UNIVERSIDADE FEDERAL DE LAVRAS

RAFAEL COUTO ROSA DE SOUZA

INVESTIGATING THE FEASIBILITY TO REMOVE SHP PANDEIROS: LESSONS FROM FISH FAUNA

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Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Ecologia Aplicada, para a obtenção do título de Doutor.

Prof. Dr. Paulo dos Santos Pompeu
Orientador

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APROVADA em 04 agosto de 2017.

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Dedico este trabalho aos peixes que sacrifiquei no intuito de conservar o ambiente no qual eles viviam, apesar de contraditório suas mortes não passaram desapercebidas. Enfim dedico aos peixes do rio Pandeiros, da bacia do rio São Francisco e de todos os rios brasileiros.

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RESUMO GERAL

A presença de usinas hidrelétricas nos rios gera impactos severos nos ambientes aquáticos em todo mundo. Apesar dos impactos serem inerentes às barragens, a identificação do tipo de alteração sofrida é variável de acordo com cada sistema no qual a usina está inserida. A dificuldade em se mensurar e avaliar a magnitude destas alterações é ainda mais crítico em ambientes aquáticos tropicais. Ainda que identificados os impactos, após a construção de uma usina hidrelétrica dificilmente estes são mitigados. Entretanto, nas últimas décadas, a remoção física de barragens tem sido adotada como medida de manejo em alguns países no mundo como parte de programas de restauração de rios e bacias hidrográficas. Neste contexto, esta tese teve como objetivo principal identificar os possíveis impactos oriundos da usina hidrelétrica presente no rio Pandeiros localizado na bacia do rio São Francisco, Brasil a fim de criar subsídio para a tomada de decisão de sua remoção. Primeiro, é realizada uma abordagem do cenário de desenvolvimento hidroelétrico e conservação de ambientes aquáticos em países em desenvolvimento com enfoque no Brasil. Explicita-se os impactos de usinas hidrelétricas e as dificuldades de se mitigar tais impactos levantando a possibilidade de utilização da técnica de remoção física de barragens como medida de manejo para restauração de ambientes aquáticos (Artigo 1). Segundo, é uma avaliação empírica dos efeitos de uma usina hidrelétrica nas assembleias de peixes (riqueza, abundância e composição) separadas por uma ela (Artigo 2). O terceiro, é uma avaliação da variação das assembleias de peixes ao longo do rio Pandeiros sob a perspectiva da dinâmica trófica e influência da barragem nesta dinâmica (Artigo 3). Para as análises foram utilizados dados de dois anos de amostragens (2014-2016) em oito pontos de coleta ao longo do rio, compreendendo diferentes regiões em um gradiente longitudinal considerando o grau de influência da barragem. A análise, de forma geral, dos resultados encontrados enfatizam as alterações na comunidade e na dinâmica trófica da ictiofauna provocadas pela PCH Pandeiros. A barragem atua como barreira geográfica e fator de alteração do habitat, principalmente nas regiões mais próxima dela. Assim observou-se diferenças na riqueza, abundância e composição entre os pontos separados pela barragem. Nas três abordagens realizadas discutiu-se sobre os possíveis efeitos da remoção da barragem no rio Pandeiros, enfatizando que a ictiofauna presente em determinados pontos do rio é oriunda de alterações provocadas pela barragem. Conclui-se que é esperado que após a remoção ocorra uma reestruturação da comunidade de peixes resultando possivelmente na dinâmica e condição semelhantes encontradas anterior à PCH Pandeiros.

Palavras-chave: Remoção de barragens. Ictiofauna. Ecologia trófica. Usinas hidrelétricas. Restauração de ambientes aquáticos.

ABSTRACT

The presence of hydroelectric power plants in rivers causes severe impacts on the aquatic environment around the world. Although the impacts are inherent to dams, the identification of the type of change suffered varies according to each system in which the plant is inserted. The difficulty of measuring and assessing the magnitude of these changes is even more critical for tropical aquatic environments. Even if the impacts are identified, after the construction of a hydroelectric power plant these are rarely mitigated. However, in the last decades, as part of river and basin restoration programs mainly in the United States of America and some countries in Europe, the physical removal of these dams has been adopted as a management measure to reestablish the natural characteristics before the plants. In this context, this thesis aims to identify the possible impacts from the hydroelectric plant present in the Pandeiros River located in the São Francisco River basin, Brazil in order to create subsidy for the decision making of its removal. First, an approach is taken to the scenario of hydroelectric production and conservation of aquatic environments in developing countries with a focus on Brazil, demonstrating the impacts of hydroelectric power plants and the difficulties of mitigating such impacts, raising the possibility of using the technique of physical dams removal As a management measure to restore aquatic environments (Article 1). Second, it is an empirical evaluation of the effects on the fish community (richness, abundance and composition) separated by a hydroelectric plant (Article 2). The third, is evaluation of the variation of the fish assemblages along the river Pandeiros from the perspective of the trophic dynamics and influence of the dam in this dynamic (Article 3). To reach the objectives it's were used two-year (2014-2016) sampling data at eight sampled sites along the river, comprising a longitudinal gradient considering the influence of the dam. In general, the results found emphasize the changes in the community and in the trophic dynamics of the ichthyofauna caused by the SHP Pandeiros. In the three approaches we discuss the possible effects of the removal of the dam on the Pandeiros River, emphasizing that the ichthyofauna present in certain sites of the river it's caused by the dam. Concluding that it is expected that after the removal occurs a restructuring of the community of fishes possibly resulting in the similar dynamics prior to the SHP Pandeiros.

Keywords: Dam removal. Freshwater fishes. Trophic ecology. Hydroelectric plants. Restoration of aquatic environments.

SUMÁRIO

PRIMEIRA PARTE

1 APRESENTAÇÃO GERAL

A adoção da água como recurso para produção de energia elétrica tem sido incentivada em diversos países como alternativa à utilização de combustíveis fósseis a fim de reduzir as emissões dos gases do efeito estufa (ZARFL et al., 2015). Entretanto a construção de usinas hidrelétricas com ou sem reservatórios é fonte de profundos impactos no sistema aquático (SMITH et al., 2017). A maior parte dos países com grande potencial hidroelétrico são países em desenvolvimento que ainda possuem extensas áreas com grande biodiversidade e elevado grau de endemismos tanto no ambiente aquático quanto terrestre (WINEMILLER et al., 2016). Desta forma tem sido motivo de grande preocupação os avanços do setor hidrelétrico e as perdas de biodiversidade em função deste desenvolvimento (LEES et al., 2016).

O Brasil com extensas redes hidrográficas já possui como principal fonte de energia elétrica a hidroeletricidade (ANEEL, 2017). Contudo já é bem estudado os impactos deste forma de produção de energia no ambiente aquático e para muitos a mitigação deles não é eficiente, em alguns casos podendo agravar o problema (PELICICE; AGOSTINHO, 2008). Por isso, o estudo de novas formas de mitigar ou restaurar o ambiente impactado por barragens se fazem necessários. Dentre as possibilidades de se restaurar surge a remoção física de barragens que em alguns países tem se tornado uma medida viável a diversos empreendimentos que não se observa sentido (econômico, ambiental e social) de mantê-los (AMERICAN RIVERS, 1999; POFF; HART, 2002).

Porém, no Brasil e em países em desenvolvimento esta medida não tem sido discutida embora a necessidade de se estabelecer um melhor planejamento da expansão de usinas hidrelétricas conciliando com a conservação de ambientes aquáticos seja evidente. Assim, a adoção da remoção de barragens surge como uma possibilidade de medida viável e efetiva para muitos empreendimentos.

1.1 Objetivos e estrutura da tese

Neste contexto ambiental e de desenvolvimento do sistema hidroelétrico brasileiro esta tese possui o objetivo principal identificar os possíveis impactos gerados por uma pequena central hidrelétrica na comunidade de peixes do rio Pandeiros na bacia do rio São Francisco criando suporte para a tomada de decisão da remoção da barragem levantando a discussão sobre a possiblidade de uso da remoção de barragens como uma medida a ser considerada no planejamento hidrelétrico em bacias hidrográficas. Eu utilizei dados oriundos de dois anos de amostragem padronizada da ictiofauna do rio Pandeiros no intuito de comparar as assembleias a montante e jusante da Pequena Central Hidrelétrica de Pandeiros. No mesmo intuito de comparar as assembleias separadas pela barragem, também utilizamos uma abordagem de ecologia trófica com a utilização da técnica de quantificação de isótopos estáveis (^{13}C e ^{15}N) em algumas espécies para investigar a influência da PCH. A tese de acordo com o formato de artigos em versão preliminar de submissão estando dividida em três artigos. O primeiro, aborda o cenário da produção hidrelétrica e conservação de ambientes aquáticos de países em desenvolvimento com enfoque no Brasil, demonstrando os impactos de usinas hidrelétricas e as dificuldades de se mitigar tais impactos levantando a possibilidade da utilização da técnica de remoção física de barragens como medida de manejo para restauração de ambientes aquáticos (Artigo 1). Segundo, é uma avaliação empírica dos efeitos na comunidade de peixes (riqueza, abundância e composição) separadas por uma usina hidrelétrica (Artigo 2). O terceiro, é avaliação da variação das assembleias de peixes ao longo do rio Pandeiros sob a perspectiva da dinâmica trófica e influência da barragem nesta dinâmica (Artigo 3). Os três capítulos estão preparadas para submissão na Brazilian Journal of Water Resources (Artigo 1), Neotropical Ichthyology (Artigo 2) and Hydrobiologia (Artigo 3).

2 CONCLUSÕES GERAIS

Os resultados e discussões desenvolvidos ao longo desta tese são os primeiros no contexto da possibilidade da remoção de uma usina hidrelétrica considerando Brasil e países em desenvolvimento. É o primeiro que estabelece um estudo de referência com base na ictiofauna e ecologia trófica proporcionando subsídios para a tomada de decisão da retirada da barragem de acordo com os impactos desta na dinâmica da comunidade de peixes do rio Pandeiros.

No atual contexto sócio, econômico e ambiental em que a utilização da água para geração de energia elétrica é apontada como umas das principais alternativas à combustíveis fósseis (ZARFL et al., 2015), os barramento de rios por usinas hidrelétricas se tornaram uma realidade que pode ser observada em todo o mundo (POFF et al., 2007). Entretanto, atualmente a construção de novas usinas se dá principalmente em países em desenvolvimento como no Brasil (WINEMILLER et al., 2016). Embora, os impactos de usinas hidrelétricas e seus reservatórios seja amplamente difundidos (BAXTER 1977; SMITH et al., 2017), a remoção de barragens como medida de manejo não tem a mesma abrangência. Esta tese levanta a discussão da remoção de barragens como possibilidade de medida de manejo no Brasil, entretanto chega à conclusão de que esta medida não acontecerá a curto prazo, e que esta abordagem deve ser considerada no âmbito da pesquisa, sociedade e dos setores tomadores de decisão como órgãos ambientais.

Os resultados encontrados neste trabalho demonstram que mesmo uma pequena usina hidrelétrica é fonte de impactos à ictiofauna. Estes impactos estão relacionados à atuação da barragem como barreira física e como fonte de alteração do regime de vazão natural do rio, possibilitando assim a introdução e estabelecimento de espécies exóticas e causando alteração na dinâmica e distribuição das espécies nativas acima e abaixo da barragem. Estas alterações por sua vez também afetam a forma como a comunidade de peixes do rio Pandeiros utiliza os recursos alimentares, principalmente nas regiões onde a barragem influencia diretamente, alterando a proporção de grupos tróficos nesta áreas comparadas com regiões sem a influência do barramento.

2.1 Prioridades para pesquisas futuras

No contexto do rio Pandeiros, se a opção pela remoção da barragem for adotada, deve ser realizado um novo levantamento da ictiofauna nos pontos já amostrados para que estabeleça um retrato de como a comunidade de peixes está para se ter um comparativo mais recente da situação antes da remoção. Após a remoção, deve ser realizada uma amostragem mais sistemática principalmente em relação ao tempo e dos pontos mais próximos à barragem tanto a montante quanto jusante.

Entretanto, a remoção da barragem não deve acontecer antes que ocorra um trabalho de conscientização da população que mora próxima da barragem e do rio Pandeiros. O que se observa na literatura é a junção dos aspectos econômico, ambiental e social na tomada de decisão da remoção, muitas vezes com a comunidade agindo direta e decisivamente na tomada de decisão da remoção da barragem, este aspecto social ainda foi pouco explorado no contexto da PCH Pandeiros e deve ser fomentado nas próximas etapas do processo.

