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Research Article

Physical habitat condition as a key tool to maintain freshwater biodiversity in neotropical artificial ponds

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ABSTRACT

In areas highly affected by anthropogenic disturbances, artificial (human-made) freshwater ecosystems can provide habitat for maintaining and conserving regional freshwater biodiversity. We assessed how the physical habitat of artificial ponds affected the structure of benthic macroinvertebrate assemblages. To do so, we tested two hypotheses. (1) Physical habitat disturbances are not detrimental to the diversity of nearby artificial ponds, and (2) Physical habitat disturbances do not cause significant shifts in taxonomic composition. Our results rejected both null hypotheses, i.e., macroinvertebrate diversity metrics correlated significantly and positively with Physical Habitat Integrity index scores, and only sites with high habitat condition scores were significantly associated with sensitive indicator taxa. Our results highlight the importance of maintaining physical habitat conditions for sustaining the ecological health of artificial ponds.

1. Introduction

Anthropogenic activities have changed the surface geomorphology of the Earth, often resulting in modifications to freshwater ecosystems ranging from the alteration of existing waterbodies, to the construction of new ones (Briggs et al., 2019; Cerini et al., 2020). Artificial freshwater ecosystems are now ubiquitous components of modern landscapes. However, their condition and provisioning of ecosystem services are largely underexplored and likely underestimated, especially in the face of other anthropogenic activities (Clifford and Heffernan, 2018; Pfaff et al., 2023).

Globally, anthropogenic activities over the last century have caused biodiversity losses in aquatic ecosystems, a trend caused primarily by habitat loss (Vörösmarty et al., 2010; Chiu et al., 2017; Reid et al., 2019; Leal et al., 2020). In many human-impacted areas such as those characterized by urbanization and intensive agriculture, natural freshwater ecosystems have been drained, dammed, or otherwise highly altered (Rolke et al., 2018; Gething and Little, 2020). Within these altered areas, artificial freshwater ecosystems can provide viable refuge and habitat for maintaining and conserving regional biodiversity (Coccia et al., 2016; Davis and Moore, 2016; Hill et al., 2016; Pfaff et al., 2023).

Good physical habitat quality is crucial for artificial ecosystems to act as a refuge for the purpose of maintaining regional diversity (Brasil et al., 2020). The conversion of natural landscapes into agricultural land represents a major threat to global biodiversity (Souza et al., 2020; Espinoza-Toledo et al., 2021). Although they are exceedingly simplified habitats compared to natural ecosystems, artificial freshwater ecosystems can still be valuable in terms of their biological diversity (Clifford and Heffernan, 2018; Briggs et al., 2019; Cerini et al., 2020). Considering their physical conditions, these ecosystems can sustain relatively high biodiversity, which is defined by their Maximum Ecological Potential (Fanny et al., 2013, Molozzi et al. 2013b).

Among the many taxa that comprise freshwater ecosystem biodiversity, benthic macroinvertebrates are one of the most widely used as

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bioindicators because of their ability to respond predictably to ecosystem changes (Bonada et al., 2006; Cortes et al., 2013; Ruaro et al., 2020; Linares et al., 2021). Extensive literature exists on the effects of land use and other anthropogenic stressors at regional extents on the structure of benthic macroinvertebrate assemblages (Ligeiro et al., 2013; Macedo et al., 2014; Firmiano et al., 2021). However, few studies on how management of artificial ecosystems can be used to maintain and conserve their biodiversity in anthropogenically altered land matrices exist. When they do, they have focused mainly on temperate areas (Davis and Moore, 2016; Rolke et al., 2018; Gething and Little, 2020).

We assessed how the physical habitat conditions around artificial ponds affect the structure of benthic macroinvertebrate assemblages. To do so, we tested two hypotheses: (1) Physical habitat disturbances are not detrimental to the diversity of nearby artificial ponds. We predicted that benthic macroinvertebrate taxonomic richness, Ephemeroptera, Plecoptera, Trichoptera (EPT) abundance, Shannon-Wiener diversity, and Margalef diversity would not correlate positively with Physical Habitat Integrity Index (PHII) scores. (2) Physical habitat disturbances will not cause significant shifts in taxonomic composition. We predicted that sampling sites with high habitat condition scores (e.g., good ecological condition) would not have significantly different taxonomic compositions than impaired ones.

