Ecological Indicators 117 (2020) 106674

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Why are they here? Local variables explain the distribution of invasive mollusk species in neotropical hydropower reservoirs

Marden S. Linares[a,*], Diego R. Macedo[b], Rodrigo L. Massara[c,d], Marcos Callisto[a]

[a] Universidade Federal de Minas Gerais, Instituto de Ciências Biológicas, Departamento de Genética, Ecologia e Evolução, Laboratório de Ecologia de Bentos, Av. Antônio Carlos 6627, Pampulha, CP 486, Belo Horizonte, MG CEP 30270-901, Brazil
[b] Universidade Federal de Minas Gerais, Instituto de Geociências, Departamento de Geografia, Laboratório de Geomorfologia e Recursos Hídricos, Av. Antônio Carlos 6627, Pampulha, Belo Horizonte, MG CEP 30270-901, Brazil
[c] Universidade Federal de Minas Gerais, Instituto de Ciências Biológicas, Departamento de Genética, Ecologia e Evolução, Laboratório de Ecologia e Conservação, Programa de Pós-graduação em Ecologia, Conservação e Manejo da Vida Silvestre, Av. Antônio Carlos 6627, Pampulha, CP 486, Belo Horizonte, MG CEP 30270-901, Brazil
[d] Instituto SerraDiCal de Pesquisa e Conservação, Rua José Hemetério de Andrade, No. 570, Buritis, Belo Horizonte, MG CEP 30493-180, Brazil

ARTICLE INFO

Keywords:
Bivalvia
Gastropoda
Land use and cover
Physical habitat structure
Water quality

ABSTRACT

Reservoirs are a common sight in most rivers systems in the world and a frequent problem related to them is the introduction of non-native invasive mollusk species. We aimed to determine which local variables (near-site land use, physical habitat structure, water quality) were most strongly associated with the local distribution of invasive non-native mollusks in neotropical hydropower reservoirs. We used data from three neotropical reservoirs to calculate which local variables most influenced the presence or absence of the three non-native invasive mollusk species (i.e., *Corbicula fluminea*, *Limnoperna fortunei* and *Melanoides tuberculata*) found in them. We found that the presence of both *C. fluminea* and *L. fortunei* were positively correlated with local anthropogenic disturbances, likely because it was associated with more frequent human access to the water body and increased introductions of larval mollusks. Conversely, *M. tuberculata* was negatively correlated with total phosphorus concentration, which is linked to agriculture and urbanization in the reservoir catchments. Additionally, we found that *C. fluminea* and *M. tuberculata* presence was positively related to each other, implying a biological facilitation process between these two species. Our findings suggest that anthropogenic disturbances are important for the local distribution of invasive non-native mollusks in neotropical reservoirs and can be used by environmental managers and decision-makers to help manage invasive mollusk populations in neotropical hydropower reservoirs.

1. Introduction

Dams and reservoirs are an increasingly common sight in river systems worldwide, because of increased demands for drinking water and energy sources (Anderson et al., 2015). These human-altered habitats provide many ecosystem services to human populations, such as recreational areas, water storage and supply, and food sources (Fearnside, 2014). Despite these benefits, dams and reservoirs also cause alterations in lotic ecosystem structure and function, including facilitation of biological invasions, thereby threatening the ecosystem services they provide (Poff et al., 2010; Stanford and Ward, 2001; White, 2014).

Biological invasions are the second most important cause of biodiversity loss globally (Mack et al. 2000; Simberloff et al. 2013; Thomaz et al. 2015; Reid et al. 2018). This ecological process is especially common in hydropower reservoirs, where the anthropogenically altered ecological conditions facilitate the introduction and establishment of non-native invasive species (Boltovskoy and Correa, 2015; Karatayev et al., 2007b; Linares et al., 2019; Ricciardi, 2007). Mollusks are one of the most successful groups of freshwater invasive species in reservoirs because their physiological and ecological adaptations confer the capacity to reproduce and generate fertile offspring with a high probability of survival (Bosso et al., 2017; Jarić et al., 2019; Karatayev et al., 2007a, Xiong et al., 2018). Another important factor is that many non-native invasive mollusk species act as ecosystem engineers, species that alter the physical habitats and biological processes of the ecosystems where they establish themselves (Jones et al., 1994). This means that these species can become important factors in the structure and function of the ecosystems where they are prevalent (Egan 2017; (Linares et al., 2017).

* Corresponding author.
E-mail addresses: mslinares@ufmg.br (M.S. Linares), diegorm@ufmg.br (D.R. Macedo), rmassara@gmail.com (R.L. Massara), callistom@ufmg.br (M. Callisto).

https://doi.org/10.1016/j.ecolind.2020.106674
Received 21 April 2020; Received in revised form 22 June 2020; Accepted 26 June 2020

Most studies of mollusk invasive species in reservoirs focus on the role of these human-made ecosystems in the invasive mollusks establishment in regional scales (Johnson et al., 2008; Nakano et al., 2015; Oliveira et al., 2011) or their effects on the structure and function of benthic communities (Boltovskoy et al., 2009; Linares et al., 2018, 2017). Therefore, there is a gap in the knowledge regarding what local habitat factors explain the establishment of invasive mollusks populations and their local site distribution inside hydropower reservoirs.

Mollusk invasive species are prevalent in reservoirs and other freshwater ecosystems in South America (Karatayev et al., 2007a). Having likely arrived in the continent in ballast water (Simberloff et al., 2013), these species were initially registered in the 60′s and 70′s in river basins with ports associated with international commerce, such as the Plata and Paraná river basins, and in the following decades they spread to be present in all major river basins in the continent (Barbosa et al., 2018). Invasive mollusks can cause significant ecological impacts, mainly due to alterations in the physical habitat and in the ecosystem functioning (Linares et al., 2017, 2019), and economic impacts, mainly by their biofouling activity in water-dependent economical activities such as hydropower generation (Sousa et al., 2013).

