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Can fishways restore river connectivity? A case study using β diversity as a method of assessment

Passagens para peixes podem restaurar a conectividade fluvial? Um estudo de caso usando diversidade β como método de avaliação

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Abstract: Aim: β diversity was used as an indicator to test the hypothesis that a fishway can increase river connectivity, as a reduction in the value of this metric indicates greater similarity among fish assemblages. **Methods:** Quarterly sampling was performed with gillnets upstream and downstream of the Porto Primavera dam, Upper Paraná Basin, before the opening of the fishway between February 1999 and May 2001, and between February 2003 and May 2005 with the fishway in operation (10 samples per period/site). The correlation between the fish assemblages and sites was verified by applying two Mantel tests (downstream *versus* upstream before and one equivalent after the fishway) using the distance matrices generated by the Bray-Curtis index. The β diversity between downstream and upstream was calculated using the Sørensen index for each sample for the comparison of such values before and after the operation of the fishway, which were tested with Asymptotic Wilcoxon-Mann-Whitney Test. To summarize changes in the structure of the fish assemblages between the sites and periods nonmetric multidimensional scaling (NMDS) was applied based on Bray-Curtis dissimilarities, using multi-response permutation procedures (MRPP). **Results:** The Mantel tests showed no correlation between the upstream and downstream assemblages before the operation of the fishway but greater correlation after. β diversity was lower after than before the fishway, representing an increase in similarity between downstream and upstream with the fishway. MRPP analysis indicated that the fish assemblages between the sites differed more than was expected by chance, with smaller divergence between the sampling sites after the fishway (A = 0.08) than before it opened (A = 0.09). **Conclusions:** Although fishways remain an incipient and controversial theme for neotropical fish, the Porto Primavera fishway appears to be effective in terms of the restoration of connectivity.

Keywords: fish passage; fish assemblage; fluvial connectivity; β diversity; conservation.

Resumo: Objetivo: Testamos a hipótese de que sistemas de transposição de peixes (STP) aumentam a conectividade fluvial usando a diversidade β como indicador, uma vez que valores mais baixos dessa métrica indicam maior similaridade entre as assembleias de peixes. **Métodos:** Coletas trimestrais com redes de emalhar foram realizadas em uma área a jusante e outra a montante da barragem de Porto Primavera, bacia do Alto Paraná, antes (fevereiro/1999 a maio/2001) e após (fevereiro/2003 a maio/2005) o início de operação do STP. Inicialmente verificamos a correlação das assembleias de peixes entre as áreas aplicando dois testes de Mantel (jusante *versus* montante, antes e após a operação do STP), usando matrizes de distância geradas a partir do índice de Bray-Curtis. A seguir calculamos

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a diversidade β usando o índice de Sørensen entre jusante e montante, visando comparar os valores antes e após a operação do STP, com aferição pelo teste Assintótico Wilcoxon-Mann-Whitney. Para sumarizar as alterações de estrutura da assembleia entre áreas e períodos foi aplicado um escalonamento multidimensional não-métrico (NMDS) baseado nas dissimilaridades de Bray-Curtis, com uso de procedimentos de permutação multi-resposta (MRPP). **Resultados:** Os testes de Mantel demonstraram ausência de correlação entre as assembleias de jusante e montante antes da operação do STP e existência de correlação após. A diversidade β apresentou valores inferiores antes em relação à depois, evidenciando o incremento da similaridade entre jusante e montante após a operação do STP. A análise por MRPP indicou que as alterações nas assembleias de peixes entre as áreas não foram ao acaso, ocorrendo diferenças menores após (A = 0.08) a abertura do STP que antes (A = 0.09). **Conclusões:** Embora as passagens para peixes continuem a ser um tema incipiente e controverso para a região Neotropical, o STP de Porto Primavera provavelmente é efetivo no aspecto de restauração da conectividade.

Palavras-chave: sistemas de transposição de peixes; assembleia de peixes; conectividade fluvial; diversidade β; conservação.

1. Introduction

The fragmentation of habitat and the loss of connectivity are some of the main impacts of river impoundment (Agostinho et al., 2002, 2016; Godinho & Kynard, 2009; Pompeu et al., 2012; Pelicice et al., 2015). Fish passage facilities (FPF) are commonly suggested as a tool for the restoration of fluvial connectivity by providing a passage (Larinier, 2002) that allows migratory fishes to complete their migration (Godinho & Kynard, 2009). Fishways are structures which aim to allow the free movement of fish when artificial barriers are added to natural fluvial environments (Makrakis et al., 2015), as dam construction should not hamper the migration and dispersion flows of aquatic organisms, nor cause demographic and genetic isolation among such populations (Lucas & Baras, 2001).