2. Material and methods

2.1. Study area

The study was conducted in a eucalyptus (*Eucalyptus* sp.) plantation in Nova Monte Carmelo Farm, Minas Gerais State, southeastern Brazil. The plantation covers approximately 52,000 ha, of which about 38,000 ha are used for commercial eucalyptus silviculture, and about 12,000 ha are regeneration areas and protected riparian vegetation and wetlands (Borges et al., 2021). From a total of 21 artificial ponds (Richardson et al., 2022), we selected nine through an *ad hoc* selection process based on access, level of riparian vegetation conservation, and minimum direct anthropogenic disturbance (Fig. 1). We selected sites with no direct anthropogenic impacts in the water body, such as eutrophication or water abstraction, but with different levels of riparian zone disturbance. In each pond, we randomly selected one sampling site along the margin. Each of the ponds was formed as a result of damming streams for activities related to eucalyptus silviculture (e.g. road building).

2.2. Physical Habitat Integrity Index

To assess the ecological quality of the sampling sites, we used the Physical Habitat Integrity Index (PHII) (Nessimian et al., 2008, Brasil et al., 2020), modified to assess artificial ponds instead of streams. This index relies on a qualitative evaluation of a set of parameters (Table 1). The observed value of each parameter is then divided by the maximum potential value of that parameter. The final value of the index is the mean value of the product of the division of all parameters. This results in a score between 0 and 1, where higher scores represent superior ecological conditions. We considered sampling sites with a score >0.7 as having Maximum Ecological Potential (Molozzi et al. 2013a) and good ecological condition, and those with lower scores were considered impaired (Table 2). To characterize pond water quality, we measured Conductivity, Total Dissolved Solids, Turbidity, and Water Temperature at each sampling site (Table 2).

2.3. Benthic macroinvertebrate sampling

In each of the nine sampling sites, we collected benthic macroinvertebrates by using a D-net sampler (250 μm mesh, 0.09 m^2 opening) by dredging a 1 m long transect from the margin for 2 min (Callisto et al., 2021). The samples were stored in plastic bags, fixed with 70% alcohol, and transported to the laboratory, where they were washed over a sieve (250 μm mesh) to separate invertebrates from detritus and sand. The invertebrates retained in the sieve were placed in plastic jars and fixed with 70% ethanol. The specimens were identified to family level for Insecta, class level for Mollusca, and subclass level for Annelida, using Hamada et al. (2014). Those levels of taxonomic resolution require significantly less analytical time without compromising the performance