Our objective was to determine which local factors (near-site land use, physical habitat structure or water quality) are most important for the local-site distribution of non-native invasive mollusk species in neotropical hydropower reservoirs in which these species occur. We hypothesized that local anthropogenic disturbances would increase the presence probability of invasive mollusks, and thus we expected that variables that are linked to local anthropogenic disturbances would be the most determinants to influence the local distribution of the three species of invasive mollusks.

2. Material and methods

2.1. Study area

We used data from three Neotropical hydropower reservoirs (Nova Ponte, Três Marias and Volta Grande; Supplementary Material S1), located in the State of Minas Gerais, southeastern Brazil (Fig. 1). In each reservoir we defined 40 sampling sites through use of random spatially balanced procedures (Macedo et al., 2014; Stevens and Olsen, 2004), focusing on the littoral zone, which is the area with the highest richness and diversity (Martins et al. 2015; de Morais et al. 2017). From a randomly selected point, sampling sites were systematically distributed by dividing the perimeter into at equidistant distances from each other (Macedo et al., 2014). In total, we selected 120 sampling sites, 40 in each reservoir. Samplings occurred in 2010 (Nova Ponte), 2011 (Três Marias), and 2012 (Volta Grande) in April, at the end of the rainy season, ensuring that the reservoirs were at the highest possible water level and consequently with the highest possible habitat diversity (Callisto et al., 2019).

2.2. Local variable assessment

To assess the physical habitat variables, we followed the methodology described by Kaufmann et al. (2014) and de Morais et al. (2017). At each sampling site, human disturbance, vegetation cover, shoreline morphology and substrate type were recorded. Subsequently, those data were used to calculate a series of physical habitat metrics (Supplementary Material S2).

Additionally, in each sampling site, we measured water temperature, pH, electrical conductivity and total dissolved solids in situ with a multiprobe Yellow Spring (model YSI 6600), total depth with a handheld SONAR unit, euphotic zone depth with a Secchi disk, and turbidity with a turbidimeter (Digimed - model DM-TU). We also took water samples for laboratory determination of chlorophyll-a, pheophytin, total nitrogen and total phosphorus concentrations using Standard Methods procedures (APHA – American Public Health Association, 2005). All these variables are widely used by several studies in neotropical reservoirs because they are good predictors of the presence or absence of invasive mollusks (*e.g.*, Anacléto et al., 2018; Azevedo et al., 2017; de Morais et al., 2017; Martins et al., 2015; Molozzi et al., 2013).

For estimating local land use and cover, we used a 500-m diameter buffer zone centered on each sampling site. The buffer land use and cover were delimited on an image obtained through a TM sensor onboard the Landsat 5 satellite, taken during the sampling periods. Inside each buffer, polygons for the definition and quantification of land use categories were delimited and classified (natural cover, pasture, agriculture and buildings), and computed as percentage. Images obtained from Google Earth satellite images (Google Corporation) were employed as ancillary data in this assessment (de Morais et al., 2017; Macedo et al., 2014). Additionally, we calculated the Integrated Disturbance Index (Ligeiro et al. 2013; de Morais et al. 2017). This index was calculated using site physical habitat disturbance (Local Disturbance Index - LDI) and the disturbance of land use in a buffer zone of 500 m (Buffer Disturbance Index - BDI). BDI was estimated using the land use percentages weighted by the intensity of disturbance they represent (Ligeiro et al. 2013), modified for use in reservoirs (de Morais et al., 2017). It was calculated using the following formula:

$$\text{BDI (Buffer Disturbance Index)} = 4 \times (\%\text{residential}) + 2 \times (\%\text{agricultural areas} + \%\ \text{bare soil}) + (\%\text{pasture} + \%\ \text{Eucalyptus})$$

LDI was calculated using the index of the near-shore anthropogenic disturbance intensity and extent (RDis_IX) (Kaufmann et al. 2014).

2.3. Invasive mollusk sampling

In the littoral zone of each site, we sampled benthic macroinvertebrate assemblages by using three Eckman-Birge grabs (0.0675 m^2 total area). The samples were stored in plastic bags and fixed in 10% formalin, then they were washed through a sieve (0.5 mm mesh) in the laboratory. Invasive mollusks were identified to species under a stereomicroscope using specialized literature (Mugnai et al. 2010; Simone 2006). Sampling sites were then classified with each identified invasive mollusk species 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.

2.4. Data analysis

To explore our hypothesis that local anthropogenic disturbance increases the probability of invasive mollusks presence, we used a model selection approach (Burnham and Anderson, 2002). We first tested for correlation among our continuous variables (Supplementary Material S3), eliminating those that were highly correlated ($|r| \geq 0.7$) and retaining the most ecologically relevant metrics, which were chosen based on previous knowledge from the scientific literature (Anacléto et al., 2018; de Morais et al., 2017; Martins et al., 2015). Subsequently, we used our selected variables as predictor variables in three generalized linear models (GLMs) with a binomial distribution, where the response variables in each of the GLMs were the detection/non-detection of the invasive species. Using our most parameterized model, we evaluated for a possible lack of fit (i.e., overdispersion; $\hat{c} > 1$) in each analysis. Likewise, because the sampling units placement may resulted in a lack-of-independence (or spatial autocorrelation) among our sites, we performed a Moran's I test for spatial autocorrelation (Lecocq et al., 2019; Smeraldo et al., 2020) using the residuals of our most parameterized model in each of the three GLM analysis, using the spdep package (version 1.1.2; Bivand and Wong, 2018) in R (R Development Core Team, 2015). We then constructed models based on all possible additive variable combinations that may have influenced the