De forma geral, existem muitas usinas de pequeno porte que se encontram em situação semelhante à PCH Pandeiros, inserida em um contexto econômico e ambiental desfavorável onde a possibilidade de remoção seja a melhor alternativa para possibilitar um processo de restauração eficaz. Assim, a ideia de remoção deve ser considerada e ampliada para estas usinas em todo o país.

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SEGUNDA PARTE - ARTIGOS

ARTIGO 1

Will dam removal be a management option in Brazil in the near future?

(formatação segundo a revista Brazilian Journal of Water Resources)

ABSTRACT

Electrical power has become a key element in contemporary society. For over 100 years the use of water for this purpose has provided electricity production throughout developing world. In recent decades, hydroelectricity became one of the most used alternatives especially considering the context of climate change and concerns about greenhouse gas emissions. Therefore, the number of dams already significant, affecting more than half of the large rivers in the world, has experienced a new boom in construction of new power plants. The purpose of this article is to conduct a survey on the impacts of hydropower plants and discuss the adoption of dam removal as an option for management in developing countries, with focus on Brazil. The impacts of dams are varied and most of them are rarely mitigated. For this reason, the physical removal of dams has been used in some countries to improve environmental conditions, improve the safety and avoid economic losses. The number of removals has increased every year and most of these removals aims at environmental restoration of rivers and basins. However, in developing countries, such as Brazil, this possibility seems remote, little discussed and many still don't know although it is a unique opportunity to restore river basins with large biodiversity (e.g. Amazon, Congo and China) and to avoid to be heavily impacted by hydroelectric plants. Even so, the discussion, initially just in the scientific community, should be encouraged in order to facilitate possible removal projects that may arise as the case of the small hydroelectric plant of Pandeiros in the São Francisco River basin.

Keywords: Environmental management – Hydroelectric development – Aquatic environment conservation – Freshwater conservation

INTRODUCTION

Electrical power is one of the main elements that drives and characterizes contemporary society. For over 100 years we have used water to generate electricity, and hydroelectricity currently represents approximately 16% of the total produced globally (IHA 2015). In recent decades the use of renewable resources (*e.g.* wind, solar, geothermal, hydro, biomass, waves and tidal) to generate electricity has increased in an effort to reduce greenhouse gas emissions, but electricity production is still responsible for 35% of the global emissions of these gases (COP 21 2015). In this sense, hydropower arises as an abundant, effective and low-cost alternative, besides providing reservoirs for other purposes (Kumar et al 2011). Today, hydroelectricity represents approximately 70% of all renewable energy production in the world (REN21 2016).

There are a huge number of dams around the world, with more than 45,000 above 15 m in height, and more than a half of large river systems being regulated by dams (Dynesius & Nilsson 1994, Nilsson et al 2005). The great variety of functions that dams provide make them an attractive option, including relatively secure, generally cheap and efficient energy production, flow control, water supply, navigation, irrigation and leisure.

There has been a new boom in hydropower plant construction in several countries that have appropriate hydro potential (Zarfl et al 2015). This growth appears to be determined by the economic condition of countries and/or regions. Most of such growth has been observed in developing countries in Africa (Congo, Rwanda, and Cameroon), Asia (China, Russia and Turkey) and South America (Argentina, Brazil and Colombia). These countries are improving their hydroelectricity-based energy matrix, thus increasing the pressure in regions with high aquatic biodiversity, that have until recently been relatively unaffected by hydropower plants. For example, the Congo, Mekong and Amazon river basins (Ziv et al 2012, Winemiller et al 2016, Lees et al 2016).

As a result of that recently there has been an increased focus and concern on the ecological impacts of hydropower plant construction in developing countries, particularly in regions with high biodiversity (Fearnside 2006, Winemiller et al 2016). For example, there are about 846 fish species endemic to the Congo River basin, which are threatened by 64 hydropower plants that are proposed and/or under construction (Winemiller et al 2016). The situation in the Amazon and Mekong river basins is even more worrisome due to the impressive species richness and great interest in hydroelectric development. There, more than

1000 hydropower plants are planned or under construction, thus reinforcing the idea that such regions represent true hotspots of aquatic biodiversity (Winemiller et al 2016). In other words, they are areas with a high diversity, especially of aquatic organisms, which are also highly threatened by habitat destruction (Myers et al 2000).

Herein we briefly discuss the possibility of mitigating the impact of dams on aquatic organisms, and raise the discussion of dam removal as a management option in Brazil and the developing countries where hydropower is growing as an energy source.

IMPACTS OF DAMS ON AQUATIC ORGANISMS: ARE THEY MITIGATED?

Dams and their reservoirs have substantial impacts on a basin scale (Ligon et al 1995, Syvitski et al 2005, Dudgeon et al 2006), and some cases are emblematic. The Balbina Hydroelectric Power Plant (Amazonas State, Brazil) represents one dramatic example of a disastrous planned project. It was constructed to generate electricity, but generates much less than expected and created a reservoir with an area of over 2,300 km² (Fearnside 1989). That reservoir was responsible for the local extinction and decline of several populations of invertebrates and vertebrates, what led it to be considered a true environmental disaster (Benchimol & Peres 2015). A study conducted on the Mekong River identified that the construction of hydroelectric power plants in the basin would reduce fish biomass, estimating that in a scenario of least environmental impact, fish biomass loss would range from 0.3% (~1,700 tons/year) to 4% (25,300 tons/year) for each addition of 1 TWh/y (TeraWatt hour per year) (Ziv et al 2012).

The impacts of hydropower plants already account for the decline of biodiversity in aquatic environments at a global scale (Poff et al 2007, Vörösmarty et al 2010) and are mainly related to the alteration of the natural hydrological regime of rivers, blockage of migratory routes and habitat changes in the impounded area.

The main impacts of hydroelectric development are the transformation from lotic to lentic systems due to the formation of reservoirs and the regulation of the natural flow (Baxter 1977, Poff et al 2007, Vörösmarty et al 2010, Pelicice et al 2015). As the flood pulse drives the transportation of nutrients, sediments and organic matter, such modifications are responsible for changes on both structure of habitats and biotic communities, altering the biodiversity and the biotic integrity of rivers (Poff et al 1997, Bunn & Arthington 2002, Poff et al 2007, Nestler et al 2012). Together with river fragmentation caused by the barrier created by the dam (Nilsson et al 2005), such impacts interfere directly with the recruitment of fish species, especially those that require the flood plain and/or long parts of the river to complete their life cycles.

Artificial flooding has been adopted as one strategy to mitigate the impacts of dams on the natural flow regime, and may be efficient and contribute to the reestablishment of abiotic and biotic variables of the river (Bednarek & Hart 2005, Olden & Naiman 2010). The gains in fish production could even surpass the costs associated with energy loss (Godinho et al 2007), but the operation of artificial floods seems to be a distant reality in a scenario of increasing water and energy demand (Olden et al 2014). Furthermore, those strategies only affect regions downstream of the dams, and have no impact on the reduced connectivity between upstream and downstream regions and habitat loss due to the reservoir formation.

In Brazil, fish stocking and the construction of fish passes are the main mitigation actions undertaken. However, the precarious conservation status of different species clearly indicate that such strategies have been ineffective (Agostinho et al 1994; Cesp 1996; Agostinho et al 2002, 2004). Attempts to promote self-sustaining native populations from stocking were mainly unsuccessful, since stocking decisions were made without considering the status of wild stocks, environmental restrictions or requirements of target species (Agostinho et al 2008).

The construction of fish passes represents another widely used strategy to mitigate the impact of dams on migratory species. There are several knowledge gaps concerning the efficiency of fish passes, so there is no consensus on their effectiveness (Kemp, 2016a). In South America, the failure of fish passes in mitigating the impacts of dams on migratory species may be attributed to several aspects: the lack of knowledge on basic aspects of behavior and species life history; the lack of critical habitats upstream of the reservoir or downstream of the dam, such as reproduction sites and nursery areas, and the absence of downstream passages (Pompeu et al., 2012). In some situations, the lack of remaining lotic systems sufficient to allow species to complete their life cycle (Pelicice & Agostinho 2008) in a dammed catchment is the main reason for their failure to maintain fish populations. Moreover, the presence of large reservoirs that act like behavioral barriers to the fish movements (Pelicice et al., 2015) represents an additional obstacle rarely manipulated or mitigated. Therefore, some of the most significant impacts of dams, especially when big reservoirs are created, are poorly mitigated (Pelicice & Agostinho 2008, Orr et al 2012, Lees et al. 2016, Sánchez-Zapata et al. 2016), especially in heavily fragmented basins.

DAM REMOVAL AS AN ALTERNATIVE TO RESTORATION

The impacts on biodiversity as a result of dam construction are evident and widely described in the literature (*e. g.* see Baxter 1977, Poff et al. 2007). Mitigation options are either spurious, or are currently insufficient to be fully effective, especially in developing countries (Kemp, 2016b).

For a long time, dams were thought to be permanent structures, but this point of view has changed and proposals to remove them are becoming increasingly common (O´Connor et al. 2015). In the United States, for instance, 1,384 dam have been removed since 1912, with average of 47 removals per year recorded between 1999 and 2016 (American Rivers 2017). Most of them are still small sized dams (Figure 1) and only a small proportion are Hydropower Plants (Figure 2).

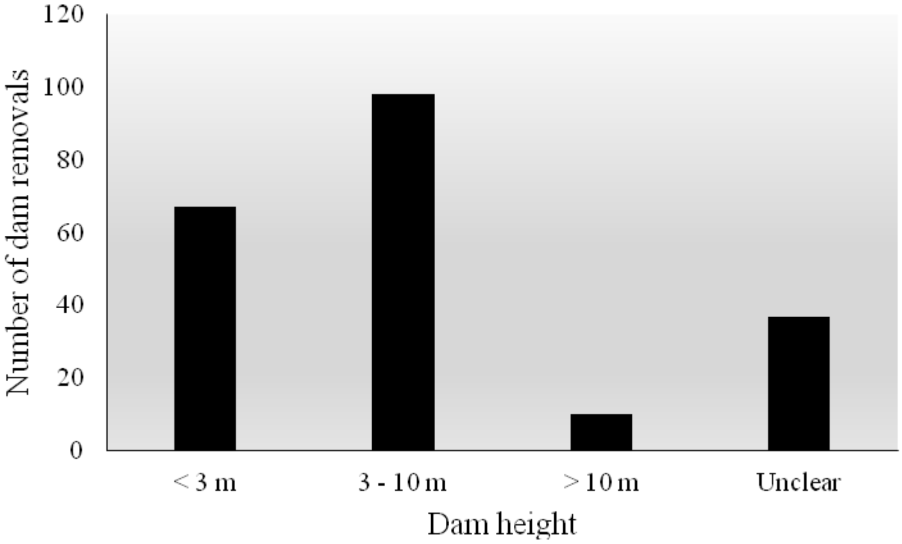

Figure 1 Number of dams removed in the last three years in the United States of America, separated by height (according American Rivers 2017).

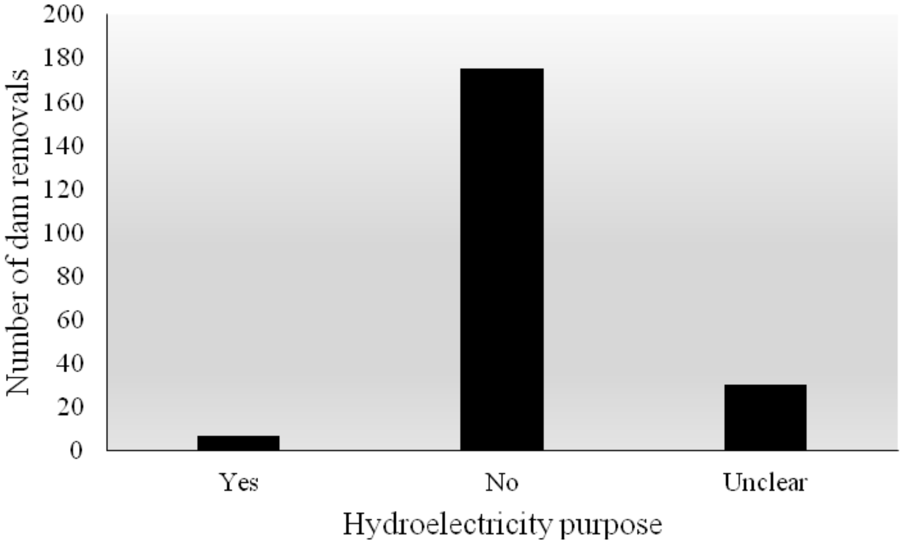

Figure 2 Number of dams removed in the last three years separated by whether the dam had a hydroelectricity purpose before the removal process (according American Rivers 2017).