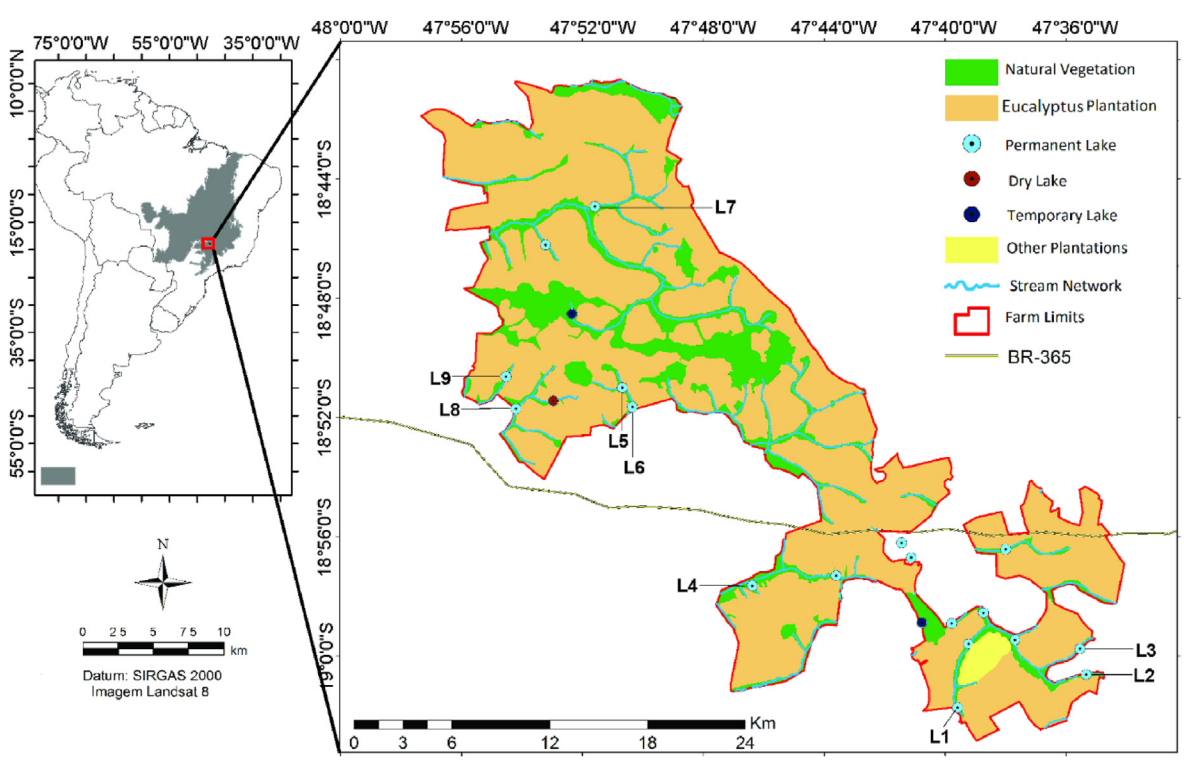

Fig. 1. Artificial pond locations.

Table 1
Parameters, observed conditions, and scores for the modified Physical Habitat Integrity Index (Nessimian et al., 2008) used to assess pond condition.

Parameter		Observed Condition	Value
P1	Land Use (Beyond Riparian Zone)	Silviculture or natural vegetation	3
		Silviculture and annual crops	2
		Annual crops	1
P2	Wetland (Upstream)	>0.8 km^2	4
		0.4 km^2–0.8 km^2	3
		0 km^2–0.4 km^2	2
		No wetland	1
P3	Riparian Zone Condition	Conserved	5
		Conserved with invasive species	4
		Regenerating	3
		Regenerating with invasive species	2
		Dominated by invasive species	1
P4	Vegetated Riparian Zone Width	>100 m	5
		>30 m–100 m	4
		>5 m–30 m	3
		1 m–5 m	2
		No vegetation	1
P5	Aquatic Macrophytes	All Functional Groups	4
		Two Functional Groups	3
		One Functional Group	2
		No Macrophytes	1
P6	Detritus	Mainly leaves and wood	3
		Some leaves and wood	2
		No leaves or wood	1
P7	Trash	Absent	2
		Present	1

of the tested indices (Silva et al., 2016; Heino et al., 2018).

2.4. Data analyses

To test if physical habitat disturbances are not detrimental to the diversity of nearby artificial ponds, we ran Generalized Linear Models between Taxa Richness, EPT Abundance, Shannon-Wiener diversity, and Margalef diversity versus the PHII. The models were built with a quasi-Poisson (Richness and EPT Abundance) or Gaussian (Shannon-Wiener and Margalef diversity indices) distributions, accordingly to the best fit for the distribution of the response variable data (Zuur et al., 2009; Sellers and Shmueli, 2010; Warton et al., 2016). All models were tested with an analysis of deviance (F test), and all tests were run in R software with the "vegan" package version 2.5–6 (Oksanen et al., 2019).

To test if physical habitat disturbances will not cause significant shifts in taxonomic composition, we considered the sampling sites with a PHII score >0.7 as having Maximum Ecological Potential (MEP), and those with lower scores were considered impaired. Then we ran a PERMANOVA to test if the composition showed a significant difference ($p < 0.05$) between those two categories. Finally, to supplement these results, we ran taxa indicator value analysis (Dufrene and Legendre, 1997) with the "labdsv" version 1.3-1 in R software (Roberts, 2007).