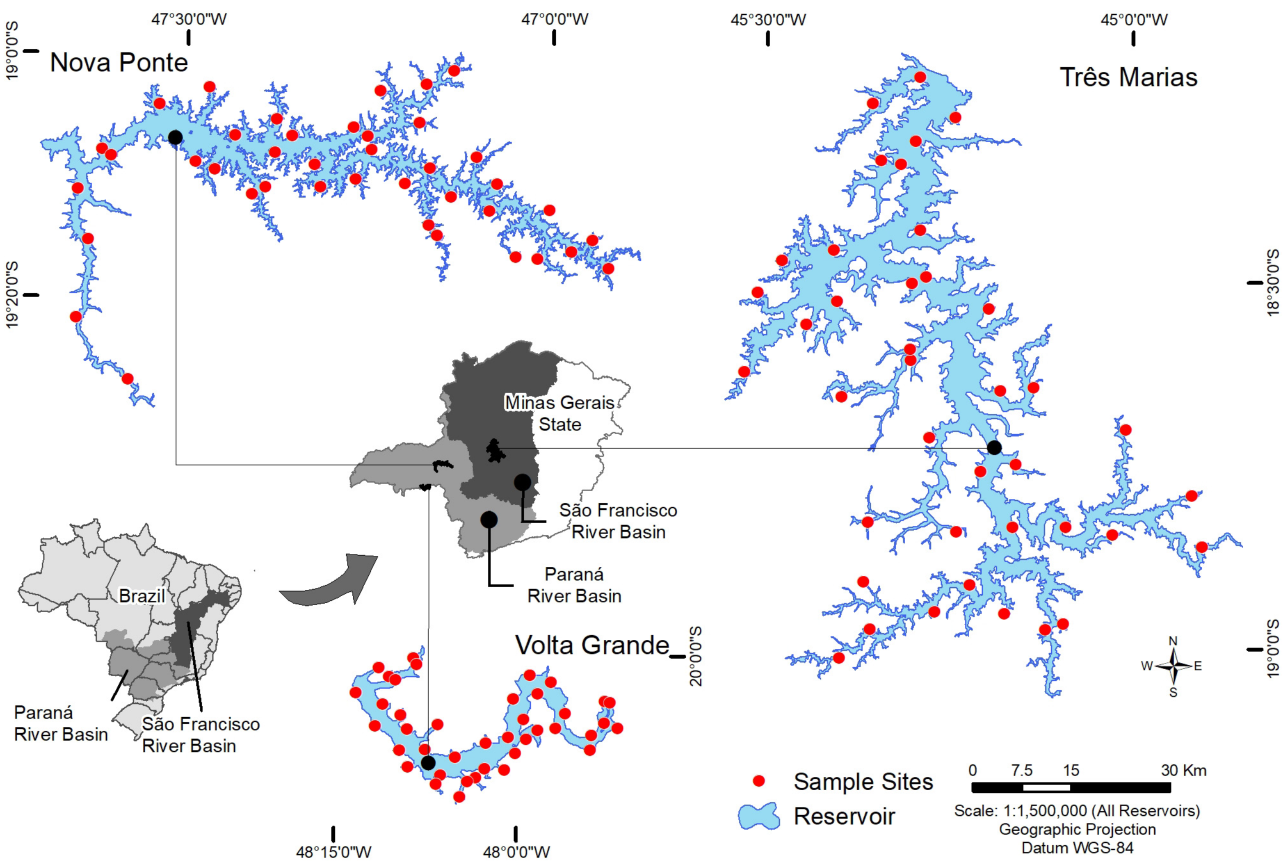

Fig. 1. Location of Nova Ponte, Volta Grande and Três Marias reservoirs and distribution of sampling sites.

probabilities of presence for each of the invasive species (Doherty et al., 2012). Importantly, the intercept-only model structure (i.e., null model) was also included in each of the model sets. This strategy resulted in a balanced model set for each analysis, which allowed us to calculate the cumulative AICc weights (w_+) for each variable and evaluate which were the most likely ($w_+ \geq 0.50$) to have influenced the presence for each of the invasive species (Burnham and Anderson, 2002). For *C. fluminea* and *M. tuberculata* we used data from all 120 sampling sites. Because *L. fortunei* was detected only in the Volta Grande reservoir, we used only the 40 sites of this reservoir. Statistical analyses were implemented using the MuMIn package (Bartón, 2019) in R.

3. Results

Three invasive mollusk species were identified in our sampling sites: *Corbicula fluminea* (Bivalvia: Corbiculidae), *Limnoperna fortunei* (Bivalvia: Mytilidae) and *Melanoides tuberculata* (Gastropoda: Thiaridae). Both *C. fluminea* and *M. tuberculata* were found in all three reservoirs, in a total of 38 (31.66%) and 36 (30.00%) sites, respectively. *L. fortunei* was only found at 11 (9.17%) sites in Volta Grande reservoir.

A total of 26 metrics remained after our screening process (Table 1). Among them, Presence of Non-Agricultural Disturbances in the Riparian zone, Riparian Vegetation Cover Complexity Index, Littoral Cover Complexity Index, Littoral–Riparian Habitat Complexity Index, Buffer Zone Disturbance Index and Local Disturbance Index were considered metrics of direct human disturbance.

We did not find any evidence of overdispersion in our analyses (i.e., $\hat{c} = 1$ for all GLM's). Also, the results of the Moran's I test revealed a lack of spatial autocorrelation among our sampling units (P-value $>$ 0.05 for all Moran's I tests; Supplementary Material S4). The most important predictor variables differed for the three mollusk species Table 2). The presence of *Corbicula fluminea* was linked positively with the presence of *M. tuberculata* and with the area of overhanging fish cover and negatively with electrical conductivity and the Littoral-Riparian Complexity Index. The presence of *Melanoides tuberculata* was negatively linked with total phosphorus concentration and positively linked with the presence of *C. fluminea*. *Limnoperna fortunei* presence was positively linked with the Buffer Zone Disturbance Index (BDI) and negatively linked with the area of emergent macrophytes.