Thus, the removal of dams arises as an alternative to traditional mitigation trying to reverse the impacts they cause (Bednarek 2001, Bernhardt et al 2005), and the number of studies related to the effects of dam removal on aquatic fauna is fast growing (Figure 3).

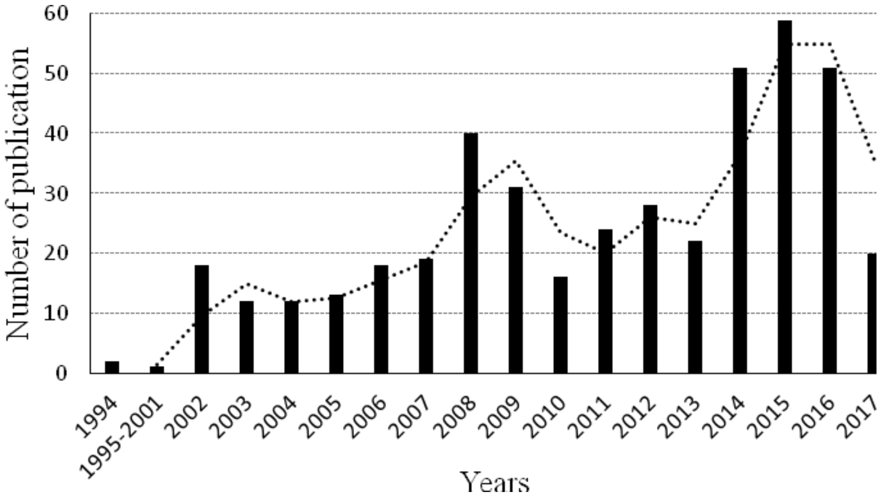

Figure 3 Number of publications concerning dam removal. A search from Web of Science (30 05 2017) was used, using "dam removal" as the basic search for all years. The line represents a mean of consecutive years.

In recent decades, dam removal has begun to enter discussions in basin restoration programs (Shuman 1995). European countries, like Spain, France and England (McCulloch 2008; Lejon et al 2008; 2009), as well as Japan and Taiwan have already experienced such removals (De Leaniz 2008, Lejon et al 2009, Chiu et al 2013, O’Connor et al 2015, Kemp 2016b), most of them in an effort to restore the aquatic environment. However, except for the United States of America, the number of documented removals (reported in the scientific literature) per country is still low. Among the developing countries, only Poland have already recorded the effects of the removal of a small dam (Tszydel et al 2009).

The justification for the removal of a dam depends on the context in which it was installed and may generally be divided into three main reasons: environmental, safety and economic (Maclin & Sicchio 1999). Most dam removals were performed to increase connectivity for fish migration (mainly salmon). Safety reasons relate to excess sediment in reservoirs, which also impacts the lifetime of dams and the related costs for their maintenance (Maclin & Sicchio 1999, Poff & Hart 2002, O’Connor et al 2015).

Dam removal in the United States is ranked as the sixth cheapest method of environmental restoration of rivers, with a mean cost of US$98,000 (Bernhardt et al., 2005). However, such costs will increase as proposals for removal of large plants become more common (Stokstad 2006) (Figure 4).

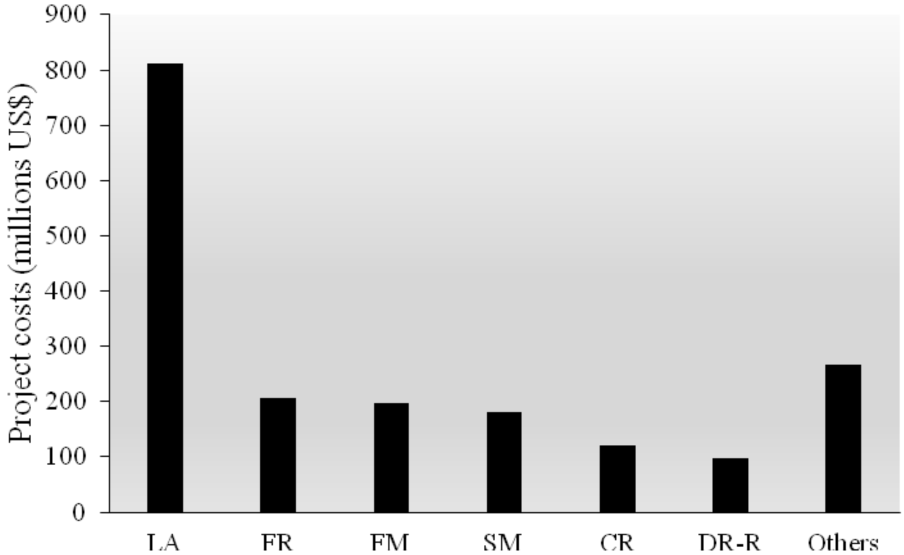

Figure 4 Cumulative cost of dam removal projects records in the USA. Abbreviations: Land acquisition (LA), Floodplain reconnection (FR), Flow modification (FM), Stormwater management (SM), Channel reconfiguration (CR), Dam removal/retrofit (DR-R) (Adapted from Bernhardt et al. 2005).

When the possibility of removing a dam is evaluated, impacts related to the sediment discharge and short-term biodiversity loss (Bednarek 2001, Stanley & Doyle 2003, East et al 2015) must be considered, as well as the benefits of returning the river to a more natural condition (Stanley & Doyle 2003). Although many removal projects did not provide adequate monitoring (Bednarek 2001), those available indicate that the impacts are mostly positive (especially on the medium and long term) and met the purpose of environmental restoration, even when a small obstacle was removed (De Leaniz 2008).

THE FUTURE OF DAM REMOVAL IN DEVELOPING COUNTRIES AND BRAZIL

Developing countries are the future hotspots for hydropower development; countries like Brazil, China and Democratic Republic of Congo will experience a boom in dam construction in near future (Zarfl et al 2015). Part of this development is an effort to decrease the emission of greenhouse gases. However, sustainable expansion based on developing renewable electricity generation in developing countries may result in the construction of large projects that fail to fully consider the environmental, social and economic consequences (Ansar et al 2014).

Good planning is required not only for individual projects, but also for integrated development throughout the basin with the aim to conserve environmental and social aspects while producing electricity with as low impact as possible (Ziv et al 2012). In this sense, even in a scenario of increasing demand for energy, the removal of dams could have a central role in basin management, mainly because there are several obsolete hydroelectric plants with silted reservoirs, or built without a proper analysis of social/environmental costs and energy generation.

In Brazil there are 4,673 electrical developments registered by the National Energy Electricity Agency that are able to produce 152,356,283 kW. Of these, 1,266 are Hydropower plants of different sizes with an installed potential of 98,239,061 kW. Approximately 95% of this production are produced by relatively few dams (219), and around 83% of the total existing dams (small dams) in Brazil contribute with less than 4% of the total electricity produced in the country (ANEEL 2017). Most of hydropower plants installed in Brazil are small (ANEEL 2017), but they can cause similar environmental impacts (fragmentation, regulation, habitat loss) as large dams (Graf 1999, Zimmy et al. 2013, Klunne 2015, NID 2016, ANEEL 2017). Therefore, integrated development, including consideration of environmental, social and economic issues, should consider dam removal as a management option to improve environmental conservation, social welfare and responsible economic development.

Unlike several developed countries that have their rivers almost completely regulated by dams (Graf 1999, Zimmy et al 2013), Brazil and others developing countries maintain their hydrographic networks in a relatively good condition, and large stretches retain pristine conservation status (Winemiller et al 2016). It is necessary to think in the long term before habitat loss and fragmentation reach levels that will cause species loss that can be difficult to restore, even following dam removal.

FINAL REMARKS

The use of hydroelectric energy has increased, and it will be one of the main alternatives to meet electricity demand and avoid further greenhouse gas emissions in the future. In this context, developing countries will have a fundamental role to reach the goal intended by international agreements regarding the reduction of greenhouse gas emissions. However, such expansion will cause impacts to important regions for the conservation of aquatic environments and their surroundings (*e.g.* marginal lakes, flood plains, tropical forests).

Therefore, dam removal would only be a possible management measure if immediately integrated into the national environmental and energy strategies of these countries. It could represent a more effective tool for medium to long-term environmental restoration (Hart et al 2002, Fox et al 2016), even in a scenario of growing river regulation and fragmentation.

In this context, Brazil could experience its first dam removal in the near feature. The ANEEL (The Brazilian power national agency) required the CEMIG (Minas Gerais Power Company) to conduct a feasibility study to remove a small hydropower plant in the north of Minas Gerais state. The plant is located on the Pandeiros River, inside a mosaic of conservation areas, including National Parks (*e.g.* Peruaçu caves national park and Grande Sertão Veredas national park), and State protected areas (*e.g.* State Wildlife Refuge - Pandeiros).

The Pandeiros Power plant has a small dam (9 meters), which generated less than 30 MW up until 2008 when it was disabled. The dam continues to act as a barrier to fish movements, segregating the aquatic communities from the downstream and upstream areas (*e.g*. macroinvertebrates and fishes). Investigations have been conducted to improve the understanding of the dam's impact on the river's fauna in order to assess the feasibility of such removal. This is the first documented case assessing the possibility of removing a dam in South America. In the near future, this potential decommissioning will provide the first information on the capacity of tropical rivers to recover in South America, including the responses of river biota.

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ARTIGO 2

Subsidies for removal of a dam: Fish fauna of Pandeiros River
(formatação segundo a revista Neotropical Ichthyology)

ABSTRACT

The impacts of hydropower plants are varied and context dependent. However, the natural flow regime changes and hydrological connectivity losses are inherent in almost all the dams from smaller to power plants with huge reservoirs. These impacts cause profound changes in the aquatic system and biodiversity that depends on the dynamics and environments without of physical and physiological barriers. So several techniques have been developed to mitigate such impacts, although these techniques are usually inefficient and this scenario is worse in tropical. In this context, the removal of dams is an option that can restore not only populations of certain stretches, as well as the entire river dynamics found before the construction of the dam. Thus, this study has as main objective to assess the impacts of a small hydroelectric plant on fish community discussing the effects of a possible dam removal. We sampled during two years (2014 to 2016) along eight sites in the Pandeiros River. It were identified 2821 individuals belonging to 62 species from four orders. We observed an influence of the dam in the differentiation of ecological attributes between the fish assemblages above and below the dam. Richness and diversity were attributes that showed higher values in downstream region and the composition were different between the assemblages separated by the dam. Thus, it was possible to identify the influence of the dam on hydrological connectivity causing such differences, and also impacts on natural flow regime, mainly in regions immediately upstream from the dam. Therefore, the SHP Pandeiros despite its reduced size is still a source of impact on the aquatic environment, considering the ichthyofauna, and its removal probably the restructuring of fish assemblages, returning the features previous to the dam.

Keywords: Fish community – Dam impacts – Decommissioning of a dam - Floodplain

Introduction

Energy production is essential to the development of contemporary society. One of the sources of energy whose demand has been notably growing is water, resulting in the damming and regulation of rivers worldwide (Nilsson et al. 2005, IEA 2015). However, despite being a renewable energy source, the use of hydropower plants is not free of environmental impacts, including those related to climate change (Fearnside 2004, Fearnside & Pueyo 2012, Deemer et al. 2016), and some of these effects are intensified as the number of plants increase in a river (Barbosa et al. 1999, Rosenberg 1997, Rosenberg 2000).

The negative impacts of hydroelectric power plants, both above and below the dam, are widely studied and well documented in aquatic ecosystems around the world (Agostinho et al. 2007, Poff & Hart 2002, Winemiller et al. 2016). They are mainly related to alterations on natural flow regime and hydrological connectivity (Poff et al. 1997, Pringle 2003).

The natural flow of rivers is considered the main factor determining their physical habitats and their aquatic community structure (Bunn & Arthington, 2002). Hence, the resultant changes in the natural flow regime to meet power demand generally cause changes in organisms that live in this environment, from algae and aquatic plants to invertebrates and fishes (Bunn & Arthington, 2002). All the components of the natural flow (magnitude, frequency, duration, timing and rate of change) are essential to the river's ecological integrity (Poff et al. 1997), and can be modified by hydropower plants (Poff et al. 1997, Mims & Olden 2013).

Hydrological connectivity is the water-mediated transfer of matter, energy or organisms between and/or within the elements of the hydrological cycle (Pringle 2001). Crook et al. (2015) list three areas of knowledge required for a strategy to mitigate against connectivity loss on aquatic environments: (1) Autoecology - the knowledge of species-specific relationships between the individual and their environment are essential to understand how habitat changes caused by connectivity loss can affect certain populations. (2) Population structure - population structure studies have supported the development of conceptual models of ecological connectivity in rivers, in addition to being critical to understanding the effects of translocation of organisms or artificial connection of elements of the hydrological cycle. (3) Environmental tolerance/Phenotypic plasticity – identify the species that have less dispersion capacity and lower resilience to environmental alterations, and can help to avoid local extinction by connectivity alteration.