However, the effectiveness of fishways as a conservation tool remains an incipient and controversial issue in neotropical basins (Agostinho et al., 2002; Pelicice & Agostinho, 2008; Pompeu et al., 2012; Lira et al., 2017). Among factors that contribute to this controversy are the large number of neotropical migratory species (Carolsfeld et al., 2003) with great diversity of migratory patterns and life histories (Makrakis et al., 2012b), and the lack of a long-term or permanent evaluation of the effectivity of fishways for conservation. Most FPF studies in neotropical basins focus on the performance of the fish passages, without a broader approach (Lira et al., 2017), meaning that the debate over key issues remains incipient. There are few studies on genetic structuring in migratory fishes (e.g. Lopes et al. (2007); Gomes et al. (2013); Ferreira et al. (2017)), for example, despite evidence of the effectivity of European FPF in mitigating this process (Gouskov et al., 2016). In addition, studies on physiological efforts and selectivity along the passage (e.g. Volpato et al. (2009)) remain incipient. When addressing post-passage migration to spawning sites, upstream recruitment success and downstream migration or long-term population viability, most available studies concentrate mainly on conceptual aspects, without specific field studies (e.g. Pelicice & Agostinho (2008); Godinho & Kynard (2009); Pelicice et al. (2015)). Important issues such as the role of migratory fishes as material and process subsidies in riverine systems (Flecker, 1996; Flecker et al., 2010; Wheeler et al., 2015), which are also dependent on river connectivity, remains poorly understood in neotropical basins (Flecker, 1996). As connectivity is a keystone for consequent issues in fish migration (overcoming dam barriers, upstream recruitment, genetic flows etc.), the aim of the present study was to test the hypothesis that the Porto Primavera fishway increases river connectivity for fish assemblages.

2. Material and Methods

The Engenheiro Sérgio Motta Hydropower Plant (or as it is known and shall be called herein Porto Primavera) is located on the Paraná River (22°28'S, 52°57'W), Upper Paraná Basin, southeastern Brazil; on the border between the states of São Paulo and Mato Grosso do Sul. The reservoir was filled in two stages, the first of which was completed in December 1998 (elevation of 253 m), and the second of which was completed in March 2001 (elevation of 257 m). The FPF, a pool-and-weir-orifice fishway 520 m long, five m wide and with a discharge ranging from 3.0 to 3.5 $m^3.s^{-1}$ (Wagner et al., 2012) (Figure 1), began operation in October 2001.

Quarterly standardized samplings were performed downstream and upstream of the dam (Figure 1) before the opening of the fishway, from

February 1999 to May 2001 and February 2003 to May 2005, after the operation of the fishway had begun, consisting of 10 samples per period in each treatment. The fishes were collected with a set of gillnets (30-to-200 mm mesh) exposed at each sampling site for 24 hours.

The abundance of each species was indexed by catch per unit effort (CPUE), expressed as the number of individuals caught per 1000 m^2 of gillnet set for 24 hours. The correlation of fish assemblages between the sites in the two periods was verified applying two Mantel tests (downstream *versus* upstream before and after the operation of the fishway) using the distance matrices generated by the Bray-Curtis index. To calculate β diversity, the Sørensen dissimilarity index between downstream