4. Discussion

Our results partially corroborated our hypothesis that the presence of local anthropogenic disturbances increase the chance of finding non-native invasive mollusk species in the three studied reservoirs. Both *C. fluminea* and *L. fortunei* local distributions were linked with anthropogenic disturbance, namely a negative relation with the Littoral-Riparian Complexity Index for *C. fluminea* and a positive relation with the Buffer Zone Disturbance Index for *L. fortunei*. On the other hand, *M. tuberculata* presence showed a negative correlation with total phosphorus concentration, an indicator of agricultural and urban disturbances in the reservoir catchment.

The positive correlation of the local distribution of both *C. fluminea* and *L. fortunei* with anthropogenic disturbances may be explained by the facilitation of human access to the hydropower reservoir. Human access to the water body is likely related to increased accidental introductions of larvae from recreational activities and water abstraction (de Marco Júnior 1999; Johnson et al. 2008; Lercari and Bergamino 2011; White 2014) as well as initial intentional introductions. This manmade increase of propagules is important for the distribution of invasive species, especially for sessile ones like these two bivalve species (Dias et al., 2014; Karatayev et al., 2007b; Zhan et al., 2015). Other studies found similar results, indicating that human access to the water body is related to the introduction and maintenance of these species in

Table 1
Metrics used to determine which local factors (near site land use, physical habitat structure or water quality) were most important for the local-site distribution of non-native invasive mollusk species in neotropical hydropower reservoirs. Mean and range (minimum–maximum) of each continuous predictor variable were calculated from 120 sampling sites. For Corbicula, Melanoides and Limnoperma we used whether we detected (1) *Corbicula fluminea*, *Melanoides tuberculata* and *Limnoperna fortunei* or not (0) at each sampling site as a categorical predictor variable. See methods for details.

Metrics	Metric Type	Description	Mean (min–max)
Depth	Physicochemical	Water Depth (m)	0.94 (0.80–1.00)
Secchi	Physicochemical	Secchi Disc Depth (m)	0.94 (0.2–3.0)
Water_Temp	Physicochemical	Water Temperature (°C)	23.74 (18.68–24.98)
pH	Physicochemical	Water pH	9.24 (6.74–12.60)
Conductivity	Physicochemical	Water Electrical Conductivity (µS/cm)	27.9 (19.00–33.00)
Turbidity	Physicochemical	Water Turbidity (NTU)	2.28 (0.57–8.45)
Dissolved_O	Physicochemical	Water Dissolved Oxygen Concentration (mg/L)	8.35 (1.40–10.70)
Total_P	Physicochemical	Water Total Phosphorus Concentration (µ/L)	7.43 (0–49.34)
Chlorophyll_a	Physicochemical	Water Chlorophyll *a* Concentration (mg/L)	0.51 (0–3.55)
hiiNonAg_Ind	Physical Habitat	Presence of Non-Agricultural Disturbances in the Riparian Zone (Kaufmann et al 2014)	0.75 (0–4.10)
rvfcGndWoody	Physical Habitat	Mean Ground Cover Area of Woody Vegetation (Kaufmann et al. 2014)	0.19 (0.04–0.25)
rviLowWood	Physical Habitat	Sum of Mean Low Layers of Canopy Cover (Kaufmann et al. 2014)	0.51 (0.10–1.06)
RvegQ_2	Physical Habitat	Riparian Vegetation Cover Complexity Index (Kaufmann et al. 2014)	0.10 (0.02–0.27)
fcfcLivetrees	Physical Habitat	Mean Area of Living Trees Fish Cover (Kaufmann et al. 2014)	0.05 (0–0.22)
fcfcOverhang	Physical Habitat	Mean Area of Overhang Fish Cover (Kaufmann et al. 2014)	0.19 (0–0.7)
fcfcSnag	Physical Habitat	Mean Area of Snag Fish Cover (Kaufmann et al. 2014)	0.03 (0–0.24)
fcfcAquatic	Physical Habitat	Mean Area of Aquatic Fish Cover (Kaufmann et al. 2014)	0.19 (0–0.87)
amfcSubmerg	Physical Habitat	Mean Cover Area of Submerged Macrophytes (Kaufmann et al. 2014)	0.15 (0–0.87)
amfcEmergent	Physical Habitat	Mean Cover Area of Emergent Macrophytes (Kaufmann et al. 2014)	0.13 (0–0.79)
LitCvrQ_b	Physical Habitat	Littoral Zone Cover Complexity Index (Kaufmann et al. 2014)	0.50 (0.12–1.08)
LitRipHQ	Physical Habitat	Littoral–Riparian Habitat Complexity Index (Kaufmann et al. 2014)	0.38 (0.08–0.67)
BDI	Disturbance	Buffer Zone Disturbance Index (Ligeiro et al. 2013)	0.38 (0–0.79)
LDI	Disturbance	Local Disturbance Index (Ligeiro et al. 2013)	0.53 (0–1.56)
Corbicula	Biological	Detection of *Corbicula fluminea*	–
Melanoides	Biological	Detection of *Melanoides tuberculata*	–
Limnoperna	Biological	Detection of *Limnoperna fortunei*	–

Table 2
Cumulative AICc weights (w_+) and estimates of variable effects (β parameters) for predictor variables used to model the local presence probability of invasive mollusk species in neotropical hydropower reservoirs. Values of w_+ in bold are those considered to be more likely ($w_+ \geq 0.50$). Estimates of variable effects are based on the most parsimonious model that included that variable and are given only for variables with $w_+ \geq 0.50$.