Despite being well known, the impacts of dams are rarely mitigated against. This is particularly true in the tropics (Pompeu et al. 2012, Pelicice et al. 2015a), where alternative measures that are widespread in temperate zones, such as fish passages, can even create additional impacts (Agostinho et al. 2007, Pelicice & Agostinho 2008). In such context, dam removal arises as a potential measure to reverse a whole range of impacts caused by the dam (Bednarek 2001, Poff & Hart 2002, Lovett 2012). However, the decommissioning of hydropower plants as a restoration strategy has mainly been restricted to North America and Europe (Stanley & Doyle 2003, O´Connor et al. 2015).

The process of removing a dam can cause not only negative environmental impacts, but also generate economic and social conflicts (Stanley & Doyle 2003, Lejon et al. 2009, Fox et al. 2015). Therefore, it is necessary to identify the cost and benefits of removal. Dam removal can cause different impacts, in different timescales, the most important of which is considered to be sediment release from the reservoir (Grant 2001, Poff & Hart 2002, Ashley et al. 2006, Service 2011, East et al. 2015). However, even the biggest dam removal study to date has demonstrated the ability of rivers to restore natural conditions (East et al. 2015). Therefore, removing a dam is a complex decision that incorporates different economic, ecological, social and safety aspects.

In South America there are no available studies regarding dam decommissioning and its potential effects on fish communities. The Pandeiros small hydroelectric plant (SHP Pandeiros) is located on the river of the same name, in Southeast Brazil. Due to the accelerated sedimentation process of the reservoir, the dam regularly discharged sediment. As the dam’s operation was not properly monitored in order to understand its environmental impact, the power company decided to stop power production in the SHP Pandeiros in 2007, after receiving environmental fines. In 2010, the Brazilian national electric energy agency (ANEEL) recommended a viability study to remove the Pandeiros dam.

The main goal of this study is to evaluate the influence of the SHP Pandeiros on ecological attributes (richness, composition, diversity, and seasonal changes) of fish assemblages along the Pandeiros River to understand the potential benefits of removing the Pandeiros dam on the local fish community.

Material and Methods

Study area

The São Francisco River basin is one of the major river basins of South America, and covers about 7.5% of Brazil’s land area. The basin contains a great fish diversity with high levels of endemism (Carolsfeld 2003, Godinho & Godinho 2003, Abell et al. 2008). The middle part of São Francisco River is known to harbour a complex and rich floodplain with marginal lakes (Godinho & Godinho 2003, Carolsfeld 2003). These areas can act as breeding and initial development areas for several species, including migratory fishes, which are the most important species to the commercial fishery in the São Francisco River basin (Camargo e Petrere 2001). The Pandeiros River is a tributary of the left bank of the São Francisco River, and has a huge floodplain in its lower course, connected to the middle São Francisco floodplain system.

In 1992, the Pandeiros River became a “permanent preservation river” (Minas Gerais State law 10.629). It is considered a migration route and a fish spawning site, and is approximately 145 kilometres in length. In the lower course of the Pandeiros River, the floodplain has an area of 50 km², and it is considered an important nursery area for migratory fishes (Carolsfeld 2003, Nunes et al. 2009).

The SHP Pandeiros (Lat 15°30'14.87"S; Lon 44°45'27.59"O) is located 50 km upstream of the mouth of the Pandeiros River. The power plant began operation in 1958, with a reduced flow stretch of around 600 meters. The dam has a maximum height of 10.3 meters with 0,28 km² flooded by the reservoir (Fonseca et al. 2008). Downstream of the dam there are three waterfalls, two of them between the dam and the powerhouse, the largest about 9 meters high. The power plant stopped operation in 2008, when the river began to flow entirely through the natural channel. Nonetheless, despite being non-operational the SHP Pandeiros physical structure still regulates the water level above the dam. The reservoir is completely filled with sediment, resulting in a small, shallow and lotic reservoir, and a lateral lake, which was once temporary, but nowadays is perennial and regulated by the dam.

Fish sampling

Fish collections were carried out over two years (2014 to 2016), comprising five samples in the dry season (Jul/14; Sep/14; Apr/15, Jun/15 and Sep/15) and six in the wet season (Nov/14, Dec/14, Jan/15, Feb/15, Dec/15, Feb/16). Eight sample sites were distributed along the Pandeiros River (Figure 1), encompassing four distinct segments of the basin (upper river, impounded areas, lower river and floodplain), and the regions upstream and downstream of the dam (Tab. 1).

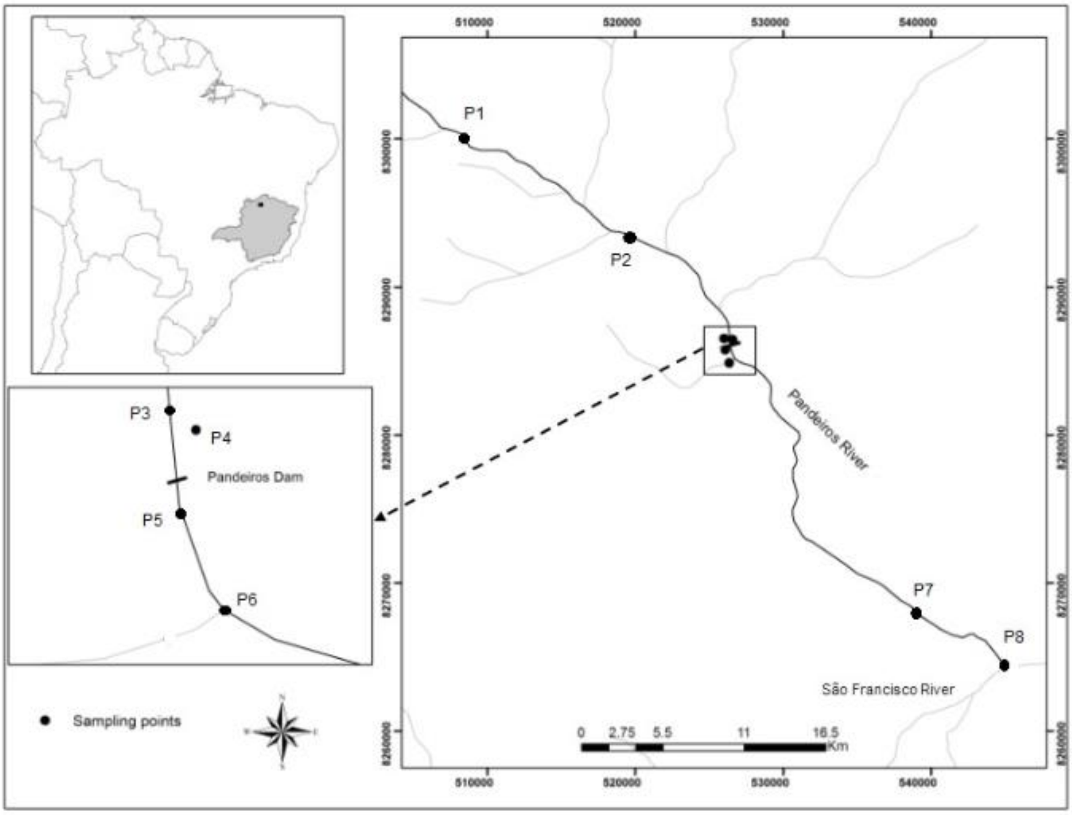


Figure 1 – Distribution of study sites along Pandeiros River, with focus on the region near the Pandeiros dam.

Table 1. Location of sampled sites with a brief description and separation in segments.

Sites	Region (upstream and downstream)	Segments	Coordinates	Description
Site 1	U	Upper	15°22'55.69"S/ 44°55'26.65"W	Site further away from the dam, sandy substrate with some riffle
Site 2	U	Upper	15°26'27.25"S/ 44°49'14.83"W	Site upstream without dam influence, rocky substrate with rifle
Site 3	U	Impounded	15°29'55.34"S/ 44°45'27.41" W	Reservoir site, sandy substrate
Site 4	U	Impounded	15°29'57.61"S/ 44°45'8.26" W	Lateral lake site, macrophytes substrate
Site 5	D	Lower	15°30'20.03"S/ 44°45'24.24" W	Site between dam and waterfalls, rocky substrate
Site 6	D	Lower	15°30'48.63"S/ 44°45'15.03" W	Site below the waterfalls, rocky and gravel substrate
Site 7	D	Floodplain	15°40'11.11"S/ 44°38'11.46" W	Site on the river in the floodplain, sandy substrate
Site 8	D	Floodplain	15°41'46.06"S/ 44°34'30.01" W	Marginal lake in the floodplain, near the São Francisco river

Fish were sampled using a set with 10 gillnets per site with mesh sizes ranging from 12 mm to 60 mm between opposite knots, armed for 12 hours. To capture smaller species, sampling was also conducted with sieves made from mosquito net (80 cm in diameter, 1 mm mesh) and seine net (3 m long, 5 mm mesh) in Jan/15, Feb/15 Apr/15 and Dec/15. These data from smaller species was not used to data analysis and were used only to improve knowledge of the number of species in the river basin.

The specimens collected were fixed in 10% formalin and taken to the Fish Ecology laboratory, at the Federal University of Lavras (UFLA) in Minas Gerais, where they were transferred to 70% alcohol and subsequently deposited at the UFLA Fish Collection (CI-UFLA).

Data analysis

The list of fish species in the Pandeiros river basin was updated based on previous studies (Godinho 1986, Alves & Leal 2010, Santos et al. 2015). Sampling efficiency was evaluated for both upstream and downstream regions using species accumulation curves with 1000 permutations, using the gillnet data.

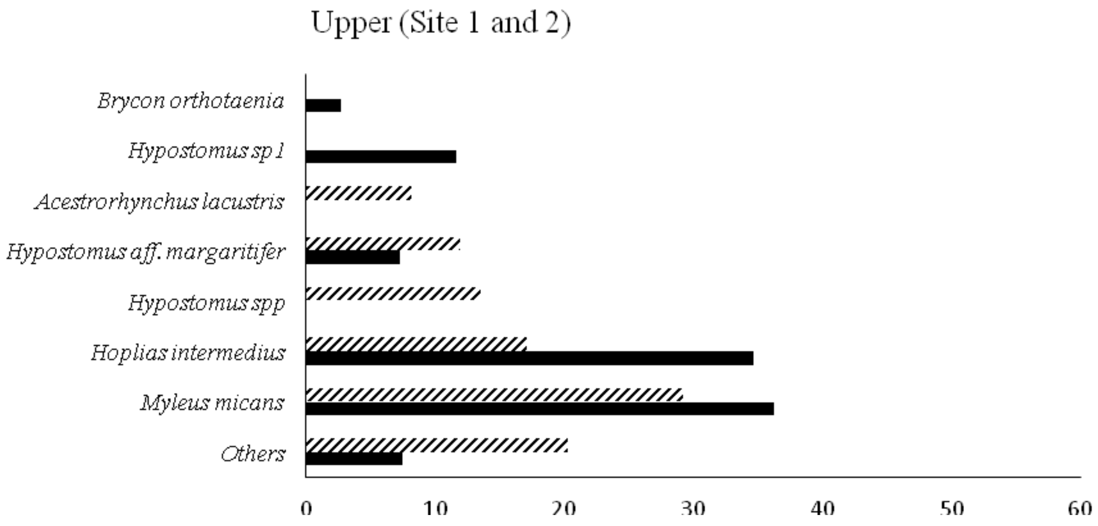
The Student’s t test was used to test for differences in richness and Shannon diversity between upstream and downstream sites with no separation between dry and wet season. The data were tested for normality and when necessary a logarithmic scale transformation was used.

