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Anthropogenically physically changed habitats enable an easier propagation of invasive bivalve in neotropical headwater streams

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Abstract *Corbicula fluminea* is one of the most successful invasive species in neotropical freshwater ecosystems. As alien species' distribution in invaded regions is often facilitated by the presence of anthropogenic altered ecosystems, such as artificial channels and reservoirs. The present study is part of a larger joint scientific assessment of the ecological effects of a run-of-river dam in the Pandeiros River Basin, Brazil, aiming at supporting decision making regarding its possible decommissioning. Our focus was to determine which in-stream physical habitat metrics are most important for the distribution of *C. fluminea* in Pandeiros river basin, a Neotropical dammed Savanna-river basin. We found that its occurrence was linked positively with sheltered margins and pipes in the riparian zone, and negatively with the distance from the Pandeiros River dam. These results show that *C. fluminea* distribution is closely linked to anthropogenic alterations in the physical habitat and, due to the dam influence in enhancing this invasive species distribution, we could recommend the decommissioning of the Pandeiros River dam, built in 1957, but whose economic activities, including electrical power generation, have been totally deactivated since 2007.

Keywords *Corbicula fluminea* · Headwater streams · Physical habitat · Bivalve invasion

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Introduction

Biological invasions are the second greatest cause of biodiversity loss in global scale, behind only to habitat loss (Simberloff et al. 2013; Ortega et al. 2015; Thomaz et al. 2015). Freshwater ecosystems are especially impacted by biological invasions, due to the historical and widespread influence of anthropogenic

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disturbances over these ecosystems (Dudgeon et al. 2006; Petsch 2016). Invasive species' distribution in the invaded regions is often facilitated by the presence of anthropogenic altered ecosystems, such as channels and reservoirs, with these artificial (man-made) habitats usually serving as stepping stones for their distribution (Johnson et al. 2008; Zipp et al. 2019; Linares et al. 2020b).

Among the many invasive species in neotropical freshwater ecosystems, *Corbicula fluminea* (Bivalvia, Corbiculidae) is one of the most successful, being widespread through most South American river basins (Fernandez et al. 2003; Rosa and Dantas 2020; Darrigran et al. 2020). This species was first registered in the Plata estuary in the 1970's, and nowadays is present in all of the continent's major river systems (Cataldo and Boltovskoy 1998; Boltovskoy et al. 2009; Reshaid et al. 2017). *Corbicula fluminea* establishment can cause significant environmental disturbances, by the impact of this invasion on aquatic macroinvertebrate assemblages, by displacing native bivalves and other filter-feeders and serving as vectors of parasites, and economic losses, by biofouling (Sousa et al. 2008, 2009; Crespo et al. 2015; Labaut et al. 2021).

The invasive success of *C. fluminea* and its widespread dispersion are mostly derived from its reproductive characteristics (e.g., rapid growth, earlier sexual maturity, and high fecundity) and association with human activities (e.g., water exploitation, river damming, etc.), species of *Corbicula* present different reproductive strategies according to the type of environment they inhabit (Cao et al. 2017). Besides, *C. fluminea* shows much lower physiological tolerance to environmental variations if compared to other invasive bivalves, such as *Limnoperna fortunei* (Sousa et al. 2008; Pérez-Quintero 2008). Therefore, knowledge about how the physical habitat influences the distribution of *C. fluminea* is crucial for the management of this invasive species and there is still a lack of information. The distribution of *C. fluminea* and its relation with physical habitat metrics was previously studied in hydropower reservoirs and other anthropogenically altered ecosystems (Linares et al. 2020b), but there is a gap in the knowledge about its distribution in headwater streams.

The presence of dams, even small run-of-river dams, can cause significant alterations in the benthic fauna along an entire river basin (Mbaka and Wanjiru Mwaniki 2015; Wang et al. 2016; Fantin-Cruz et al. 2016). Due to that, the presence of dams is an important environmental factor for species distributions in river systems (Malmqvist and Rundle 2002; Oliveira-Junior et al. 2017; Linares et al. 2018). This is especially true for invasive species, that benefit from the presence of these anthropogenic altered habitats, using them as stepping stones for their distribution in river systems (Johnson et al. 2008; Linares et al. 2019).