Metrics	*Corbicula fluminea*		*Melanoides tuberculata*		*Limnoperna fortunei*	
	w_+	β	w_+	β	w_+	β
Depth	< 0.01	–	0.06	–	0.06	–
Secchi	< 0.01	–	0.05	–	0.05	–
Water_Temp	0.06	–	0.12	–	0.05	–
pH	0.02	–	0.06	–	0.05	–
Conductivity	**0.74**	−0.16	0.40	–	0.06	–
Turbidity	0.15	–	0.05	–	0.07	–
Dissolved_O	0.1	–	0.06	–	0.26	–
Total_P	0.07	–	**0.92**	−0.31	0.06	–
Chlorophyll_a	0.02	–	0.28	–	0.08	–
hiiNonAg_Ind	0.04	–	0.05	–	0.17	–
rvfcGndWoody	< 0.01	–	0.04	–	0.08	–
rviLowWood	0.01	–	0.05	–	0.20	–
RvegQ_2	0.01	–	0.12	–	0.08	–
fcfcLivetrees	0.05	–	0.09	–	0.18	–
fcfcOverhang	**0.59**	10.44	0.04	–	0.29	–
fcfcSnag	0.05	–	0.04	–	0.08	–
fcfcAquatic	0.05	–	0.04	–	0.06	–
amfcSubmerg	0.07	–	0.09	–	**0.85**	−50.33
amfcEmergent	0.03	–	0.04	–	0.05	–
LitCvrQ_b	0.02	–	0.07	–	0.16	–
LitRipHQ	**0.64**	−10.65	0.18	–	0.07	–
BDI	0.08	–	0.04	–	**0.58**	17.43
LDI	0.19	–	0.05	–	0.06	–
Corbicula	–	–	**0.97**	2.27	0.06	–
Melanoides	**0.99**	3.74	–	–	0.05	–

reservoirs (Barbosa et al., 2018; Sousa et al., 2013).

The negative correlation of the presence of *M. tuberculata* with total phosphorus concentration suggests that this species is negatively affected by diffuse anthropogenic impacts. Both of these metrics are associated with diffuse human disturbances in the catchment of hydropower reservoirs (Junqueira et al., 2016; Silva et al., 2017). Such impacts can also increase the amount of fine sediment deposition in the reservoir (Hawkins and Murphy, 2016; Kaufmann et al., 2009). Feeding primarily on periphyton (Cummins et al., 2005), *M. tuberculata* benefits from hard substrates, that can become embedded by fine sediments thereby reducing or eliminating periphyton. Previous studies in neotropical freshwaters found similar indications that *M. tuberculata* is related to hard substrates (Linares et al., 2017, 2018, 2019).

The strong correlation of *C. fluminea* and *M. tuberculata* might result from a process of biological facilitation. Because of its digger habit, *C. fluminea* can easily colonize the soft bottom substrate that usually characterizes reservoirs (Crespo et al., 2015; Darrigran, 2002; Karatayev et al., 2003). Over time their hard shells can accumulate and provide a modified hard substrate (Jones et al., 1994), facilitating the colonization of species associated with hard substrates, such as *M. tuberculata*. Also, because they are powerful filter feeders, *C. fluminea* provides a strong link between production in the water column and benthic habitats. Resources produced in the water column captured by invasive bivalves may then become available to benthic communities in the form of their feces and pseudo-feces and can constitute an important food source for other benthic animals (Sardiña et al., 2008). This can open a new energetic pathway for the benthic community, an ecological effect observed in previous studies elsewhere (Linares et al., 2018, 2017).

5. Conclusions

Our results provide important tools for environmental managers and decision-makers in the complex process of managing invasive mollusk species in neotropical hydropower reservoirs. They highlight the importance of natural macrophyte cover in the littoral zone to prevent the establishment of invasive mollusk species.

Our results are especially important for the management of hydropower reservoirs that double as human consumption reservoirs. Such reservoirs usually have oligotrophic conditions and good water quality. However, anthropogenic disturbances next to their margins and in their catchments facilitate the establishment of non-native invasive species. Therefore, human consumption reservoirs need special attention to prevent damage caused by these species.

CRediT authorship contribution statement

Marden S. Linares: Conceptualization, Methodology, Formal analysis. **Diego R. Macedo:** Methodology, Writing - review & editing. **Rodrigo L. Massara:** Methodology, Writing - review & editing. **Marcos Callisto:** Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research has been continually funded by Programa Peixe Vivo/ Companhia Energética de Minas Gerais, Programa de Pesquisa e Desenvolvimento Tecnológico do Setor de Energia Elétrica-Companhia Energética de Minas Gerais (P&D Aneel-Cemig GT-487, GT-550, GT-599, and GT-611) and by Fundação de Amparo à Pesquisa de Minas Gerais (APQ-01961-15). This study was financed in part by CAPES – Finance Code 001. MC was awarded National Council for Scientific & Technological Development (CNPq) research productivity grants (303380/2015-2) and by Fundação de Amparo à Pesquisa do Estado de Minas Gerais research grant (PPM 00104-18). DRM received support from Pró-Reitoria de Pesquisa (PRPq)-UFMG, and CNPq. The Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) provided grants to RLM. The team of undergraduate and graduate students of the Laboratório de Ecologia de Bentos/ICB-UFMG supported the field activities. We thank Dr. Robert Mason Hughes and Dr. Matthew C. I. Medeiros for an early review of this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2020.106674.

References

Anacléto, M.J.P., Ligeiro, R., Barbosa, J.E.L., Molozzi, J., Callisto, M., 2018. Effects of an atypical drought on the benthic macroinvertebrate community in a tropical reservoir. Biota Neotropica 18 (2), e20170352. https://doi.org/10.1590/1676-0611-bn-2017-0352.