3. Results

We collected 6566 individuals belonging to 31 taxa (Supplementary Material S1). As expected, the numbers of individuals and taxa differed amongst ponds, with individuals in the impaired ponds numbering from 179 to 2049 and taxa richness ranging from 4 to 11. EPT number and Margalef Index ranged from 0 to 3 and from 1.00 to 1.36, respectively. In the less impaired ponds individuals numbered from 514 to 1117 and taxa richness varied from 13 to 19. EPT number and Margalef Index ranged from 2 to 38 and from 1.76 to 2.64, respectively.

Pond L1 was classified as Impaired (PHII 0.68). Its conductivity (3.00 μS/cm) was the highest for Impaired sites. It also showed the highest Temperature (29.49 °C). In this pond we collected 179 individuals belonging to 8 taxa (Chironomidae; Ceratopogonidae; Chaoboridae; Hydropsychidae; Hydroptilidae; Hydrophilidae; Belostomatidae; Oligochaeta), with Chironomidae being the most abundant (74 individuals).

Pond L2 was classified as Impaired (PHII 0.45). Its conductivity (2.00 μS/cm) was amongst the lowest measured, and the TDS (0.50 mg/L) was amongst the highest. Its turbidity (1.83 NTU) was the lowest for Impaired ponds. In this pond we collected 427 individuals belonging to 4 taxa (Chironomidae; Ceratopogonidae; Caenidae; Oligochaeta), with Chironomidae being the most abundant (392 individuals).

Pond L3 was classified as Impaired (PHII 0.46). Its conductivity (2.00 μS/cm) was amongst the lowest registered, and the TDS (0.50 mg/L) was among the highest registered. Its Turbidity (5.23 NTU) was the highest registered. In this pond we collected 2049 individuals belonging to 11 taxa (Chironomidae; Ceratopogonidae; Caenidae; Aeshnidae; Hydrophilidae; Noteridae: Notonectidae; Corixidae; Veliidae; Naucoridae; Oligochaeta), with Chironomidae having the greatest abundance (1153 individuals).

Pond L4 was classified as Maximum Ecological Potential (PHII 0.78). Its conductivity (6.00 μS/cm) was amongst the highest registered. Its Turbidity (1.58 NTU), TDS (0.14 mg/L) and Temperature (20.87 °C) were the lowest registered. In this pond we collected 928 individuals belonging to 13 taxa (Chironomidae; Ceratopogonidae; Baetidae; Caenidae; Libellulidae; Gyrinidae; Hydrophilidae; Noteridae; Notonectidae; Naucoridae; Belostomoatidae; Oligochaeta; Hirudinea), with Chironomidae having the greatest abundance (631 individuals).

Pond L5 was classified as Maximum Ecological Potential (PHII 0.73). Its conductivity (6.00 μS/cm) was amongst the highest registered. In this pond we collected 623 individuals belonging to 18 taxa (Chironomidae; Ceratopogonidae; Chaoboridae; Tabanidae; Culicidae; Baetidae; Leptohyphidae; Leptophlebiidae; Hydropsychidae; Hydroptilidae; Xiphocentronidae; Libellulidae; Perilestidae; Dytiscidae; Hydrophilidae; Noteridae; Elmidae; Oligochaeta), with Chironomidae being most abundant (525 individuals).

Pond L6 was classified as Maximum Ecological Potential (PHII 0.78). No water quality metric was outstanding. In this pond we collected 593 individuals belonging to 13 taxa (Chironomidae; Ceratopogonidae; Chaoboridae; Tabanidae; Baetidae; Caenidae; Hydroptilidae; Aeshnidae; Hydrophilidae; Noteridae; Veliidae; Oligochaeta; Hirudinea), with Chironomidae having the highest abundance (545 individuals).

Pond L7 was classified as Maximum Ecological Potential (PHII 0.84).

Table 2
Measured physical habitat and water quality metrics.