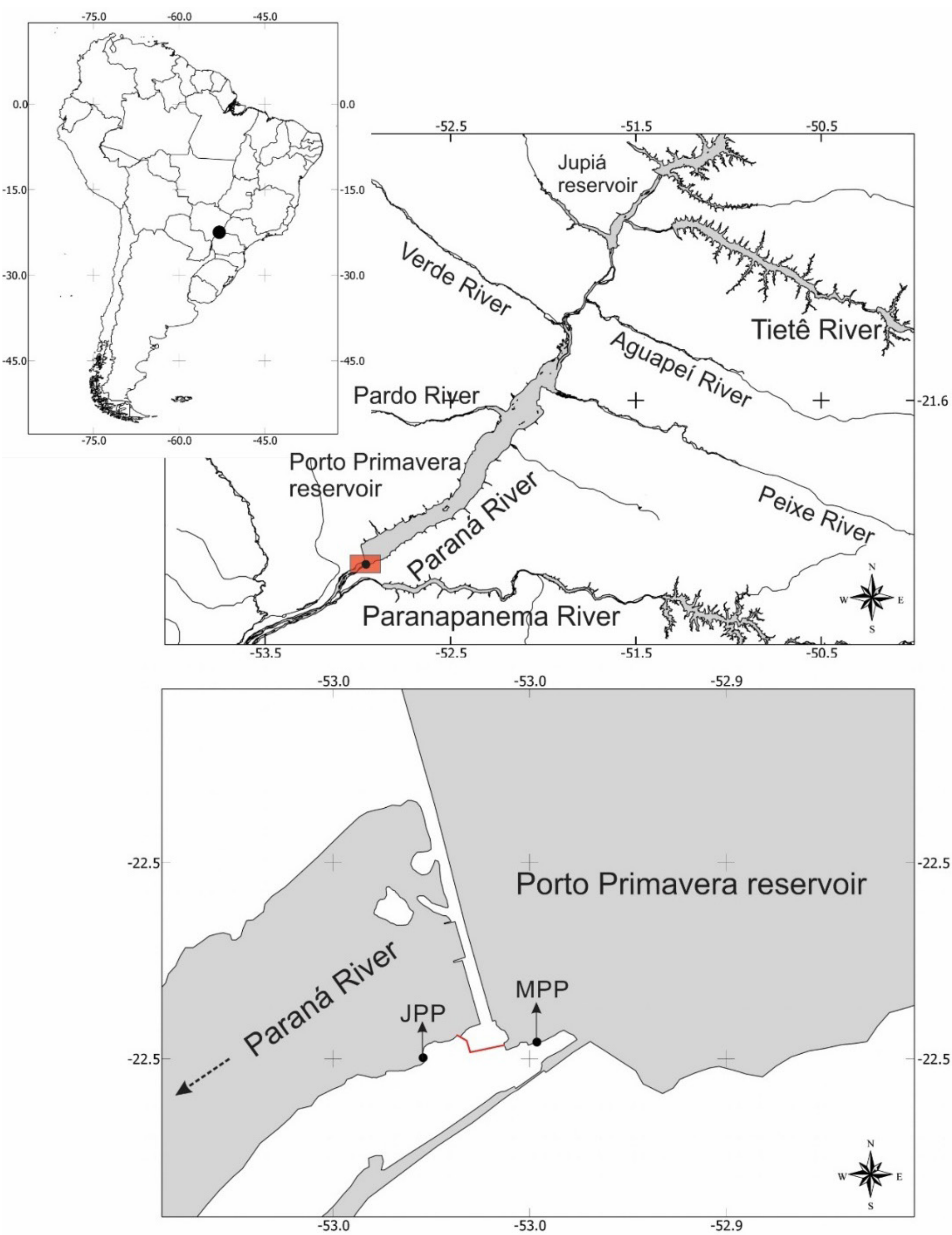

Figure 1. Location of Porto Primavera dam and its fishway (in red), as well as the two sampling sites downstream (JPP) and upstream (MPP) of the dam.

and upstream was applied for each sample. β diversity, as a metric of the difference between spatial units in terms of species composition (Magurran, 2004), was adopted as an indicator of connectivity, as a lower value in this metric implies a greater similarity between fish assemblages as a result of river connectivity. The Asymptotic Wilcoxon-Mann-Whitney Test was used to compare Sørensen dissimilarity values before and after the operation of the FPF.

To summarize the structure of fish assemblages between the sites (upstream and downstream of the dam) for each period (before and after the opening of the fishway), nonmetric multidimensional scaling (NMDS) based on Bray-Curtis dissimilarities (Legendre & Legendre, 1998) was applied. NMDS is a robust and widely used ordination technique in fish community ecology (Smith et al., 2016). Following ordination, multi-response permutation procedures (MRPP) were used to test whether the assemblage structure differed significantly between the sites in each period and to compare the magnitude of this difference (i.e., the effect size). This is a robust technique, with the advantage over related techniques in that it does not require distributional assumptions, such as normality and homogeneity of variance (McCune & Grace, 2002). The procedure was performed with 999 permutations, based on Bray-Curtis distance. All statistical analyses were performed with free to use software R (R Core Team, 2016).

3. Results

No correlation was found in the Mantel tests between the upstream and downstream assemblages before the FPF (r=0.120; p=0.3) but a correlation was identified following its operation (r=0.322, p=0.03). β diversity was lower after (median 0.47) than before (median 0.57) the FPF operation (Z=-2.08, p=0.04, Figure 2).

