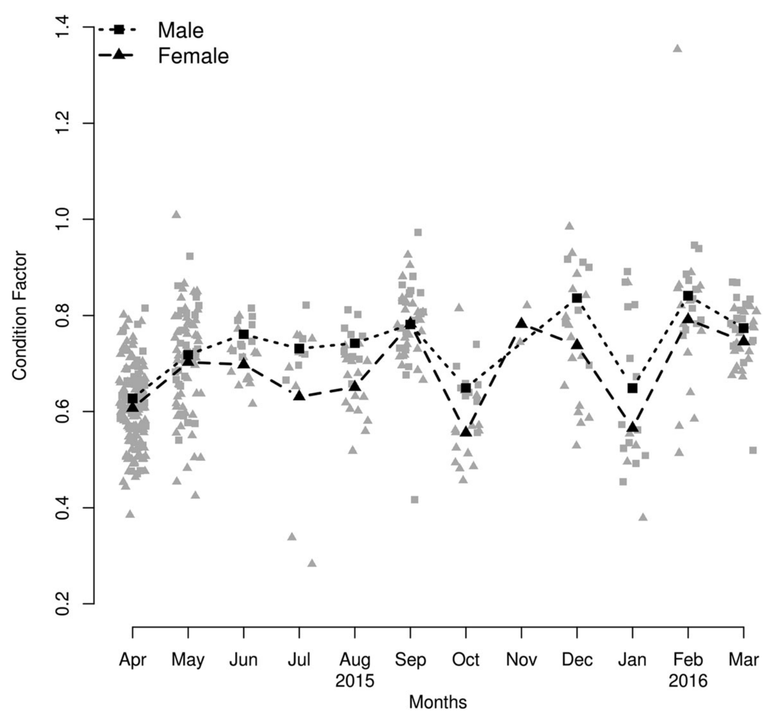

Fig. 5 Condition factor (mean ± SE of total length) of *Melanorivulus rossoi* males and females from April 2015 to March 2016. No males were collected in November

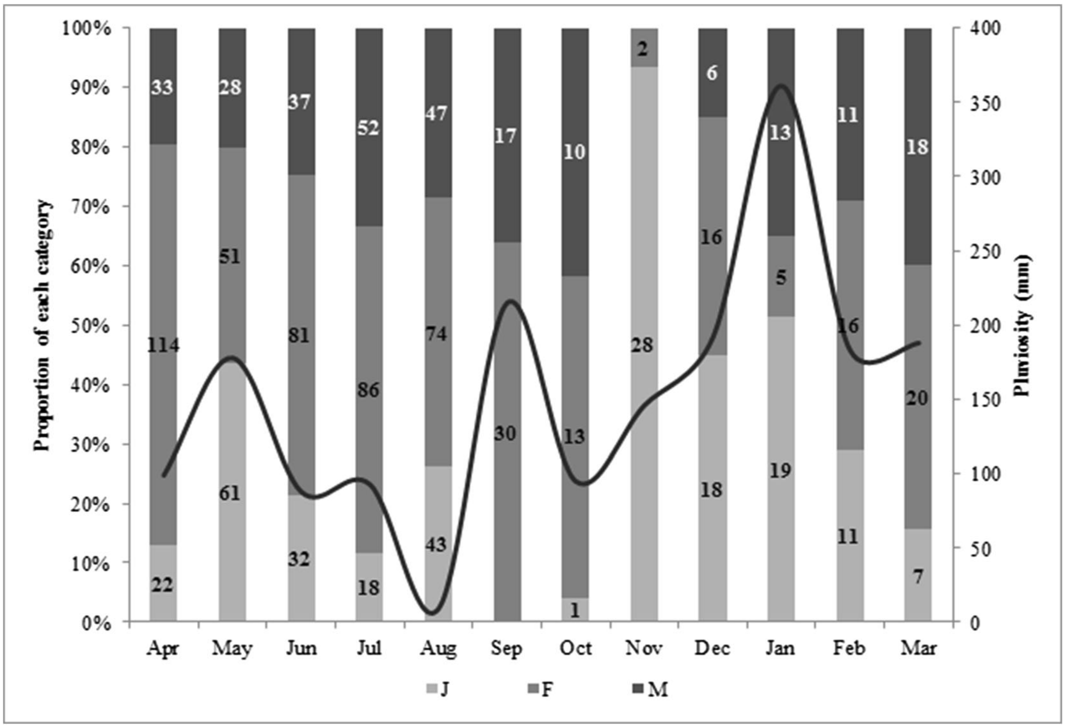

Fig. 6 Proportions of *Melanorivulus rossoi* juveniles, females and males and monthly rainfall throughout one sampling year