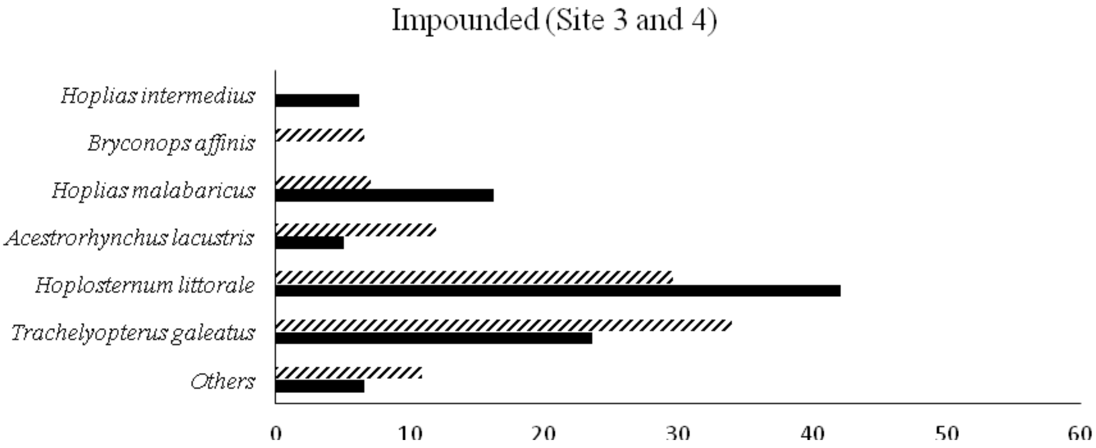
To test whether if the dam influence on variation seasonal (wet and dry season) and composition between the assemblages above and below the SHP Pandeiros were used nMDS and PERMANOVA using standardized CPUEn (catch-per-unit-effort in numbers; number of individuals/m²*12h^{-1}) from the gillnet data.

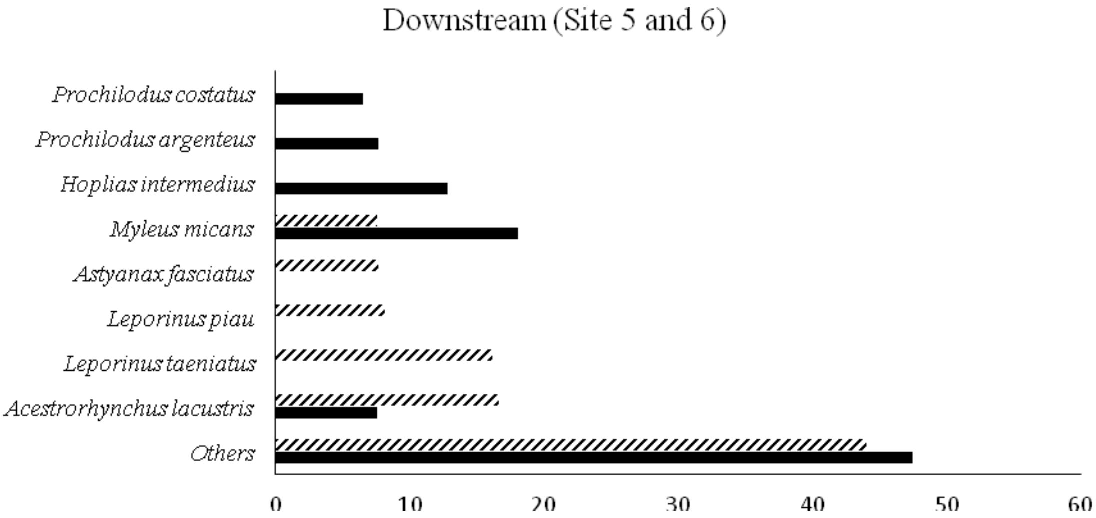
To understand the dam influence on each site were conducted PERMDISP tests of homogeneity of dispersions (a proxy of heterogeneity) to compare if the closest sites of the dam has lower variation along sampling events, were used CPUEn and CPUEb (catch-per-unit-effort in numbers biomass; grams/m²*12h^{-1}) from the gillnet data. The Tukey *post hoc* test for pairwise comparison was used to test for significant variation between sites. All analyses were carried out using R statistical software (Oksanen et al. 2015).

Results

A total of 2821 individuals belonging to four orders and 62 species were collected (Table 2). Incorporating previous studies, 88 species have now been registered for the entire basin (Table 3). Different species were most abundant in different segments (Fig 2), with a greater abundance of migratory species being observed in the lower and floodplain segments, and the massive presence of exotic species at the impounded sites (Tab 2).




Impounded (Site 3 and 4)
Hoplias intermedius
Bryconops affinis
Hoplias malabaricus
Acestrorhynchus lacustris
Hoplosternum littorale
Trachelyopterus galeatus
Others
0
10
20
30
40
50
60


Downstream (Site 5 and 6)
Prochilodus costatus
Prochilodus argenteus
Hoplias intermedius
Myleus micans
Astyanax fasciatus
Leporinus piau
Leporinus taeniatus
Acestrorhynchus lacustris
Others
0
10
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50
60

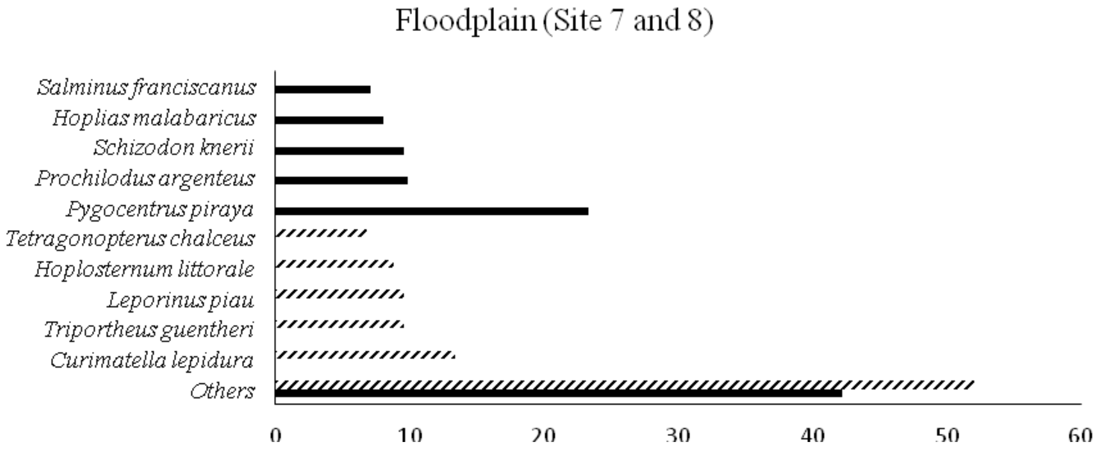

Floodplain (Site 7 and 8)
Salminus franciscanus
Hoplias malabaricus
Schizodon knerii
Prochilodus argenteus
Pygocentrus piraya
Tetragonopterus chalceus
Hoplosternum littorale
Leporinus piau
Triportheus guentheri
Curimatella lepidura
Others
0
10
20
30
40
50
60

Figure 2 Percentage of most abundant (CPUEnumeric and CPUEbiomass) species in the four segments of the Pandeiros River. The x-axis is percentage of CPUE (black bar is biomass and dashed bar is numeric). See Fig 1 and Tab 1 for details of the sampled sites.

Table 2. Number of individuals (**N**) per species sampled in each site along the Pandeiros River (E = exotic species; M = migratory species). See Figure 1 and Table 1 for details of the sampled sites.

Species	P1	P2	P3	P4	P5	P6	P7	P8	**N**
Acestrorhynchus lacustris	12	8	25	97	42	102	5	3	294
Apareiodon spp.					2				2
Astronotus ocellatus^E								1	1
Astyanax fasciatus	12	8	3		43	23	1		90
Astyanax lacustris	8		10	7	4	27	4	3	63
Brycon orthotaenia^M		2					3	3	8
Bryconops affinis		1	17	53			1	1	73
Centromochlus bockmanni	5								5
Characidium lagosantense				1					1
Characidium zebra	4								4
Cichla piquiti^E							1		1
Cichlasoma sanctifranciscense	2	3	4	26				6	41
Corydoras multimaculatus	8								8
Crenicichla lepidota						1		2	3
Cyphocharax gilberti								7	7
Curimatella lepidura						43	6	61	110
Eigenmannia virescens	6	5	1		2		1	1	16
Gymnotus carapo	1		1	5				1	8
Hemigrammus marginatus			1	5			3		9
Hisonotus sp.	8	6				5	1		20
Hoplerythrinus unitaeniatus				1					1
Hoplias intermedius	15	31	6	7	20	27	1	4	111
Hoplias malabaricus			18	56		19		14	107
Hoplosternum littorale	3	1	12	304				45	365
Hypostomus aff. alatus						4			4
Hypostomus aff. margaritifer	2	28	11		42	20			103
Hypostomus sp1	7	28	3		26	3			67
Hypostomus spp			1		3	13			17
Leporellus vittatus						3			3
Leporinus obtusidens^M			1		2	1	1		5
Leporinus piau						71	10	38	119
Leporinus reinhardti^M						21	4	23	48
Leporinus taeniatus						140		1	141
Lophiosilurus alexandri						1	3		4
Metynnis lippincottianus			4	10		3		1	18
Moenkhausia sanctae-filomenae							1		1
Myleus micans	38	45	19	3	58	13	2		178
Orthospinus franciscensis				1			6	1	8
Pachyurus francisci								1	1

Pamphorichthys hollandi			6						6
Parodon hilarii		2			3	1			6
Phenacogaster franciscoensis		3					5		8
Pimelodus fur								2	2
Pimelodus maculatus^{M}						2		16	18
Prochilodus argenteus^{M}						10	6	22	38
Prochilodus costatus^{M}						11		5	16
Pseudoplatystoma corruscans^{M}								3	3
Pterygoplichthys etentaculatus							1	1	2
Pygocentrus piraya							20	9	29
Rhamdia quelen					1	2			3
Rineloricaria pentamaculata						1			1
Salminus franciscanus^{M}						8	5	15	28
Schizodon knerii						18	4	28	50
Serrapinnus piaba	4		3						7
Serrassalmus brandtii						1	5	26	32
Steindachnerina elegans	1	9			4	7		3	24
Sternopygus macrurus								1	1
Tetragonopterus franciscoensis						20	15	19	54
Trachelyopterus galeatus	2	3	41	309	10	9		6	380
Triportheus guentheri							11	37	48
Total	138	183	187	885	262	630	126	410	2821

Table 3. Comparison of the species collected in the different studies performed in the Pandeiros River basin.

Species	**Godinho 1986**	**Alves & Leal 2010**	**Santos et al. 2015**	**Current**
Anchoviella vaillanti	X			
Acestrorhynchus britskii	X			
Acestrorhynchus lacustris	X	X	X	X
Apareiodon spp.				**X**
Astronotus ocellatus				**X**
Astyanax fasciatus	X	X	X	X
Astyanax lacustris		X	X	X
Astyanax rivularis			X	
Australoheros facetum		X		
Brycon orthotaenia	X	X	X	X
Bryconamericus stramineus			X	
Bryconops affinis		X	X	X
Centromochlus bockmanni				**X**
Characidium fasciatum	X			
Characidium lagosantense		X		X
Characidium aff. *zebra*		X	X	X
Cichla piquiti			X	X
Cichla ocellaris		X		
Cichlasoma cf. *facetum*			X	
Cichlasoma sanctifranciscense	X		X	X
Corydoras multimaculatus	X		X	X
Corydoras polystictus		X		
Crenicichla lepidota	X	X		X
Curimatella Gilberti				**X**
Curimatella lepidura	X	X	X	X
Cyphocharax gilbert		X		
Eigenmannia virescens	X	X	X	X

Gymnotus carapo	X	X		X
Harttia longipinna			X	
Hemigrammus marginatus	X	X		X
Hisonotus sp.		X		X
Hoplerythrinus unitaeniatus		X	X	X
Hoplias intermedius	X	X	X	X
Hoplias malabaricus	X	X	X	X
Hoplosternum littorale		X	X	X
Hypostomus spp.		X		X
Hypostomus aff. *alatus*				**X**
Hypostomus aff. *margaritifer*				**X**
Hypostomus francisci			X	
Hypostomus lima			X	
Hypostomus sp1				**X**
Hyphessobrycon santae		X		
Hyphessobrycon sp.		X		
Imparfinis minutus		X		
Leporellus vittatus			X	X
Leporinus macrocephalus		X		
Leporinus obtusidens	X	X	X	X
Leporinus piau	X	X	X	X
Leporinus reinhardti	X	X	X	X
Leporinus taeniatus	X	X	X	X
Lophiosilurus alexandri	X			X
Metynnis lippincottianus				**X**
Moenkhausia costae	X	X		
Moenkhausia sanctaefilomenae	X	X	X	X
Myleus altipinnis			X	
Myleus micans	X	X	X	X
Orthospinus franciscensis	X	X		X
Pachyurus francisci	X			X
Pachyurus squamipinnis	X			
Pamphorichthys hollandi		X		X
Parodon hilarii			X	X
Pimelodella cf. *lateristriga*	X	X	X	
Pimelodus fur	X			X
Piabina argentea			X	
Phenacogaster franciscoensis				**X**
Pimelodus maculatus	X	X	X	X
Planaltina sp.			X	
Prochilodus argenteus	X	X	X	X
Prochilodus costatus	X	X		X
Psellogrammus kennedyi		X		
Pseudoplatystoma corruscans	X	X	X	X
Pterygoplichtys etentaculatus	X	X	X	X
Pygocentrus piraya	X	X	X	X
Rhamdia quelen				**X**
Rineloricaria pentamaculata				**X**
Roeboides xenodon	X	X		
Salminus franciscanus	X	X	X	X
Schizodon knerii	X	X	X	X
Serrapinnus heterodon		X		
Serrapinnus piaba	X	X		X
Serrasalmus brandtii	X	X	X	X
Steindachnerina elegans	X	X	X	X
Sternopygus macrurus		X		X
Synbranchus marmoratus		X		
Tetragonopterus chalceus	X	X		X
Trachelyopterus galeatus	X	X	X	X
Trichomycterus sp.			X	

Triportheus guentheri	X	X

Among the 52 species sampled only with gillnets, 51 were captured in the downstream section of the river and 22 were captured upstream. The accumulation curves in both regions had the same inclination pattern, with both next to the asymptote (Figure 3). Only one species was restricted to the upstream region (*H. unitaeniatus*) and 30 species were captured exclusively downstream of the dam. Fish richness (Student's t test, t = 3.82, $P < 0.05$; Figure 4) and diversity index (Student's t test, t = 3.71, $P < 0.05$; Figure 5) were higher downstream of the dam.