Pond	PHII	Ecological Condition	Conductivity (μS/cm)	Turbidity (NTU)	Total Dissolved Solids (mg/L)	Water Temperature (°C)
L1	0.68	Impaired	3.00	3.08	0.33	29.49
L2	0.45	Impaired	2.00	1.83	0.5	27.82
L3	0.46	Impaired	2.00	5.23	0.5	28.30
L4	0.78	Maximum Ecological Potential	6.00	1.58	0.14	20.87
L5	0.73	Maximum Ecological Potential	6.00	3.73	0.17	22.00
L6	0.78	Maximum Ecological Potential	3.00	2.43	0.33	24.65
L7	0.84	Maximum Ecological Potential	2.00	1.70	0.50	28.52
L8	0.68	Impaired	2.00	4.56	0.50	26.13
L9	0.76	Maximum Ecological Potential	3.00	4.10	0.33	25.44

Its Conductivity (2.00 μS/cm) was among the lowest values recorded, while its TDS (0.50 mg/L) was among the highest registered. Its Temperature (28.52 °C) was the highest for the Maximum Ecological Potential ponds. In this pond we collected 1117 individuals belonging to 19 taxa (Chironomidae; Ceratopogonidae; Chaoboridae; Tabanidae; Baetidae; Ephemeridae; Caenidae; Hydroptilidae; Xiphocentronidae; Libellulidae; Aeshnidae; Coenagrionidae; Perilestidae; Noteridae; Notonectidae; Veliidae; Belostomatidae; Oligochaeta; Hirudinea), with Chironomidae being the most abundant (816 individuals).

Pond L8 was classified as Impaired (PHII 0.68). Its Conductivity (2.00 μS/cm) was among the lowest values recorded, while its TDS (0.50 mg/L) was among the highest registered. In this pond we collected 151 individuals belonging to 6 taxa (Chironomidae; Ceratopogonidae; Coenagrionidae; Notonectidae; Oligochaeta; Hirudinea), with Chironomidae having the highest abundance (112 individuals).

Pond L9 was classified as Maximim Ecological Potential (PHII 0.76). Its Turbidity (4.10 NTU) was the highest for Maximum Ecological Potental ponds. In this pond we collected 514 individuals belonging to 15 taxa (Chironomidae; Ceratopogonidae; Chaoboridae; Tabanidae; Hydropsychidae; Libellulidae; Aeshnidae; Coenagrionidae; Gomphidae; Dytiscidae; Hydrophilidae; Notonectidae; Mesoveliidae; Oligochaeta; Hirudinea), with Chironomidae being the most abundant (344 individuals).

Regarding the tested benthic macroinvertebrate metrics (Table 3), three out of four were significantly correlated with PHII (Fig. 2). EPT abundance was the variable with the highest correlation with PHII scores ($p = 0.03$; $R^2 = 0.57$). Margalef diversity ($p = 0.05$; $R^2 = 0.45$) and taxa richness ($p = 0.04$; $R^2 = 0.47$) were also significantly correlated with PHII scores. Shannon-Wiener diversity was not significantly correlated with PHII ($p = 0.62$; $R^2 = 0.04$).

Regarding taxonomic composition, the PERMANOVA results showed a significant difference between Impaired and Maximum Ecological Potential sites ($p = 0.03$; F model: 2.61). The taxa indicator value analysis showed that only sites with maximum ecological potential were significantly correlated with taxa (Table 4). Ceratopogonidae, Libellulidae, and Tabanidae were all significantly correlated with sites having Maximum Ecological Potential.

4. Discussion

We rejected the first null hypothesis because most of the biological diversity indices (except for Shannon-Wiener diversity) correlated significantly and positively with the PHII scores. Our second null hypothesis was also rejected because only sites having high PHII scores were significantly associated with indicator taxa.

The significant positive correlation of the diversity measures with PHII indicate that landscape disturbances can cause significant alteration in the taxonomic structure of pond benthic macroinvertebrate assemblages (Simaika et al., 2016; Clifford and Heffernan, 2018). The different responses between Margalef and Shannon-Wiener diversity indices can be attributed to the latter's weight on evenness and the former's higher weights to richness and abundance, which are both substantially higher in sites with high PHII (Iglesias-Rios and Mazzoni, 2014). Those alterations are corroborated by the significant difference in composition between impaired sites and those with maximum ecological potential. These results also show that conserved riparian zones and wetlands can serve as buffers for lentic ecosystems, minimizing direct impacts. Similar results were found in studies of neotropical streams (Dala-Corte et al., 2020; Borges et al., 2021; Manoel and Uieda, 2021). The importance of intact riparian zones to lentic biota has also been reported for temperate lakes (O'Connor et al., 2000; Kaufmann et al., 2014).