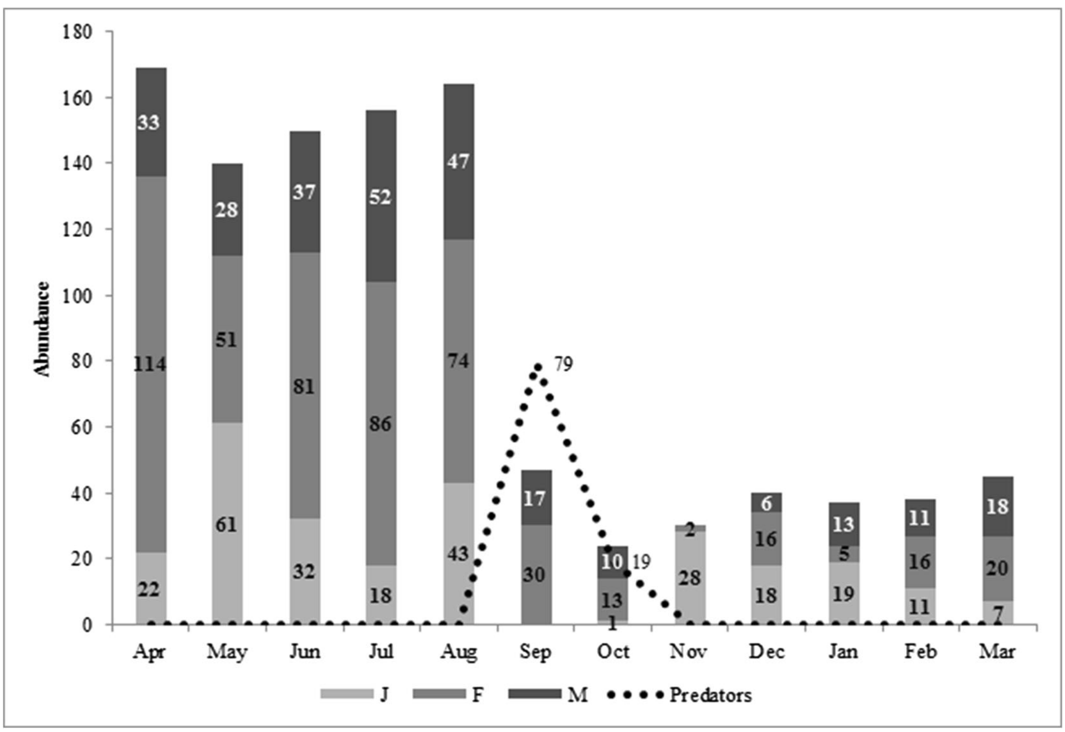

Fig. 7 Monthly abundance of juveniles, females and males of *Melanorivus rossoi* and its predators (*Hoplias malabaricus* and *Hoplerythrinus unitaeniatus*)

peak of rainfall in this month that may have influenced the feeding of *M. rossoi* individuals through drift of regular food supplies. Preliminary data revealed a diet exclusively comprised of autochthonous items, such as Diptera larvae, especially from the Chironomidae and Culicidae families (Severo-Neto unpublished data). However, further studies on the reproduction and feeding habits of *M. rossoi* are necessary to validate this hypothesis.