Therefore, the aim of this study is to determine which physical habitat metrics are most important for the distribution of *C. fluminea* in a Neotropical Savanna river basin. We hypothesized that anthropogenic disturbances will increase the probability of the presence of the *C. fluminea* in the stream sites, predicting that the majority of the physical habitat metrics related to the distribution of *C. fluminea* in the Pandeiros River streams will be disturbances related.

Material and methods

Study area

The Pandeiros River is a tributary of the São Francisco River, whose basin is located in the northern region of the state of Minas Gerais, Brazil, in the Cerrado biome and has an area of 3960 km^2 (Fig. 1). Its floodplains are considered by state law to be of "Special Biological Importance" because of their unique nature in the state and high biodiversity in the wetlands (Santos et al. 2015). An Area of Environmental Protection covers almost 4,000 km^2 and includes the entire Pandeiros River Basin in the municipalities of Januária, Bonito de Minas, and Cônego Marinho (Linares and Callisto 2019). The Pandeiros River dam was installed in 1957, and its reservoir covers 280 ha, with a free-crest dam height of 10.3 m (Fonseca et al. 2008). The powerhouse was deactivated in 2007 and since then, all economic activities of the dam and reservoir have ceased.

We sampled 26 stream sites (Fig. 1), located in the Pandeiros River basin, during the dry season (April–June 2016). The stream sites were selected using a probability-based procedure, resulting in a spatially balanced design (Olsen and Peck 2008; Macedo et al. 2014) and they were located upstream of Pandeiros River dam.

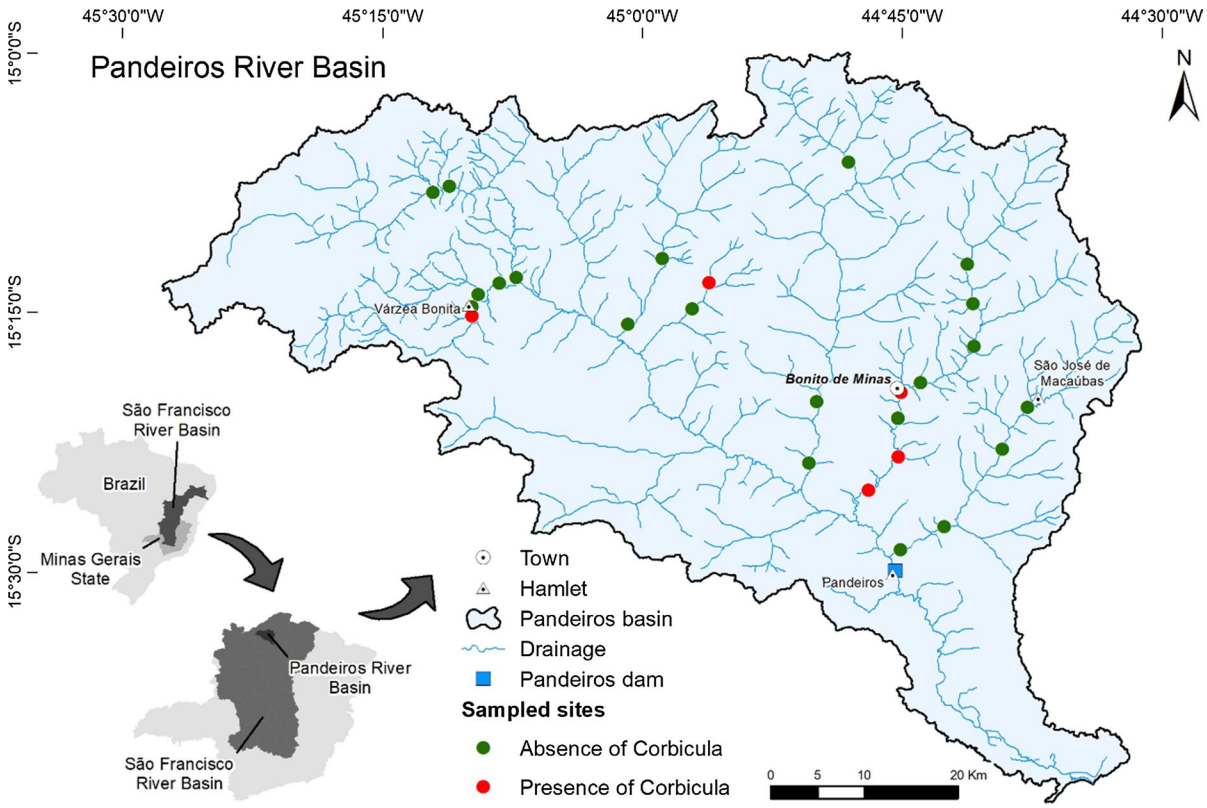

Fig. 1 Location of the Pandeiros River basin and the sampled sites. Sites with occurrence of *Corbicula fluminea* are marked in red