Anderson, D., Moggridge, H., Warren, P., Shucksmith, J., 2015. The impacts of 'run-of-river' hydropower on the physical and ecological condition of rivers. Water Environ. J. 29, 268–276. https://doi.org/10.1111/wej.12101.

APHA – American Public Health Association, 2005. Standard methods for the examination of water and wastewater, 21th ed, American Public Health Association/ American Water Works Association/Water Environment Federation. American Public Health Association, Washington, DC.

Azevedo, E.L., Anacleto, M.J., Gomes, L., Barbosa, J.E.L., Callisto, M., Molozzi, J., 2017. Application of a statistical model for the assessment of environmental quality in neotropical semi-arid reservoirs. Environ. Monit. Assess. 1, 1–12.

Barbosa, N.P.U., Ferreira, J.A., Nascimento, C.A.R., Silva, F.A., Carvalho, V.A., Xavier, E.R.S., Ramon, L., Almeida, A.C., Carvalho, M.D., Cardoso, A.V., 2018. Prediction of future risk of invasion by Limnoperna fortunei (Dunker, 1857) (Mollusca, Bivalvia, Mytilidae) in Brazil with cellular automata. Ecol. Ind. 92, 30–39. https://doi.org/10.1016/j.ecolind.2018.01.005.

Bartón, K., 2019. Package 'MuMIn'. https://cran.r-project.org/web/packages/MuMIn/index.html.

Bivand, R., Wong, D.W.S., 2018. Comparing implementations of global and local indicators of spatial association. Test 27 (3), 716–748. https://doi.org/10.1007/s11749-018-0599-x.

Boltovskoy, D., Correa, N., 2015. Ecosystem impacts of the invasive bivalve Limnoperna fortunei (golden mussel) in South America. Hydrobiologia 746, 81–95. https://doi.org/10.1007/s10750-014-1882-9.

Boltovskoy, D., Karatayev, A., Burlakova, L., Cataldo, D., Karatayev, V., Sylvester, F., Mariñelarena, A., 2009. Significant ecosystem-wide effects of the swiftly spreading invasive freshwater bivalve Limnoperna fortunei. Hydrobiologia 636, 271–284. https://doi.org/10.1007/s10750-009-9956-9.

Bosso, L., De Conno, C., Russo, D., 2017. Modelling the Risk Posed by the Zebra Mussel Dreissena polymorpha: Italy as a Case Study. Environ. Manage. 60 (2), 304–313. https://doi.org/10.1007/s00267-017-0882-8.

Burnham, K.P., Anderson, D.R., 2002. Model selection and multimodel inference: A practical information-theoretical approach. Springer-Verlag, New York, New York.

Callisto, M., Macedo, D.R., Linares, M.S., Hughes, R.M., 2019. Multi-status and multi-spatial scale assessment of landscape effects on benthic macroinvertebrates in the Neotropical Savanna. In: Hughes, R.M., Infante, D.M., Wang, L., Chen, K., Terra, B.F., (Eds.). Advances in understanding landscape influences on freshwater habitats and biological assemblages. American Fisheries Society, Symposium 90, Bethesda, Maryland. pp. 275–302.

Crespo, D., Dolbeth, M., Leston, S., Sousa, R., Pardal, M.Â., 2015. Distribution of Corbicula fluminea (Müller, 1774) in the invaded range: a geographic approach with notes on species traits variability. Biol. Invasions 17, 2087–2101. https://doi.org/10.1007/s10530-015-0862-y.

Cummins, K.W., Merritt, R.W., Andrade, P.C.N., 2005. The use of invertebrate functional groups to characterize ecosystem attributes in selected streams and rivers in south Brazil. Stud. Neotrop. Fauna Environ. 40, 69–89.

Darrigran, G., 2002. Potential impact of filter-feeding invaders on temperate inland freshwater environments. Biol. Invasions 4, 145–156. https://doi.org/10.1023/A:1020521811416.

de Marco Júnior, P., 1999. Invasion by the introduced aquatic snail Melanoides tuberculata (Müller, 1774) (Gastropoda: Prosobranchia: Thiaridae) of the Rio Doce state park, Minas Gerais, Brazil. Stud. Neotropical Fauna Environ. 34, 186–189.

de Morais, L., de Oliveira Sanches, B., Santos, G.B., Kaufmann, P.R., Hughes, R.M., Molozzi, J., Callisto, M., 2017. Assessment of disturbance at three spatial scales in two large tropical reservoirs. J. Limnol. 76, 240–250. https://doi.org/10.4081/jlimnol.2016.1547.

Dias, E., Morais, P., Antunes, C., Hoffman, J.C., 2014. Linking terrestrial and benthic estuarine ecosystems: organic matter sources supporting the high secondary production of a non-indigenous bivalve. Biol. Invasions 16, 2163–2179. https://doi.org/10.1007/s10530-014-0655-8.

Doherty, P.F., White, G.C., Burnham, K.P. 2012. Comparison of model building and selection strategies. J. Ornithol. 152:317-S323. 308.

Egan, D., 2017. The Death and Life of the Great Lakes. WW Norton, New York.

Fearnside, P.M., 2014. Impacts of Brazil's Madeira River Dams: unlearned lessons for hydroelectric development in Amazonia. Environ. Sci. Policy 38, 164–172. https://doi.org/10.1016/j.envsci.2013.11.004.

Hawkins, C.P., Murphy, M.L.., 2016. Effects of Canopy, Substrate Composition, and Gradient on the Structure of Macroinvertebrate Communities in Cascade Range Streams of Oregon Author (s): Charles P. Hawkins, Michael L. Murphy and N.H. Anderson Published by : Wiley Stable URL : htt 63, pp. 1840–1856.

Jarić, I., Heger, T., Castro Monzon, F., Jeschke, J.M., Kowarik, I., McConkey, K.R., Pyšek, P., Sagouis, A., Essl, F., 2019. Crypticity in biological invasions. Trends Ecol. Evol. 34, 291–302. https://doi.org/10.1016/j.tree.2018.12.008.