Piscivory can be a major biotic driver underlying the structure of fish assemblages through direct or indirect mechanisms (Jackson et al. 2001 and references therein). Birds and hemipterans are known as predators of annual fishes in ephemeral pools (Haas 1976; Reichard et al. 2014; Keppeler et al. 2016), but information about predators of nonannual Rivulidae in their natural habitats remains scarce. In this sense, the present work reports a potential significant negative effect of predators entering the habitat of *M. rossoi*, resulting in the dramatic reduction of fish density, mostly juveniles. Eyrthrinidae is a family of Characiformes that occurs in Central and South America, and all of its species are carnivorous fish that include other fishes in their diet. The *Hoplias* genus is the most widespread through South American basins (Oyakawa 2003). Despite its wide distribution range, information about its reproductive habits on small wetlands still scarce, and it seems to adjust its reproduction to different environments (Araújo-Lima and Bittencourt 2001). In the present study, we observed a correlation between flooding and the number of Erythrinidae juveniles, which agrees with the hypothesis that flooding may be a reproductive signal, as proposed by other authors (Oliveira et al. 2014). The peak abundance of *Hoplias malabaricus* and *Hoplerythrinus unitaeniatus* juveniles occurred at the transition between dry and rainy seasons (Aug-Sep, Figs. 5 and 6). Since *Melanorivulus* species usually live on shallow and heterogeneous marginal habitats, the amount of water might facilitate the movement of these predatory larvae toward *M. rossoi* microhabitats.

The threat of *Hoplias malabaricus* predation is a well-documented driver of changes in distribution (Gilliam and Fraser 2001), feeding (Fraser and Gilliam 1987), growth and reproduction (Fraser and Gilliam 1992) over the killifish species *Anablepsoides hartii* from Trinidad and Central America. Here we provide evidence of *H. malabaricus*, as well the first evidence of *Hoplerythrynus unitaeniatus*, as effective predators of *Melanorivulus* populations. Although our collection method limited the capture of larger *Hoplias*, it is known that its prey size increases as the individual grows in size (Winemiller 1989; Mazzoni and Costa 2007); therefore, it is plausible that *M. rossoi*, which grows to no more than 36 mm in length, can be the most frequent prey in the early stages of *Hoplias* growth and that it may be replaced by other items afterwards. *Hoplias* juveniles are commonly recognized as insectivorous in their early stages, switching to piscivory after maturity (Mazzoni and Costa 2007), but our findings suggest that these predatory juveniles (~40 mm) can base their feeding on fish as well, which may reflect a digestive tract adapted to a piscivorous diet independent of ontogenetic stage (Teixeira-de Mello et al. 2006). In addition, Brosset (1997) found evidence of aggressive mimicry between juveniles of *Erythrinus erythrinus*, another member of Erythrinidae family, and *Laimosemion agilae*, a killifish from northern South America. From this perspective, we suggest future experimental works involving *Melanorivulus* vs. Erythrinidae, especially *Hoplerythrynus unitaeniatus* that presents a remarkable resemblance to *Melanorivulus* by its shape, color and spot pattern.

Although fire may be considered a disturbance in landscapes exhibiting aquatic dynamics (Dunham et al. 2003), little is known about how Neotropical fish populations react to this sort of disturbance, especially in small and shallow environments, such as the habitat of *M. rossoi*. However, species which inhabit degraded and fragmented systems would seem to be most vulnerable to fire and fire-related disturbances (Dunham et al. 2003). In this study, a fire was observed in June, but it seemed to have no effect on the variables studied here, as no significant changes were observed immediately after the fire on the population structure of *Melanorivulus giarettai* (Costa 2008) from "vereda" habitats (Oliveira et al. 2012). As pointed out by Minshall et al. (2001), fire may affect aquatic organisms over the long term, suggesting that this population should be monitored over a long time course to determine the real effects of fire and other significant environmental disturbances. More important, the fragmentation of the wetlands and resultant isolation of the *M. rossoi* population (Fig. 1) may constitute the greater threat to this species, as it is to most Rivulidae species in Brazil (Rosa and Lima 2008). This calls for further studies to verify the effects of this landscape modification on population genetics. Although our results about predation and fire lack temporal and spatial replication, they do represent a first step toward investigating these variables in anticipation that future studies will test these hypotheses in the effort to gain more understating of population dynamics of this fish species in its natural habitat.

In conclusion, we analyzed population parameters of an endemic Brazilian Cerrado species with little previous data extending beyond description. Although some aspects of its population structure have been highlighted, some questions remain unclear, including the effects of predation on individual microhabitat use and population dynamics over time. In addition, the influence of environmental factors on reproduction and diet remains to be elucidated. We anticipate that the results of the present report will contribute to such future studies on nonannual Rivulidae populations.

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