In-stream physical habitat assessment

To assess the physical habitat metrics, we followed the methodology based on the protocols of the USEPA, adapted to the Neotropical Savanna (Callisto et al., 2019; Peck et al., 2006). At each sampling site, human disturbance, vegetation cover, shoreline morphology and substrate type were recorded. Subsequently, these data were used to calculate a series of nearly 290 physical habitat metrics (Supplementary Material S1).

At each stream site we measured a stretch of 40 times the stream width, to a minimum of 150 m, divided into 11 equally spaced transects. At each transect we quantified channel morphology metrics to measure different aspects of the channel (e.g., depth, width, margin angle). The presence of human disturbances in the riparian zone (e.g., pasture, agriculture, trash, pipes) was visually estimated. Vegetation cover in the riparian zone was visually estimated, while canopy cover in the main channel was estimated by using a densitometer. Between transects, we determined channel slope (with a clinometer) and sinuosity (with a compass). At every 1.5 m we recorded flow habitat type (e.g., riffles, pools, glides, etc.) and thalweg depth. Substrate size was sampled by visually classifying the diameter class (e.g., sand, gravel, boulder) of a total of 105 individual particles in five systematic points distributed across 21 cross-sections of the 150 m wetted channel to ensure stable and precise substrate estimates. For more details see the complete USEPA protocols (Kaufmann et al. 1999a; Peck et al. 2006). Aditionally, we measured the chanel distance of each sampling site to the dam, using drainage maps.

Corbicula fluminea sampling

We collected *Corbicula fluminea* individuals using a D-net (30 cm opening, 0.5 mm mesh sieve), using a kick-net method. The samples were taken following a zig-zag pattern along each stream site, resulting in

eleven sub-samples (0.09 m^2 each), totaling 0.99 m^2 multi-habitat composite sample for each stream site. We fixed the samples in the field with 10% formalin and took them to the laboratory. There, the individuals of *C. fluminea* were identified, and accordingly with this identification sampling sites were then classified as detected (1) or non-detected (0). All specimens collected were fixed in 70% alcohol and deposited in the Reference Collection of Benthic Macroinvertebrates, Instituto de Ciências Biológicas, Universidade Federal de Minas Gerais.

Data analyses

To explore our hypothesis, we used a model selection method (Burnham and Anderson 2002). We first ran a preliminary test, eliminating those metrics with low correlation ($|r| \geq 0.25$) with the presence of *C. fluminea*. After that we tested for correlation among the remaining variables, eliminating those that were highly correlated ($|r| \geq 0.7$) to each other and retaining the most ecologically relevant metrics. We then used our selected variables as predictor variables in a generalized linear model (GLM) with a binomial distribution, where the response variable was presence / absence (1/0 respectively) of *C. fluminea*. Next, we constructed a model based on all possible additive variable combinations that may have influenced the probability of the presence of *C. fluminea* (Doherty et al. 2012). Following this, we calculated the cumulative AICc weights (w +) for each variable and evaluated which were the most likely (w + ≥ 0.50) to have influenced the presence of *C. fluminea* (Burnham and Anderson 2002). This analysis was implemented using the MuMIn package (Bartón 2019).

Results

A total of 15 metrics, out of 291, remained after our screening process (Table 1; Supplementary Material S2). Of these, three metrics were classified as anthropogenic disturbance metrics: Channel Distance to the Dam, Pipe Proximity Index and Stretch Proportion of Human Impact (Table 2).

Corbicula fluminea was identified in 5 of 26 stream sites (~ 20%; Fig. 1), for a total of 193 identified individuals. *C. fluminea* abundance in the sites where it was detected varied between 3 and 123 individuals per site (Supplementary Material S1), with a mean value of 38.5 individuals per site. *C. fluminea* occurrence was linked positively with the Undercut Bank Shelter Proportion in the Margins (PFC_UCB) and with the Pipe Proximity Index (W1H_PIPE), and negatively with the Channel Distance to the Dam (Distance) (Table 3).