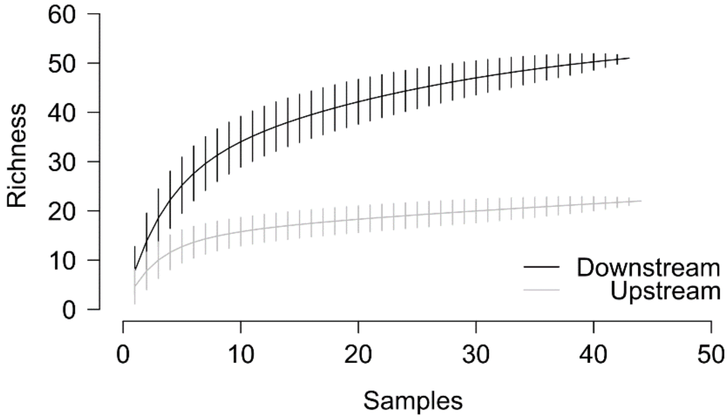


Figure 3 Species accumulation curves for upstream and downstream regions to the SHP Pandeiros with 95% confidence intervals (vertical lines).

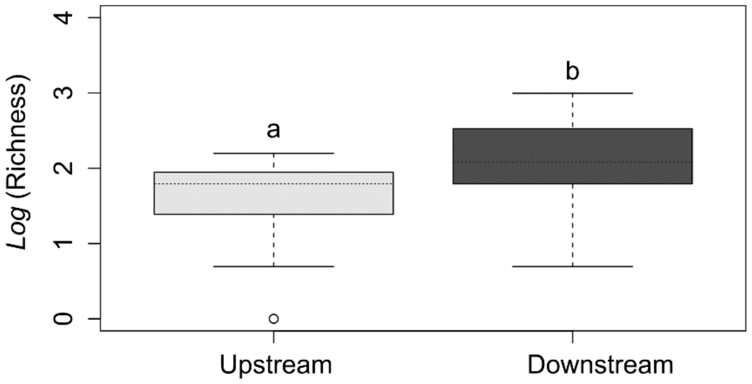


Figure 4 Box plot diagram of richness (logarithm) between upstream and downstream regions on Pandeiros River. The upper and lower boundaries represent the quartiles, the horizontal bar represents the median. The regions are significantly different (P > 0.05).

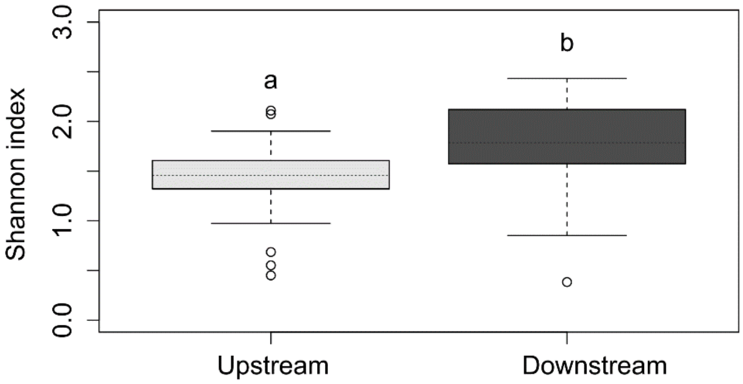
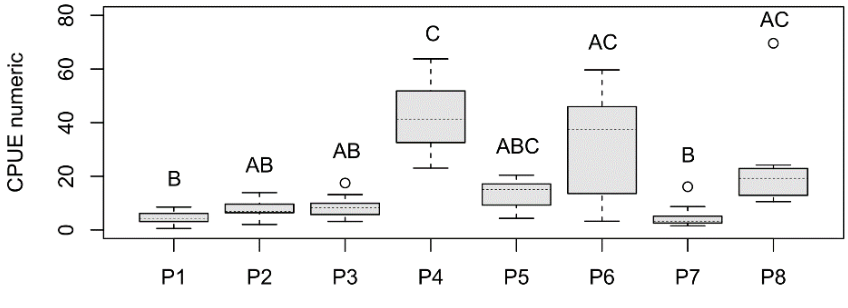


Figure 5 Box plot diagram of Diversity Shannon Index between upstream and downstream regions on Pandeiros River. The upper and lower boundaries represent the quartiles, the horizontal bar represents the median. The regions are significantly different (P > 0.05).

CPUEn and CPUEb were highest in the lateral lake (P4), whilst CPUEn was also high at the site located below the falls (P8) (Figure 6).



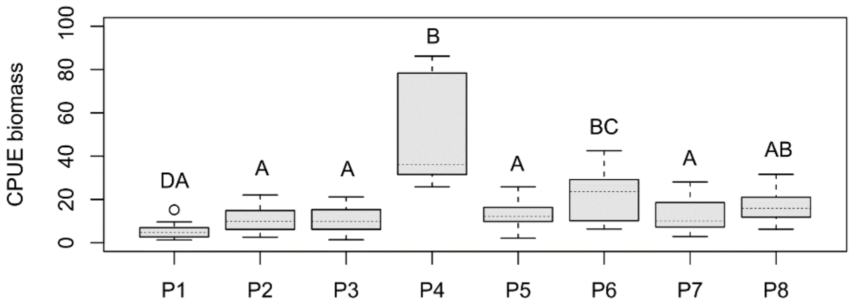


Figure 6 Box plot diagram of catch per unit effort (CPUE) in number of individuals and biomass between all sites sampled on Pandeiros River. The upper and lower boundaries represent the quartiles, the horizontal bar represents the median. The sites with the same letter are not significantly different (P > 0.05).

There were differences in the fish assemblages between the upstream and downstream regions (PERMANOVA: Pseudo-F = 8.05; P = 0.001) (Figure 7), and no differences in fish assemblages were observed between the dry and wet seasons (PERMANOVA: Pseudo F = 0.62; P = 0.83).

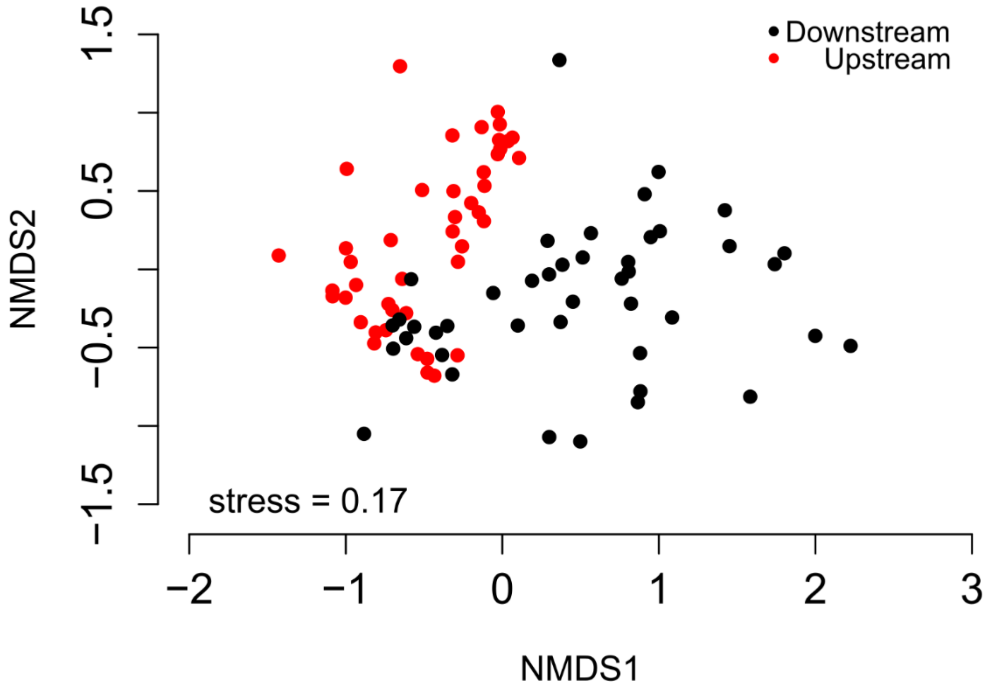


Figure 7 Non Multidimensional scaling (nMDS) plots relating CPUE numeric for different fish species at sites upstream and downstream to SHP Pandeiros.

Based on assemblage dissimilarity comparisons, the average distance from the centroid varied between sites (PERMDISP, $F_{7,\ 79}$ = P < 0.001). The lowest average distance from the centroid was found at the lateral lake (site 04), while highest was found at the Pandeiros River at the floodplain (site 07) (Figure 8).

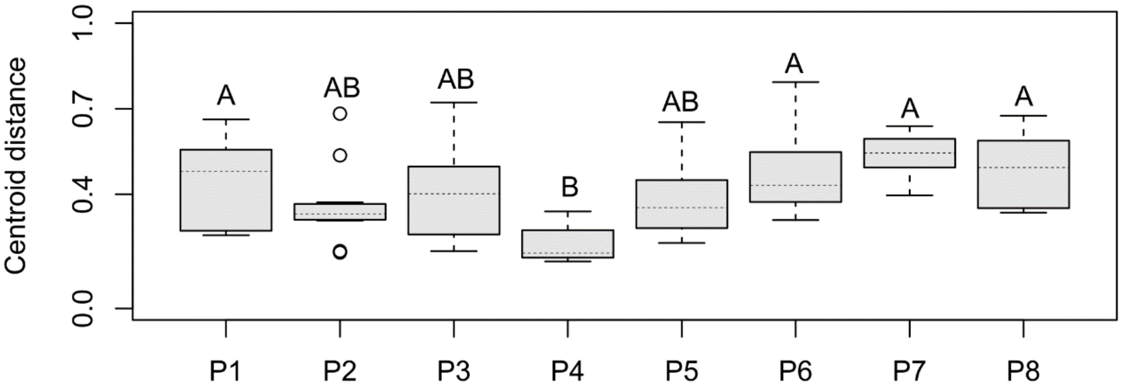


Figure 8 Box plot diagram of CPUE numeric representing results from PERMDISP between all sites sampled on Pandeiros River. The upper and lower boundaries represent the quartiles, the horizontal bar represents the median. The sites with the same letter are not significantly different (P > 0.05).

Discussion

The impacts of hydroelectric power plants on the aquatic environment are well documented globally, especially those of large companies (Nilsson et al. 2005, Agostinho et al. 2005, Winemiller et al. 2016). On the other hand, the impacts of small dams are poorly studied (Benstead et al. 1999, Cumming 2004, Santos et al. 2006), and in some cases neglected, and restricted to environmental impact reports. This study demonstrates the influence of the Pandeiros Hydropower plant, even when not in operation, on fish assemblages. Greater richness and diversity were observed below the dam, and large changes in the fish assemblages were mainly observed at the sites influenced by the dam. Moreover, the dam still seems to act as a barrier to fish displacement, restricting the existence of several migratory species in the upstream areas.

Knowledge of the Pandeiros River fish diversity has previously been concentrated on the floodplain (Godinho 1986, Alves and Leal 2010). A single study was conducted in other regions of the basin, but it covered just four sites (Santos et al. 2015). Our study recorded 11 fish species previously undocumented in the Pandeiros river basin, which is now known to harbour 30% (88 species) of the fish species in the São Francisco river basin. However, the basin richness may still be higher if we take into account that there are still smaller headwater streams that shelter a rich fauna of small sized fish species (Pompeu et al. 2009) that have not been explored in previous studies.