Johnson, P.T., Olden, J.D., Vander Zanden, M.J., 2008. Dam invaders: impoundments facilitate biological invasions into freshwaters. Front. Ecol. Environ. 6, 357–363. https://doi.org/10.1890/070156.

Jones, C.G., Lawton, J.H., Shachak, M., 1994. Organisms as Ecosystem Engineers. Oikos 69, 373–386. https://doi.org/Doi 10.2307/3545850.

Junqueira, N.T., Macedo, D.R., de Souza, R.C.R., Hughes, R.M., Callisto, M., Pompeu, P.S., 2016. Influence of environmental variables on stream fish fauna at multiple spatial scales. Neotrop. Ichthyol. 14, 1–12. https://doi.org/10.1590/1982-0224-20150116.

Karatayev, A.Y., Boltovskoy, D., Padilla, D.K., Burlakova, L.E., 2007a. The invasive bivalves Dreissena polymorpha and Limnoperna fortunei: parallels, contrasts, potential spread and invasions impacts. J. Shellfish Res. 26, 205–213. https://doi.org/10.2983/0730-8000(2007)26[205:TIBDPA]2.0.CO;2.

Karatayev, A.Y., Burlakova, L.E., Kesterson, T., Padilla, D.K., 2003. Dominance of the Asiatic clam Corbicula fluminea (Müller), in the benthic community of a reservoir. J. Shellfish Res. 2, 487–493.

Karatayev, A.Y., Padilla, D.K., Minchin, D., Boltovskoy, D., Burlakova, L.E., 2007b. Changes in global economies and trade: the potential spread of exotic freshwater bivalves. Biol. Invasions 9, 161–180. https://doi.org/10.1007/s10530-006-9013-9.

Kaufmann, P.R., Larsen, D.P., Faustini, J.M., 2009. Bed stability and sedimentation associated with human disturbances in Pacific Northwest streams. JAWRA J. Am. Water Resour. Assoc. 45, 434–459. https://doi.org/10.1111/j.1752-1688.2009.00301.x.

Kaufmann, P.R., Peck, D.V., Paulsen, S.G., Seeliger, C.W., Hughes, R.M., Whittier, T.R., Kamman, N.C., 2014. Lakeshore and littoral physical habitat structure in a national lakes assessment. Lake Reserv. Manag. 30, 192–215. https://doi.org/10.1080/10402381.2014.906524.

Lecocq, T., Harpke, A., Rasmont, P., Schweiger, O., 2019. Integrating intraspecific differentiation in species distribution models: Consequences on projections of current and future climatically suitable areas of species. Diversity and Distributions. https://doi.org/ 10.1111/ddi.12916.

Lercari, D., Bergamino, L., 2011. Impacts of two invasive mollusks, Rapana venosa (Gastropoda) and Corbicula fluminea (Bivalvia), on the food web structure of the Río de la Plata estuary and nearshore oceanic ecosystem. Biol. Invasions 13, 2053–2061. https://doi.org/10.1007/s10530-011-0023-x.

Ligeiro, R., Hughes, R.M., Kaufmann, P.R., Macedo, D.R., Firmiano, K.R., Ferreira, W.R., Oliveira, D., Melo, A.S., Callisto, M., 2013. Defining quantitative stream disturbance gradients and the additive role of habitat variation to explain macroinvertebrate taxa richness. Ecol Indic 25, 45–57. https://doi.org/10.1016/j.ecolind.2012.09.004.

Linares, M.S., Callisto, M., Marques, J.C., 2018. Thermodynamic based indicators illustrate how a run-of-river impoundment in neotropical savanna attracts invasive species and alters the benthic macroinvertebrate assemblages' complexity. Ecol. Indic. 88, 181–189. https://doi.org/10.1016/j.ecolind.2018.01.040.

Linares, M.S., Callisto, M., Marques, J.C., 2017. Invasive bivalves increase benthic communities complexity in neotropical reservoirs. Ecol. Indic. 75, 279–285. https://doi.org/10.1016/j.ecolind.2016.12.046.

Linares, M.S., Assis, W., Solar, R.R.C., Leitão, R.P., Hughes, R.M., Callisto, M., 2019. Small hydropower dam alters the taxonomic composition of benthic macroinvertebrate assemblages in a neotropical river. River Res. Applic. 2019, 1–10. https://doi.org/10.1002/rra.3442.

Macedo, D.R., Pompeu, P.S., Morais, L., Castro, M.A., Alves, C.B.M., França, J.S., Sanches, B.. O., Agra, J.U.M., Callisto, M., 2014. Sampling site selection, land use and cover, field reconnaissance, and sampling, in: Callisto, M., Hughes, R.M., Lopes, J.M., Castro, M.A. (Eds.), Ecological Conditions in Hydropower Basins. Serie Peixe Vivo 3. Companhia Energética de Minas Gerais, Belo Horizonte, Brazil, pp. 61–83.

Mack, R.N., Simberloff, D., Mark Lonsdale, W., Evans, H., Clout, M., Bazzaz, F.A., 2000. Biotic invasions: causes, epidemiology, global consequences, and control. Ecol. Appl. 10, 689–710. https://doi.org/10.1890/1051-0761(2000)010[0689:BICEGC]2.0.CO;2.

Martins, I., Sanches, B., Kaufmann, P.R., Hughes, R.M., Santos, G.B., Molozzi, J., Callisto, M., 2015. Ecological assessment of a southeastern Brazil reservoir. Biota Neotropica. 15, 1–10. https://doi.org/10.1590/1676-06032015006114.