Discussion

Our results show that anthropogenic disturbances were the most important factor influencing the distribution of *Corbicula fluminea* in the Pandeiros River basin streams, as two of the three of the habitat's physical metrics significantly related to the distribution of this invasive species are disturbance variables. Thus, our hypothesis that anthropogenic disturbances would increase the probability of *C. fluminea* occurrence in the stream sites was corroborated.

The preference of *C. fluminea* for sites with dug shelter (undercut banks) in the margins can be explained by their preference for microhabitats with low water velocity and low turbidity conditions (Cataldo and Boltovskoy 1998). Sheltered areas in stream margins usually have slower currents compared to the mean of the channel, and serve as FPOM deposit (Kaufmann et al. 1999b). As *C. fluminea* are sessile filter feeders, these conditions facilitate the establishment of their planktonic larvae, provide easier access to food items for the mature individuals, and offer protection against being driven out by strong water flow (Sousa et al. 2008; Crespo et al. 2015).

The fact of *C. fluminea* occurrence is being favored by the existence of pipes in the riparian zone can be interpreted as a positive relation of this invasive species with water exploitation. Water abstraction is closely related to the distribution of invasive bivalves, as it provides a link of natural freshwater ecosystems with anthropogenic altered habitats, such as irrigation channels and small reservoirs (Almeida et al. 2009; Lercari and Bergamino 2011; Böhm et al. 2021). Another important factor is that these areas facilitate the access for humans to the lotic ecosystem, a key factor for continual introductions of individuals of invasive species (Johnson et al. 2008; Anderson et al. 2015; Leiva et al. 2020).

The Pandeiros River is an important source of water for human consumption and for use in the local

Table 1 Values of the metrics used to determine which physical habitat variables are most important for the distribution of *Corbicula fluminea* in streams of the Pandeiros River basin