The species accumulation curves are useful to indicate sampling efficiency using a particular biological sampling tool, as well as to compare regions where they were employed (Magurran 1998, Gotelli & Colwell 2001). The general curves created in this study indicate that most of the fish species that could be captured with gillnets were registered. Therefore, the species richness sampled with gillnets gave us a reliable scenario of regional diversity in order to compare fish assemblages along the Pandeiros River, and the possible effects of the dam.

Migration can be defined as synchronized movements that go beyond a species home range, occurring at a specific stage of their life cycle (Lucas & Baras 2001). Migratory fishes are normally of great economic importance and perform fundamental ecosystem functions (Lucas & Baras 2001). In the São Francisco River basin, they are highly valued and are the main targets for commercial fishing (*e.g.* “dourado” (*Salminus francsicanus*), “surubim” (*Pseudoplatystoma corruscans*), “curimba” (*Prochilodus* spp.)). In this basin, these fish use tributaries such as Pandeiros River for both spawning and refuge against predators (Godinho & Pompeu 2003).

Among the long-distance migratory fishes of the São Francisco River basin, just the pirá (*Conorhynchus conirostris*) and tabarana (*Salminus hilarii*) were not registered during this study. These species were not sampled in previous studies either, indicating that they do not occur naturally in this region. This study shows that the Pandeiros River is a migration route for fish and its floodplain is used as a nursery area. The statement that 70% of the nursery areas in the São Francisco River basin is provided by the Pandeiros River floodplain (Fonseca et al. 2008) is exaggerated and lacks empirical support. However, the capture of large number of migratory species (juvenile and adult), and the presence of endangered species (*Lophiosilurus alexandri*) along the Pandeiros justifies its categorization as a permanent preservation area, and also the existence of the State Refuge Wildlife Pandeiros River (10.629 State law of 1992 and Decree No. 43.910 of 2004).

Our study demonstrates that the Pandeiros River is widely used by most migratory fishes of the São Francisco River basin. However, most (~ 98%) of the migratory species individuals collected were found downstream of the Pandeiros dam. Only three individuals of two species (*Brycon orthothaenia* and *Leporinus elongatus*) were registered upstream. These species are usually abundant in lotic segments in the São Francisco basin (e.g. Alves & Pompeu, 2001), indicating they are probably from relictual populations isolated by the dam. The occurrence of these species upstream, and the presence of a non-functional fish ladder by the dam, indicates that the waterfalls, at least during the highest floods, were not an obstacle for fish migration. In addition, the presence of migratory species immediately below the dam and between the waterfalls also demonstrates that they are able to pass by the waterfalls.

Many researchers indicate that the introduction and establishment of alien species is one of the main causes of species loss in aquatic environments (Allan & Flecker 1993, Dudgeon 2006). Moreover, the chance of the introduction of exotic species having negative effects is greater than the chance of having positive or neutral impacts (Vitousek et al. 1996, Simberlof et al. 2003, Simberloff et al. 2013, Pelicice et al. 2015b). In some cases, the construction or maintenance of dams can prevent the dispersal and migration of alien species (Port et al. 1999), so their distribution should be evaluated carefully in a context of dam removal (Simberloff et al. 2013).

In this study, we observed the presence of three exotic species. Their introduction is likely to be linked to deliberate introduction for sport fishing (*C. piquiti*), and accidental (improper disposal or escape) introduction related to fishkeeping (*A. ocellatus* and *M. lippincottianus*). The species *A. ocellatus* and *C. piquiti* were each represented by a single individual in the floodplain region. This density demonstrates that populations are not yet fully established, which can hide the negative effects of introduction. Although *C. piquiti* was collected in 2008 by Santos et al. (2015), greater attention should be paid to this species mainly in lentic environments, because when the species establishes it usually modifies the structure and dynamics of the native fish community (Pompeu & Godinho 2001, Pelicice et al. 2015b). The most abundant exotic species (*M. lippincottianus*) was collected above and below the SHP Pandeiros, but with higher abundance in the impounded sites, indicating that the flow modification may favor the invasion (Didham et al. 2007). *H. littorale* has been considered an exotic species in the São Francisco basin, although there are still doubts about the real distribution of the species (Pompeu & Alves 2003, Alves & Leal 2010, Salvador Jr. & Silva 2011). Regardless of its natural distribution, 83% of the individuals of this species were captured in the lateral reservoir lake.

The factors that influence the fish richness in rivers are diverse and may vary according to the scale analysed (Cumming 2004). Changes to the aquatic community usually follow a longitudinal pattern, from small streams to large rivers, but these changes are gradual and occur in a continuum of physical and biotic variation in the aquatic environment (Vannote et al. 1980). However, the impact of dams, even those small in size, are usually significant and negatively affect fish richness (Anderson et al. 2006). Our study shows the same pattern usually found in other studies where the region downstream of the dam has a significantly higher species diversity (Reyes-Gavilán et al. 1996; Port et al. 1999; Gehrke et al. 2002, Nilsson et al. 2005). This difference occurs primarily because the dam hinders colonization of upstream areas. Similarly, waterfalls can act as natural barriers for species dispersal and can define a region’s fish community (Abell et al. 2008). On the other hand, the lower course is connected with other larger rivers, a situation that usually provides great diversity (White et al. 2012).

Environments altered by humans commonly feature communities dominated by few species in large abundance (Hillebrand et al. 2008), and lower temporal heterogeneity (Ward, 1998; 1999). This dominance and homogeneity can be related to several factors such as the absence of predators and competitors in an altered environment, habitat changes and/or homogenization and attenuation of seasonal variations (Hillebrand et al. 2008), and factors that both impairs the permanence of species sensitive to variations and assists those more tolerant to disturbances. The main species responsible for the observed dominance in the lateral lake (*T. galeatus*, *H. littorale*, *A. lacustris*) are usually found in lentic environments (Fernandes et al. 2009, Maia et al. 2013), including reservoirs. These species (the first two) are also often found in eutrophic environments and are adapted to low rates of dissolved oxygen in the water (Affonso & Rantin 2005, Sánchez-Botero et al. 2008).

The present work indicates that the SHP Pandeiros, even deactivated, is still a source of impact on fish assemblages along the Pandeiros River, with marked effects on fish distribution and on the community structure in the impounded areas. The removal of SHP Pandeiros would provide an opportunity to observe changes on the river and on the fish communities that bear a greater resemblance with their natural condition before the construction of the dam.

The dam removal would enable exchange of some species and the increase of gene flow between the upstream and downstream regions reducing the observed differences in the fish assemblages. An increase in the abundance of migratory fishes in upstream areas would be highly likely. After the dam removal, and the return of the impounded areas to the natural flow regime, a drastic change in the fish communities in the lateral lake would be expected, with a possible reduction of tolerant species, including those alien species. At the reservoir, sediment would be transported to downstream areas, and an increase of the rheophilic species would be expected.

From this study, it is evident that the removal of the Pandeiros dam is adequate in order to provide an opportunity for fish to recover along the basin, possibly bringing more benefits than losses for the fish fauna. We hope that the removal itself, planned for the near future, will bring a new paradigm for developing countries, and this management strategy will be incorporated into conservation on a larger scale (Winemiller et al 2016).

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ARTIGO 3

Longitudinal changes in trophic structure along a regulated tropical river

(formatação Segundo a revista Hydrobiologia)

ABSTRACT

The main objective of this study was to describe the structure of the trophic network of river fish assemblages in four regions along a longitudinal gradient trying to identify the influence of a small hydroelectric plant in this structure. To achieve this, were separated four regions on river for comparison and evaluation of trophic structure, these regions were distributed in a longitudinal gradient with different influence of the dam. The trophic structure were analysed using community-wide trophic metrics based on stable isotopes δ13C and δ15N. The region of the middle course presented greater values of total length of isotopic niche and ranges of carbon and nitrogen. The region directly affected by the dam showed higher differentiation in isotopic niche occupation. We conclude that the trophic structure of the river varied along the longitudinal gradient and the dam altered directly the use and occupation of the isotopic niche fish assemblages and proportion of feeding guilds of each region.

Keywords: Stable isotopes – Food webs – Trophic ecology - Dams

Introduction

The composition of aquatic communities is closely related to the variation in available food, and the interactions between organisms along the river (Junk et al. 1989, Vannote et al. 1980). This dynamic defines some distinct patterns on distribution and composition of species according to the location of the region along the river/basin (Esselman et al. 2006, Ibanez et al. 2007, Araújo et al. 2009). Most of these patterns are related with the stream size and the load and quality of organic matter on rivers and streams (Vannote et al. 1980). Generally, a higher proportion of insectivore, frugivore, and herbivore feeding guilds are expected to be found in the upper reaches of a river, and a predominance of carnivores, omnivores, and detritivores in the lower reaches (Vannote et al. 1980, Aarts & Nienhuis 2003).

The influence and importance of floodplain wetlands on organism interactions was first evidenced as a scientific concept by Junk et al. (1989). One of the key aspects of this concept is that a substantial part of the primary and secondary production originates from the floodplain, and the river is just a means of transport for dissolved and/or suspended matter in the water (Junk et al. 1989). Hence, the dynamic and influence of flooding on river floodplain ecosystems represents a key characteristic of the riverine landscape (Ward et al. 1999).

Anthropic activities cause several impacts to the environment, including changes in the dynamics of biogeochemical cycles (Vitousek et al. 1997). Specifically, the presence of a dam results in a series of changes in the aquatic environment where the flow of organic matter and inorganic chemistry are altered, thereby also modifying biological interactions (Poff et al. 1997, Barbosa et al. 1999).

The elements carbon and nitrogen are fundamental to the formation of living organisms, and are important components of the atmosphere (Peterson and Fry 1987). Therefore, the use of stable isotopes of these elements (^{13}C and ^{15}N) in environmental studies is increasing because they can contribute to a better understanding of the energy transfer between organisms. This can be achieved by identifying the sources and consumers of these isotopes, allowing for the construction of trophic networks and an understanding of how their components are connected (Peterson and Fry 1987, Bearhop et al. 2004, Boecklen et al. 2011). The use of these stable isotopes focuses on the features responsible for the variation in the isotopic signatures of the diets of different organisms (^{13}C), and their trophic position (^{15}N) (Boecklen et al. 2011). However, the use of stable isotopes is not the only approach to investigate trophic networks, and its inference can be biased because there is a large natural variation in the assimilation of these isotopes (Post 2002).

In this context, this tool is becoming an important way to better understand how fish communities and the relationships among species change along rivers (Winemiller et al. 2011). Consequently, it could provide information on how hydropower plants would affect resources assimilation, and help determine the impacts of dam removal on food webs.

This paper aims to describe the food web structures in four distinct regions along the Pandeiros River in Brazil (the upper course, the region under the influence of a dam, the middle course, and the lower course), considering the presence of a small power plant. The following questions were addressed: Are there differences in food resources among regions? Are there differences in the fish trophic structure among regions? And, are the biomass proportions of fish trophic guilds different among regions? These aspects were discussed in the context of the possibility of removing the Pandeiros dam.

Materials & Methods

Study area

The São Francisco River basin is one of the most important basins in Brazil, covering around 645 km² (Araújo-Lima et al. 1995, Kohler 2003). It is the largest river basin that has its entire limits within Brazilian territory. The São Francisco basin harbors around 211 fish species, and along its course fishing plays an important role as a food source for the riverine population (Reis et al. 2016). The most commercially important fish species in the basin are migratory, such as *Pimelodus maculatus, Prochilodus* spp., *Salminus franciscanus* and *Pseudoplatystoma corruscans* (Godinho & Godinho 2003).

The Pandeiros River is an important tributary of the São Francisco River, and a migration route of spawning fish. In the lower course of the Pandeiros River, a huge floodplain (3000 - 5000 ha) is a habitat to a great diversity of organisms (Nunes et al. 2009, Rezende et al. 2012, Lopes et al. 2013). At least 88 fish species use the Pandeiros River as a habitat, for refuge, feeding or reproduction, and the floodplain as a shelter or nursery area (Chapter 2).

The Pandeiros small hydroelectric plant (SHP Pandeiros) (525974.02 m E; 8285899.58 m S) is located 50 km upstream of the mouth of the Pandeiros River, and the dam has a maximum height of 10.3 meters. The power plant began operation in 1958, but was deactivated in 2008 (Fonseca et al. 2008).

Sampling data

Fish samples were carried out over two years (2014 to 2016). In total, eight sample sites were distributed along the Pandeiros River, four of them upstream of the dam (upper and middle reaches of the Pandeiros River basin), and four downstream of the dam (covering the floodplain region of the Pandeiros River). The sites were grouped in four regions, reflecting their position in relation to the dam, and physiographic characteristics of the river (Tab. 1).

Table 1. Location and brief description of sample sites.