Stable NMDS ordinations were obtained upstream and downstream before (stress=0.15; 20 iterations) and after (stress=0.15; 20 iterations) the opening of the fishway (Figure 3). MRPP analysis indicated significant clustering (p<0.001) of the fish assemblages in both comparisons, i.e. the fish assemblages differed between the sites more than was expected by chance. The strength of these differences varied, however. The divergence between the sampling sites after the fishway, from a qualitative-quantitative perspective, was smaller (A=0.08) than before the opening (A=0.09), indicating a slight increase in similarity between fish assemblages after the operation of the FPF.

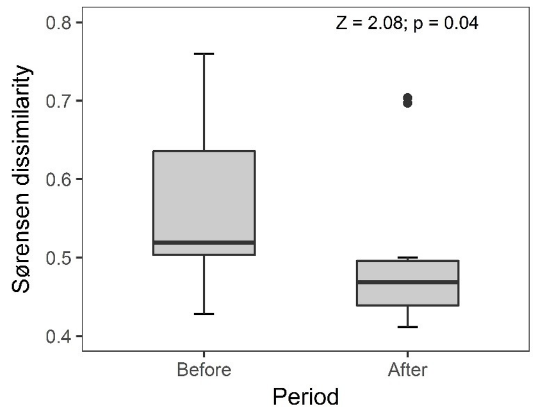

Figure 2. Comparison of the β diversity results before (February 1999 to May 2001) and after (February 2003 to May 2005) the start of operation of the Porto Primavera fishway by the Asymptotic Wilcoxon-Mann-Whitney Test, revealing a reduction in Sørensen dissimilarity.

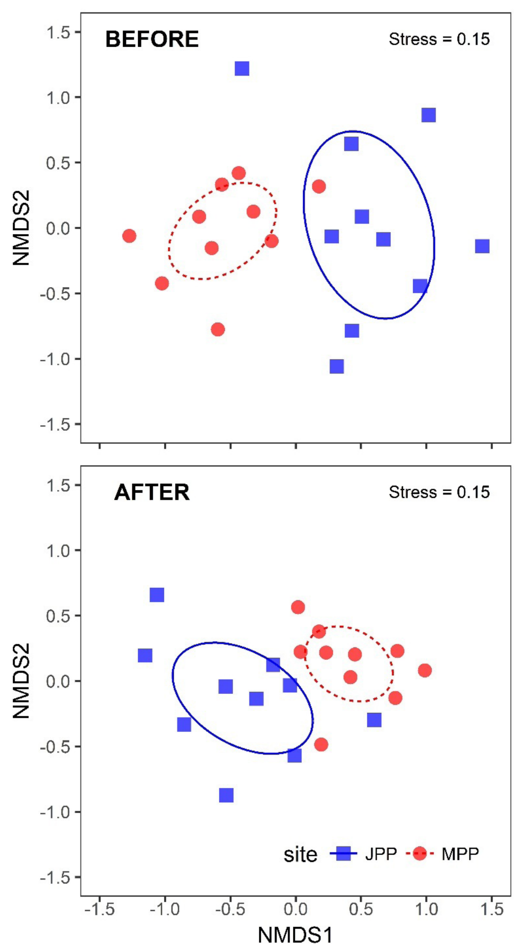

Figure 3. NMDS ordination between samples before and after the start of the Porto Primavera fishway operation.

Even though the results of the qualitative (Sørensen dissimilarity index) and qualitative-quantitative (Mantel, NMDS, and MRPP) approaches differed in degree, they indicated the same trend of decreasing β diversity and a consequent increase in similarity between the regions downstream and upstream of the dam with the operation of the FPF.

4. Discussion

The results of the present study support the conclusion that the Porto Primavera FPF has allowed the restoration of connectivity as there was a decrease in upstream and downstream β diversity following its operation. The variation in β diversity in the qualitative (Sørensen dissimilarity) and qualitative-quantitative (NMDS and MRPP, using Bray-Curtis dissimilarity) approaches can be attributed to the difference between the habitats upstream and downstream of the dam. While fishways seek to allow fish migrating upstream to overcome a barrier, they reach a lentic or semi-lentic habitat after this process, which may represent an extensive environmental filter for migratory species (Pelicice et al., 2015). In fact, studies carried out in Porto Primavera before the operation of the FPF using marking-recapture techniques demonstrated that migratory fish avoided the dammed stretch of the river, moving quickly toward either the downstream or upstream areas (Antonio et al., 2007), which could explain the lower similarity in qualitative-quantitative approaches.