Site	Distance	PCT_WD	W1H_PIPE	PCT_RA	XWXD	PCT_CB	PFC_UCB	XCB_HALL	PCTRSED	XMW	XFC_LEB	XCEMBED	XCMG	XCS	SINU
PMS0005	53.59508	0	0	1.333333	1.061551	2.857143	0.818182	0.363636	0.513333	20.45455	18.86364	78.78788	108.0682	14.54545	1.176225
PMS0029	45.79825	0.526316	0	0	6.745775	0	0	0.863636	0.940741	4.545455	10	85.18519	69.09091	2.5	1.23953
PMS0044	85.30021	0.105263	0	0	1.712124	0	0	0.636364	0.903704	10.34091	4.090909	66.33333	114.7727	9.545455	1.156016
PMS0049	57.19969	0.380952	0.068182	0	0.749143	0	0.909091	0.636364	0.106667	21.25	17.04545	49.54545	100.4545	17.04545	1.200466
PMS0055	64.34977	0.095238	0	0	4.074655	0	0.363636	0.772727	1	21.02273	1.818182	100	113.2955	15.22727	1.341461
PMS0057	50.49793	0.190476	0	0	2.218362	0	0	0.454545	0.646667	38.29545	18.18182	81.21212	104.3182	14.20455	1.052761
PMS0077	40.35275	0.190476	0.068182	4.666667	1.897578	4.761905	0	0.454545	0.58	30.79545	8.636364	64.24242	70	21.25	1.160393
PMS0090	26.79393	0.095238	0	0	2.359528	40.95238	0.090909	0.045455	0.033333	60	19.09091	29.13043	345.5682	73.75	1.287759
PMS0134	19.24893	0.095238	0	9.333333	5.051574	23.80952	0.090909	0.409091	0.126667	57.15909	14.09091	37.27273	323.9773	63.75	1.262901
PMS0135	73.1171	0.111111	0.272727	11.11111	1.53915	38.88889	0.909091	0.045455	0.103704	28.06818	8.181818	65.83333	169.6591	28.97727	1.128822
PMS0138	24.75931	0.105263	0	0	2.545575	0	0.090909	0.909091	1	8.977273	6.363636	50	77.72727	2.727273	1.302218
PMS0150	2.587321	0	0	0	1.246172	0	0	0.136364	0.992593	38.29545	22.04545	100	232.7273	27.38636	1.308304
PMS0151	70.54212	0.666667	0	0	3.151597	0.952381	1	0.136364	0.806667	18.75	14.09091	86.06061	82.15909	20.79545	1.183688
PMS0175	83.33006	0	0	0	2.978547	5.714286	0.727273	0.181818	0.76	19.09091	3.181818	86.36364	79.88636	16.13636	1.123051
PMS0182	31.5722	0.095238	0.060636	0	3.06908	0	0.272727	0.909091	0.958333	27.95455	2.272727	94.84848	161.0227	21.36364	1.191785
PMS0190	8.303863	0	0	0	2.067383	13.33333	0	0.454545	0.594406	60.11364	36.13636	60.37037	311.5909	79.20455	1.25853
PMS0202	18.80539	0.096154	0	0	1.449978	0	0.636364	0.318182	0.96	23.18182	1.363636	50	84.54545	6.136364	1.254448
PMS0215	66.17931	0.190476	0	12.66667	2.912561	42.85714	1	0.727273	0.073333	17.04545	4.090909	26.36364	87.84091	41.59091	1.259901
PMS0222	20.09343	0.6	0	0	0.486119	0	0.272727	0	1	5.454545	24.31818	73.33333	91.81818	5.227273	1.328742
PMS0245	58.82144	0	0	5.714286	1.446073	2.857143	0.363636	0.136364	0.104762	10.56818	0	20	86.70455	2.954545	0.970794
PMS0267	51.52014	0.285714	0.068182	0	4.328315	30.47619	0.363636	0.318182	0.226667	32.15909	39.77273	43.75	183.8636	38.97727	1.288082
PMS0299	60.8857	0.7	0	0	3.048684	0	0.181818	0.772727	0.791946	14.65909	10.45455	88	59.20455	32.27273	0.952719
PMS0391	72.01963	0	0.068182	0.666667	2.8647	17.14286	0.909091	0.045455	0.62	14.88636	17.04545	63.0303	115.6818	10.56818	1.377298
PMS0462	25.91084	0.857143	0.068182	0	0.925254	7.619048	0.636364	0.454545	0.833333	15.45455	15.90909	91.21212	114.5455	16.02273	1.308064
PMS0726	13.03415	0.285714	0	0	2.16978	8.571429	0.636364	0.136364	0.586667	8.636364	10	66.36364	42.84091	11.02273	1.193994
PMS1226	27.92949	0	0.136364	2.666667	2.790495	26.66667	0.181818	0	0.386667	7.613636	4.090909	59.69697	86.59091	5.909091	1.198097

agriculture and cattle raising on the region (Santos et al. 2015). As the local human population relies on these ecosystem services, we advise that a stronger focus should be put on the rational management of these water resources, aiming at minimizing the ecological effects of its use on the lotic ecosystems. The utilization of alternative water sources, such as groundwater, through wells, and rain collectors, but especially the use of more efficient irrigation and water distribution techniques can significantly diminish the negative effects on the Pandeiros River's environmental conditions (Floury et al. 2012; Leiva et al. 2020).

The waning regarding the occurrence of *C. fluminea* as a function of increasing distance from the channel to the dam suggests that the reservoir acts as a stepping stone for the distribution of this invasive species in the river basin landscape (Johnson et al. 2008; Linares et al. 2020b). Anthropogenically altered ecosystems, such as reservoirs, tend to be closely related to the distribution of *C. fluminea* (Darrigran 2002; Karatayev et al. 2007; Dias et al. 2014) and other invasive mollusks (Fernandez et al. 2003; Oliveira et al. 2011; Zhan et al. 2015; Darrigran et al. 2020). Actually, such observations are in fully agreement with previous studies carried out in the Pandeiros River main channel, that evidenced the occurrence of higher abundances of *C. fluminea* close to the dam (Linares et al. 2018, 2019). The dam presence appears therefore to increase the propagule pressure to closer streams (Oliveira et al. 2011).