Molozzi, J., Marques, J.C., Callisto, M., Salas, F., 2013. Thermodynamic oriented ecological indicators: Application of Eco-Exergy and Specific Eco-Exergy in capturing environmental changes between disturbed and non-disturbed tropical reservoirs. Ecol. Ind. 24, 543.

Mugnai, R., Nessimian, J.L., Baptista, D.F., 2010. Manual de Identificação de Macroinvertebrados Aquáticos do Estado do Rio de Janeiro. Technical Books Editora, Rio de Janeiro.

Nakano, D., Baba, T., Endo, N., Nagayama, S., Fujinaga, A., Uchida, A., Shiragane, A., Urabe, M., Kobayashi, T., 2015. Invasion, dispersion, population persistence and ecological impacts of a freshwater mussel (Limnoperna fortunei) in the Honshu Island of Japan. Biol. Invasions 17, 743–759. https://doi.org/10.1007/s10530-014-0765-3.

Oliveira, M.D., Calheiros, D.F., Jacobi, C.M., Hamilton, S.K., 2011. Abiotic factors controlling the establishment and abundance of the invasive golden mussel Limnoperna fortunei. Biol. Invasions 13, 717–729. https://doi.org/10.1007/s10530-010-9862-0.

Poff, N.L., Richter, B.D., Arthington, A.H., Bunn, S.E., Naiman, R.J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B.P., Freeman, M.C., Henriksen, J., Jacobson, R.B., Kennen, J.G., Merritt, D.M., O'Keeffe, J.H., Olden, J.D., Rogers, K., Tharme, R.E., Warner, A., 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshw. Biol. 55, 147–170. https://doi.org/10.1111/j.1365-2427.2009.02204.x.

CoreTeam, R., 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria http://www.Rproject.org.

Reid, A.J., Carlson, A.K., Creed, A.F., Eliason, E.J., Gell, P.A., Johnson, P.T.J., Kidd, K.A., MacCormack, T.J., Olden, J.D., Ormerod, S.J., Smol, J.P., Taylor, W.W., Tockner, K., Vermaire, J.C., Dudgeon, D., Cooke, S.J., 2018. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol. Rev. (2018), pp. 000–000. doi: 10.1111/brv.12480.

Ricciardi, A., 2007. Are modern biological invasions an unprecedented form of global change? Conserv. Biol. 21, 329–336. https://doi.org/10.1111/j.1523-1739.2006.00615.x.

Sardiña, P., Cataldo, D.H., Boltovskoy, D., 2008. The effects of the invasive mussel, *Limnoperna fortunei*, on associated fauna in South American freshwaters: importance of physical structure and food supply. Fundam. Appl. Limnol./Arch. für Hydrobiol. 173, 135–144. https://doi.org/10.1127/1863-9135/2008/0173-0135.

Silva, D.R.O., Herlihy, A.T., Hughes, R.M., Callisto, M., 2017. An improved macroinvertebrate multimetric index for the assessment of wadeable streams in the neotropical savanna. Ecol. Indic. 81, 514–525. https://doi.org/10.1016/j.ecolind.2017.06.017.

Simberloff, D., Martin, J.-L., Genovesi, P., Maris, V., Wardle, D.A., Aronson, J., Courchamp, F., Galil, B., García-Berthou, E., Pascal, M., Pyšek, P., Sousa, R., Tabacchi, E., Vilà, M., 2013. Impacts of biological invasions: what's what and the way forward. Trends Ecol. Evol. 28, 58–66. https://doi.org/10.1016/j.tree.2012.07.013.

Simone, L.R.L., 2006. Land and freshwater molluscs of Brazil. EGB, Fapesp, São Paulo. 400, 390 p.

Sousa, R., Novais, A., Costa, R., Strayer, D.L., 2013. Invasive bivalves in fresh waters: impacts from individuals to ecosystems and possible control strategies. Hydrobiologia 735 (1). https://doi.org/10.1007/s10750-012-1409-1.

Smeraldo, S., Bosso, L., Fraissinet, M., Bordignon, L., Brunelli, M., Ancillotto, L., Russo, D., 2020. Modelling risks posed by wind turbines and power lines to soaring birds: the black stork (Ciconia nigra) in Italy as a case study. Biodivers. Conserv. https://doi.org/10.1007/s10531.

Stanford, J.A., Ward, J.V., 2001. Revisiting the serial discontinuity concept. Regul. Rivers Res. Manag. 17, 303–310. https://doi.org/10.1002/rrr.659.

Stevens, D.L., Olsen, A.R., 2004. Spatially balanced sampling of natural resources. J. Am. Stat. Assoc. 99, 262–278. https://doi.org/10.1198/016214504000000250.

Thomaz, S.M., Mormul, R.P., Michelan, T.S., 2015. Propagule pressure, invasibility of freshwater ecosystems by macrophytes and their ecological impacts: a review of tropical freshwater ecosystems. Hydrobiologia 746, 39–59. https://doi.org/10.1007/s10750-014-2044-9.

White, D.S., 2014. The Benthic Macroinvertebrates of Kentucky Lake, a Mainstem Reservoir on the Tennessee River, U.S.A. Trans. Am. Entomol. Soc. 140, 83–99. https://doi.org/10.3157/061.140.0105.

Xiong, W., Wang, H., Wang, Q., Tang, J., Bowler, P.A., Xie, D., Pan, L., Wang, Z., 2018. Non-native species in the Three Gorges Dam Reservoir: status and risks. BioInvasions Records 7 (2), 153–158. https://doi.org/10.3391/bir.2018.7.2.06.

Zhan, A., Zhang, L., Xia, Z., Ni, P., Xiong, W., Chen, Y., Douglas Haffner, G., MacIsaac, H.J., 2015. Water diversions facilitate spread of non-native species. Biol. Invasions 17, 3073–3080. https://doi.org/10.1007/s10530-015-0940-1.