Most studies of Neotropical FPF are based on passage performance and selectivity for migratory species or a functional group of species (Lira et al., 2017), including one carried out in the Porto Primavera fishway (Wagner et al., 2012). This approach remains necessary, including for the study of hydrological and engineering aspects and the swimming ability of fish (Santos et al., 2012; Assumpção et al., 2012; Santos et al., 2007). However, there is a lack of research that uses other approaches that consider connectivity itself, such as the present study.

Assessing connectivity with β diversity appears to be a useful tool for assessing the effectivity of FPF for fish conservation, despite being rarely used for this purpose. According to Ward et al. (1999), β diversity can be used as a measure of the degree of connectivity between habitats, as in fragmented habitats connectivity is low, preventing the exchange of matter, energy, and organisms between areas and reducing biodiversity. On the other hand, excessive connectivity is likely to reduce habitat heterogeneity, inducing a reduction in biodiversity (Ward et al., 1999) and an increase in biotic homogenization (Rahel, 2002). Correlations between β diversity and connectivity have been applied on scales ranging from the local (Alves et al., 2005; Lansac-Tôha et al., 2009) to the continental (Griffiths, 2017).

Even though the results of the present study support the conclusion that the Porto Primavera FPF has been effective, at least in terms of connectivity restoration, other capital aspects not addressed by the present study should be considered for appropriate conclusions to be drawn regarding the role of the FPF as a tool for fish conservation in the Upper Paraná Basin.

One of the aims of fish passages is to allow gene flow, maintaining the evolutionary potential of a species in a fragmented habitat (Gouskov et al., 2016). Studies such as that of Ferreira et al. (2017), which aim to assess genetic diversity, are important to support decisions about gene flow in areas under the influence of damning.

Another important effect of fish passages is on flows of energy and material. The contribution of fish migration to nutrient transport is more widely documented for anadromous species in the northern hemisphere, with the study of the effects of salmon runs on river/stream productivity and riparian forests (Willson et al., 1998; Helfield & Naiman, 2001; Kohler et al., 2013). Despite not carrying marine-derived-nitrogen like anadromous migrants, potamodromous species also contribute to nutrient flow, which is important for the fish conservation and ecosystem process (Flecker et al., 2010; Wheeler et al., 2015).

In terms of passage performance, the Porto Primavera FPF has a satisfactory upstream migration passage rate (Wagner et al., 2012) and there is evidence of permeability in both directions (Gutfreund et al., 2018), according to PIT telemetry assessment. However, long term monitoring is required, including more studies of the correlation between passage and environmental variables (Wagner et al., 2012). To maximize passage efficiency, as well as increasing the number of fish that pass a barrier, the passage needs to reduce the delay caused by dams (Nyqvist et al., 2017), as every obstacle, even effective ones, create a delay in fish migration (Larinier, 2008). This delay can affect the development of gonads and secondary sexual characteristics, which may reduce reproductive fitness (Fenkes et al., 2016) and therefore recruitment.

The actual contribution of these migrators to both the upstream and downstream recruitment and the population dynamics of the migratory species needs to be better understood. Studies that consider the occurrence and density of ichthyoplankton have revealed spawning grounds in sites downstream (Reynalte-Tataje et al., 2013; Barzotto et al., 2015) and upstream (Da Silva et al., 2011, 2015; Makrakis et al., 2012a) of Porto Primavera. Assessing the balance between upstream and downstream recruitment is imperative to sustaining the operation of fishways, avoiding the risk that they will act as ecological traps, transferring populations from high-quality (riverine) to low-quality (reservoir) environments and reducing individual fitness (Pelicice & Agostinho, 2008).

In the Porto Primavera dam, the upstream tributaries also minimize the expected trend towards biotic homogenization in the reservoir (Marques et al., 2018). However, one important unintended consequence of FPF is the passage of non-native species, leading to unwanted consequences from new predator-prey and competitive interactions (McLaughlin et al., 2013). The facilitation of the movement of non-native species due to increased connectivity, can therefore cause the long-term homogenization of the fish fauna (Rahel, 2007; Vitule et al., 2012).

These and other aspects must be integrated into an ecosystemic strategy, structuring a theoretical framework on neotropical FPF that is still required. This joint approach can help solve the puzzle of the Upper Paraná Basin, which despite being widely studied, still has pieces missing.

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