This study is part of a large joint scientific research project, the first of this kind in South America, focused on the assessment of the ecological effects of a run-of-river dam in the Pandeiros river basin, in Brazil, which aims at supporting decision making regarding its possible decommissioning. In this regard, we see no objections in recommend the decommissioning of the Pandeiros Dam, as our results suggest it plays an important role in favoring the distribution and maintenance of the invasive *C. fluminea* in the Pandeiros River basin. Previous studies in the Pandeiros River basin (Linares et al. 2018, 2019, 2020a; Martins et al. 2020, 2021a, b) are actually in agreement with the present results, also illustrating that the dam and its reservoir has significant impacts on the ecology of the lotic ecosystems in the region. These studies also highlight the benefits of a decommission process can have to benthic macroinvertebrate assemblages in the Pandeiros River basin, by increasing the connectivity of its different areas to the native species and by reducing the locals which are dominated by invasive species. It is, of course, advisable to discuss these results with members of the local community, state agencies, public prosecutor's

Table 2 Metrics used to determine which physical habitat variables are most important for the distribution of *Corbicula fluminea* in streams of the Pandeiros River basin. Mean and range (minimum-maximum) of each continuous predictor variable were calculated from 26 stream sites. See methods for details

Metric	Metric Type	Description	Mean (min–max)
Distance to dam	Disturbance	Channel distance to the Pandeiros' Dam (km)	44.33 (2.59–85.30)
W1H_PIPE	Disturbance	Pipe Proximity Index	0.03 (0–0.27)
XCB_HALL	Disturbance	Stretch Proportion of Human Impact	0.40 (0–0.91)
PCT_WD	Substrate	Wood Proportion in the Substrate	0.22 (0–0.86)
PCT_CB	Substrate	Cobble Proportion in the Substrate	10.29 (0–42.86)
PCTRSED	Substrate	Fine Substrate Proportion in the Talweg	0.60 (0–1.00)
XFC_LEB	Substrate	Mean Leaf Litter Shelter	12.74 (0–39.77)
XCEMBED	Substrate	Mean Channel Embeddedness (%)	60.04 (20.00–100.00)
PCT_RA	Flow	Proportion of Rapids	1.85 (0–12.67)
XWXD	Channel Morphology	Wet Area (m^2)	2.50 (0.45–6.75)
PFC_UCB	Channel Morphology	Shelter Proportion in the Channel	0.40 (0–1.00)
SINU	Channel Morphology	Channel Sinuosity	1.21 (0.95–1.38)
XMW	Riparian Vegetation	Mean Riparian Woody Understory	23.65 (4.55–60.11)
XCMG	Riparian Vegetation	Mean Riparian Total Cover	131.46 (42.84–345-57)
XCS	Riparian Vegetation	Mean Riparian Small Tree Canopy	23.04 (2.50–79.20)

Table 3 Cumulative AICc weights (w+) and estimates of variable effects (β parameters) for predictor variables used to model the local presence probability of *Corbicula fluminea* occurrence in streams of the Pandeiros River basin. Values of w+ in bold are those considered to be more likely (w+ ≥ 0.50). Estimates of variable effects are based on the most parsimonious model that included that variable and are given only for variables with w+ ≥ 0.50

Metric	*Corbicula fluminea* occurrence	
	w_+	β
Distance to dam	**0.6**	**−4.514879**
W1H_PIPE	**0.97**	**1356.937**
XCB_HALL	0.01	–
PCT_WD	0.12	–
PCT_CB	0.01	–
PCTRSED	0.13	–
XFC_LEB	0.13	–
XCEMBED	0.13	
PCT_RA	0.13	–
XWXD	0.13	
PFC_UCB	**0.71**	**197.2874**
SINU	0.12	–
XMW	0.01	–
XCMG	0.49	–
XCS	0.24	–

office, River Basin Committee, and Brazil's national hydropower regulation agency (ANEEL).

Conclusions

Our results show that *Corbicula fluminea* distribution in river systems is closely linked to anthropogenic alterations in the physical habitat, providing basic knowledge to policy makers and environmental managers with regard to controlling the distribution of this invasive species. Such control is indispensable to effectively conserve and protect areas that are not yet invaded in this tropical river basin. As a function of the influence of the Pandeiros River dam on the dispersal of *C. fluminea*, and since economic activities, including electrical power production, have been totally deactivated since 2007, we consider its decommissioning advisable.

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Author contributions All authors contributed to the study conception and design. Data collection and analysis were performed by Marden Seabra Linares and Diego Rodriges Macedo. The first draft of the manuscript was written by Marden Seabra Linares and all authors commented and contributed on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability All data generated or analyzed during this study are included in this published article (and its supplementary information files).

Declarations

Conflict of interests The authors have no relevant financial or non-financial interests to disclose.

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