The taxa associated with maximum ecological potential (Ceratopogonidae, Libellulidae and Tabanidae) suggest that anthropogenic disturbances may act as an additional ecological filter to artificial pond colonization. These taxa rely on their terrestrial adult forms for distribution and are likely be barred from aquatic ecosystems that are surrounded by terrestrial ecosystems affected by anthropogenic stressors (Firmiano et al., 2021). This is especially true for Libellulidae, which was found only in sites classified as having Maximum Ecological Potential. Previous studies showed that converting natural areas to eucalyptus plantations reduced the quality of nearby riparian zones and consequently, Odonata diversity (Borges et al., 2021), and that Libellulidae were associated with sites having minimal anthropogenic disturbances in the riparian zone (Mendes et al., 2018; Silva et al., 2021). This implies that Libellulidae can be considered a good indicator for the ecological quality of artificial pond riparian zones. Tabanidae and Ceratopogonidae were also shown to be sensitive to physical habitat disturbances. Previous studies have shown that Tabanidae larvae are sensitive to alterations in the sediment and water chemistry, preferring undisturbed sites with preserved riparian zones (Nautiyal and Mishra, 2011; Lock et al., 2014; Guareschi et al., 2016). Ceratopogonidae larvae are sensitive to agriculture intensification (Pocock and Jennings, 2007). All three taxa are classified as predators and our results suggest that this functional group is especially susceptible to physical habitat disturbances in ponds (Amundrud and Srivastava, 2015).

Our results show that limiting the anthropogenic disturbances around artificial ponds, can be essential to maintain regional macroinvertebrate biodiversity, as three (Taxa Richness, EPT Abundance, Margalef Diversity Index) of the four tested diversity metrics had a positive correlation with good physical habitat conditions. Such investments have a payoff in conserving biodiversity and ecosystem services (Hill et al., 2016). Previous studies showed that well-maintained artificial ponds that support higher aquatic biodiversity could potentially help control populations of plague and invasive species and facilitate access to high-quality water resources for humans (Davis and Moore, 2016; Rolke et al., 2018; Pfaff et al., 2023).

5. Conclusion

Our results highlight the importance of the ecological condition of the riparian zone for the biodiversity of artificial ponds. They also implies that well-managed artificial freshwater ecosystems can help maintain freshwater biodiversity at regional extents. Environmental managers can use these results to manage aquatic ecosystems better and conserve freshwater biodiversity under their ward.

Table 3
Tested benthic macroinvertebrate assemblage diversity variables.

Pond	Ecological Condition	Taxa Richness	EPT Abundance	Shannon-Wienner Diversity Index	Margalef Diversity Index
L1	Impaired	8	3	1.24	1.36
L2	Impaired	4	2	0.35	1.16
L3	Impaired	11	2	1.24	1.31
L4	Maximum Ecological Potential	13	3	1.00	1.76
L5	Maximum Ecological Potential	18	12	0.69	2.64
L6	Maximum Ecological Potential	13	11	0.46	1.88
L7	Maximum Ecological Potential	19	38	1.19	2.56
L8	Impaired	6	0	0.85	1.00
L9	Maximum Ecological Potential	15	2	1.171	2.24

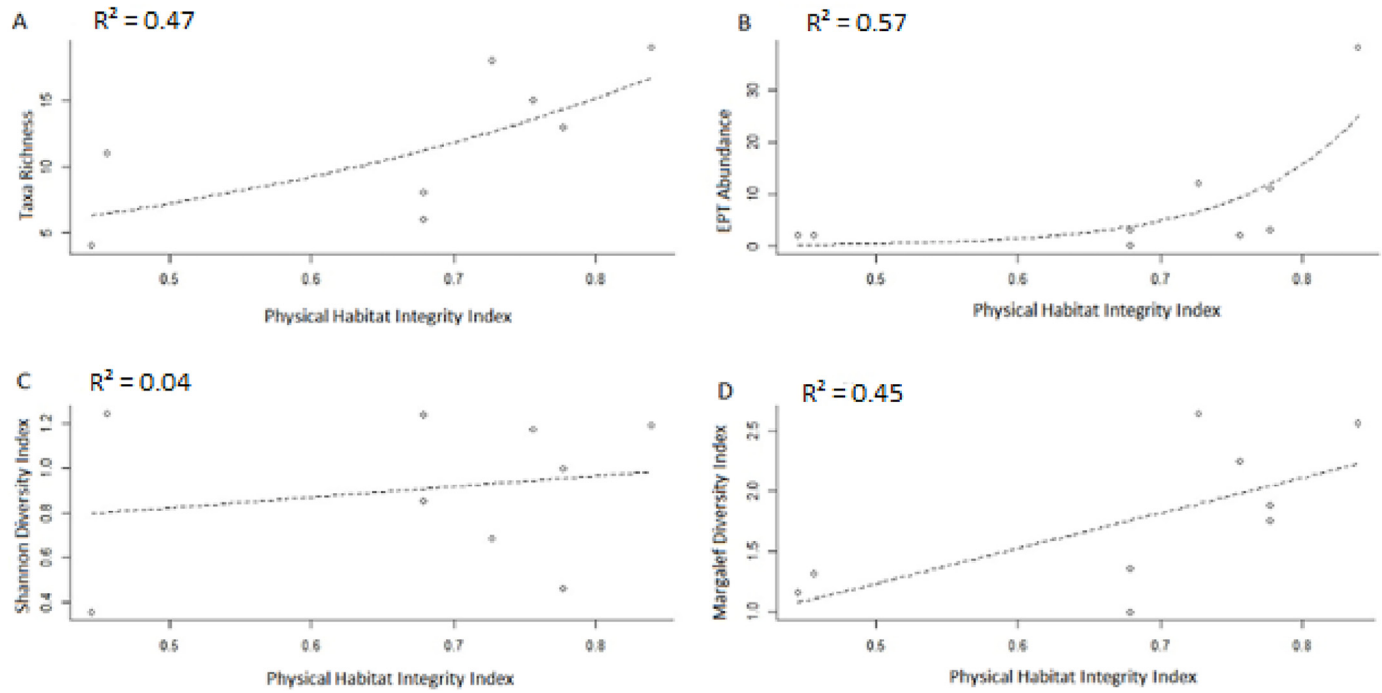

Fig. 2. "Generalized Linear Models (GLM) describing the correlation between (**A**) Taxa Richness ($F = 6.19$, $R^2 = 0.47$, $p = 0.04$), (**B**) EPT abundance ($F = 8.14$, $R^2 = 0.57$, $p = 0.02$), (**C**) Shannon-Wiener diversity index ($F = 0.27$, $R^2 = 0.04$, $p = 0.62$), and (**D**) Margalef diversity index ($F = 5.78$, $R^2 = 0.45$, $p = 0.05$). The models were built with a quasi-Poisson (Richness and EPT Abundance) or Gaussian (Shannon-Wiener and Margalef diversity indices) distributions, accordingly to the best fit for the distribution of the response variable data (Zuur et al., 2009; Sellers and Shmueli, 2010; Warton et al., 2016).

Table 4
Taxa indicator value analysis for ecological condition in artificial pond sites.

Taxa	Ecological Condition	indval	*p*
Ceratopogonidae	Maximum Ecological Potential	0.84	0.04
Libellulidae	Maximum Ecological Potential	0.80	0.05
Tabanidae	Maximum Ecological Potential	0.80	0.04

CRediT authorship contribution statement

Marden S. Linares: Conceptualization, Methodology, Writing – original draft. **Livia B. dos Santos:** Conceptualization, Methodology, Writing – review & editing. **Marcos Callisto:** Writing – review & editing. **Jean C. Santos:** Writing – review & editing.

Declaration of competing interest

MC is a member of the Editorial Board Member for Water Biology and Security and was not involved in the editorial review or the decision to publish this article. 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.watbs.2023.100189.

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