Sites	**Region**	Location (upstream and downstream)	Coordinates	Description of the site
1	**1**	U	15°22'55.69"S/ 44°55'26.65"W	Site furthest away from the dam, sandy substrate with some riffle
2		U	15°26'27.25"S/ 44°49'14.83"W	Site upstream, uninfluenced by the dam, rocky substrate with riffle
3	**2**	U	15°29'55.34"S/ 44°45'27.41" W	Reservoir site, sandy substrate
4		U	15°29'57.61"S/ 44°45'8.26" W	Lateral lake site, macrophytes substrate
5	**3**	D	15°30'20.03"S/ 44°45'24.24" W	Site between dam and waterfalls, rocky substrate
6		D	15°30'48.63"S/ 44°45'15.03" W	Site below the waterfalls, rocky and gravel substrate
7	**4**	D	15°40'11.11"S/ 44°38'11.46" W	Site on the river in the floodplain, sandy substrate
8		D	15°41'46.06"S/ 44°34'30.01" W	Marginal lagoon in the floodplain, near the São Francisco River

Stable isotopes analyses were conducted for the most abundant species in each region. Between three and nine individuals of each species were analyzed, totaling 293 isotopic fish samples taken from the white muscle tissue of fishes of similar sizes (Tab. 2).

The possible resources available in each region were also sampled, including leaves of riparian vegetation (RIP), fine particulate organic matter (FPOM), coarse particulate organic matter (CPOM), organic matter in suspension (SUSP), macrophytes (MAC), periphyton (PERI) and macroinvertebrates (MACRO), accounting for over 277 isotopic samples.

The collected samples were frozen for later isotopic composition analysis. In the laboratory, the organisms collected were taxonomically identified using identification keys for fishes of the São Francisco River basin. Smaller fish were analyzed whole, with only the digestive tract removed. Each fish and resource sample was lyophilized for 48 hours and ground to a fine homogeneous powder using a mortar and pestle; approximately 2–5 mg of dry tissue was selected for isotopic analysis.

After preparing the materials, samples were sent for isotopic analysis at the Laboratory of Isotope Ecology, which is linked to the Center for Nuclear Energy in Agriculture (Centro de Energia Nuclear na Agricultura—CENA) at the University of São Paulo (Universidade de São Paulo—USP), Piracicaba. All samples were analyzed for isotope ratios (^{13}C:^{12}C expressed as $\delta^{13}C$ and ^{15}N:^{14}N expressed as $\delta^{15}N$) of the total carbon and nitrogen content. Mass spectrometry (Continuous-flow-Isotope Ratio Mass Spectrometry—CF-IRMS) with a Carlo Erba elemental analyzer (CHN 1110) coupled to a Delta Plus mass spectrometer from Thermo Scientific was used to determine isotope ratios. Results were expressed as relative differences in international reference standards, in the delta notation (δ ‰), and calculated using the following formula:

$$\delta X = [(R_{\text{sample}}/R_{\text{standard}}) - 1] \text{ x } 10^3$$

where X is ^{13}C or ^{15}N, and R is the isotope ratio $^{13}C/^{12}C$ or $^{15}N/^{14}N$ (Barrie & Prosser, 1996).

Data analysis

To answer the first question purposed if there are differences in the availability of basal resources between regions were tested using a one-way ANOVA.

To understand the differences in the fish trophic structure among regions we used three Layman metrics (Layman et al. 2007) reformulated in a Bayesian framework by Jackson et al. (2011), nitrogen range (NR), the nitrogen range (NR) and the total area (TA), to perform comparisons between assemblages along the Pandeiros River, and to examine the dispersion of dimensional space graphics from isotope variation in $\delta^{15}N$ and $\delta^{13}C$. The nitrogen range (NR) represents the vertical structure of the community trophic network, and a higher NR among consumers suggests a higher trophic level. The carbon range (CR) is based on species with higher and lower carbon isotope concentration, thus assemblages with higher CR values are characterized by multiple basal resources. The total area (TA) is characterized by the total area between all species in space in the biplot showing variation in δ^{15}N and δ^{13}C, and represents the trophic diversity in the trophic network. These Layman metrics are related to isotopic niche width among assemblages (regions). Trophic diversity was also compared between regions by comparing the bayesian SEAc (standardized Area of the ellipse) and theta values (θ – angles in radians), which is another method to interpret stable isotope analyses (Jackson et al. 2011, Reid et al. 2016).

To test if the proportion of fish trophic guilds are different among regions all species identified were separated *a priori* according to the literature in six feeding guilds: piscivorous (pis), omnivorous (oni), herbivorous (her), insectivorous (ins), detritivorous/iliophagous (ili), zooplanktivorous (zoo) (Tab. 2). We calculate the proportion (%) of the biomass of each separate guild by region using all sampled data between 2014 and 2016. The analyses were performed using SIAR and SIBER packages developed in R statistical software (Parnell et al. 2010, Jackson et al. 2011, R Core Team 2016).

Table 2. List of species and abundance of fishes used in stable isotopes analyses in each region. See Table 1 for description of regions. 38 species were sampled and classified into feeding guilds.

Species	Abundance (**N**) per region				Feeding guilds	Reference*
	1	2	3	4		
Acestrorhynchus lacustris	5	9	5	-	Piscivorous	1
Astyanax fasciatus	5	-	-	-	Omnivorous	1
Astyanax lacustris	5	-	6	4	Herbivorous	1
Brycon orthotaenia	-	-	-	3	Herbivorous	1
Bryconops affinis	-	7	-	-	Insectivorous	2
Centromochlus bockmanni	5	-	-	-	Insectivorous	3
Characidium zebra	4	-	-	-	Insectivorous	4
Cichlasoma sanctifranciscense	-	5	-	-	Insectivorous	1
Corydoras sp.	5	-	-	-	Insectivorous	
Curimatella lepidura	-	-	5	4	Detritivorous/Iliophagous	1
Eigenmannia virescens	3	-	-	-	Omnivorous	5
Hemigrammus piaba	4	5	-	3	Insectivorous	1
Hisonotus sp.	5	-	-	-	Detritivorous/Iliophagous	
Hoplias intermedius	7	5	5	-	Piscivorous	1
Hoplias malabaricus	-	7	3	5	Piscivorous	1
Hoplosternum littorale	-	5	-	-	Insectivorous	1
Hypostomus aff. margaritifer	5	-	5	-	Detritivorous/Iliophagous	6
Hypostomus sp1	6	-	6	-	Detritivorous/Iliophagous	
Leporinus piau	-	-	6	7	Herbivorous	1
Leporinus reinhardti	-	-	3	4	Insectivorous	1
Leporinus taeniatus	-	-	9	-	Herbivorous	1
Lophiosilurus alexandri	-	-	-	3	Piscivorous	7
Metynnis maculatus	-	6	3	-	Herbivorous	8
Myleus micans	9	6	6	-	Herbivorous	1

Orthospinus franciscensis	-	-	-	7	Insectivorous	1
Phenacogaster franciscoensis	-	-	-	5	Zooplanktivorous	1
Pimelodus maculatus	-	-	-	5	Omnivorous	1
Prochilodus argenteus	-	-	-	7	Detritivorous/Iliophagous	1
Prochilodus costatus	-	-	5	3	Detritivorous/Iliophagous	1
Pseudoplatystoma corruscans	-	-	-	3	Piscivorous	1
Pygocentrus piraya	-	-	-	5	Piscivorous	1
Salminus franciscanus	-	-	-	5	Piscivorous	1
Schizodon knerii	-	-	-	3	Herbivorous	1
Serrassalmus brandtii	-	-	-	5	Piscivorous	1
Steindachnerina elegans	5	-	-	-	Detritivorous/Iliophagous	2
Tetragonopterus franciscoensis	-	-	-	-	Insectivorous	1
Trachelyopterus galeatus	-	6	5	-	Insectivorous	9
Triportheus guentheri	-	-	5	3	Insectivorous	1
Total	73	59	77	84		

*Reference number: [1]Pompeu & Godinho (2003), [2]Melo et al. (2004), [3]Cabeceira et al. (2015), [4]Casatti & Castro (1998), [5]Giora et al. (2005), [6]Gandini et al. (2012), [7]Alvim & Peret (2004), [8]Melo (2011), [9]Oliveira et al. (2016). Feeding guilds information drawn from studies using analyses of stomach contents. In some cases were considered the information known to the genus (few details about the species).

Results

The greatest variation in $\delta^{13}C$ ‰ signatures of basal resources was observed in region 2, followed by region 3, while regions 1 and 4 presented similar values (Tab. 3). However, the ANOVA results showed that there is no difference in carbon signature ranges between regions ($F(3,17) = 2.67$; $p = 0.08$).

The greatest variation in $\delta^{15}N$ ‰ signatures of basal resources was observed in region 4, followed by region 2, 3 and 1 (Tab 3). The macroinvertebrates were shown to be more enriched in $\delta^{15}N$ signatures than basal resources in all regions, and there was no difference between the nitrogen range signatures ($F(3,35) = 2.57$; $p = 0.06$).

Table 3. Mean and standard deviation values of the isotopic signatures of resources sampled in the four regions along the Pandeiros River. Resources: leaves of riparian vegetation (RIP), fine particulate organic matter (FPOM), coarse particulate organic matter (CPOM), organic matter in suspension (SUSP), macrophytes (MAC), periphyton (PERI) and macroinvertebrates (MACRO).

Sampling	[Resources]

region		$\delta^{13}C$‰±SD	$\delta^{15}N$‰±SD
Region 1			
	RIP	-29.22 ± 1.62	1.04 ± 1.45
	CPOM	-29.27 ± 1.59	0.93 ± 1.74
	MAC	-27.60 ± 1.19	2.02 ± 0.40
	FPOM	-27.95 ± 0.64	2.05 ± 0.51
	SUSP	-28.40 ± 0.56	1.91 ± 0.48
	MACRO	-27.39 ± 1.65	3.5 ± 0.62
Region 2			
	RIP	-29.05 ± 2.10	1.37 ± 1.20
	CPOM	-27.55 ± 1.31	1.54 ± 1.22
	MAC	-26.00 ± 2.10	0.70 ± 2.38
	FPOM	-26.74 ± 2.00	0.70 ± 2.10
	SUSP	-24.63 ± 3.37	0.20 ± 1.77
	MACRO	-24.81 ± 1.33	1.44 ± 1.93
Region 3			
	RIP	-28.60 ± 2.73	1.88 ± 2.35
	CPOM	-28.13 ± 2.70	1.63 ± 1.74
	MAC	-25.40 ± 2.50	2.76 ± 0.90
	FPOM	-27.02 ± 2.24	2.79 ± 0.95
	SUSP	-28.10 ± 0.15	1.75 ± 0.30
	PERI	-26.07 ± 1.91	2.61 ± 0.83
	MACRO	-25.57 ± 1.34	2.99 ± 1.30
Region 4			
	RIP	-28.06 ± 1.33	1.69 ± 1.35
	MAC	-27.95 ± 1.13	1.11 ± 0.63
	SUSP	-27.79 ± 0.13	1.99 ± 0.21
	CPOM	-29.42 ± 0.37	0.92 ± 0.21
	FPOM	-28.73 ± 0.28	0.42 ± 0.27
	MACRO	-28.18 ± 4.24	3.25 ± 1.47

The largest variation in $\delta^{13}C$ assimilated by fish (-37.22 ‰ to -16.84 ‰) seen in region 3, followed by region 4 (-39.56 ‰ to -25.81 ‰). With the exception of region 2, the range of $\delta^{13}C$ signatures of the sampled resources did not cover the entire variation of $\delta^{13}C$ assimilated by fish (Fig. 1a). This was more evident in region 4, which presented fish with signatures below -35 ‰ (Fig. 2). In this region, the species *L. reinhardti* (-35.62 ‰), *P. maculatus* (-36.1

‰), *P. argenteus* (-36.55 ‰), *P. costatus* (-36.09 ‰) and *T. guenteri* (-39.06 ‰) showed average δ^{13}C values of less than -35 ‰ (Fig. 2).

The variation in fish δ^{15}N values was similar among regions in the Pandeiros River (Fig. 1b). The species with the most enriched δ^{15}N average values were the carnivorous *P. piraya* (9.64 ‰), *P. corruscans* (9.58 ‰), *H. malabaricus* (9.35 ‰), *S. franciscanus* (9.34 ‰) and *A. lacustris* (9.30 ‰), the first four belonging to region 4 and the last to the region 1 (Fig 2). The lowest values were observed for *C. sanctifranciscense* (3.21 ‰), *M. micans* and *M. maculatus* (both with 3.50 ‰), *H. marginatus* (4.25 ‰), *Hypostomus* sp1 (4.74 ‰), the first four species collected in region 2 and the last in region 3 (Fig. 2).

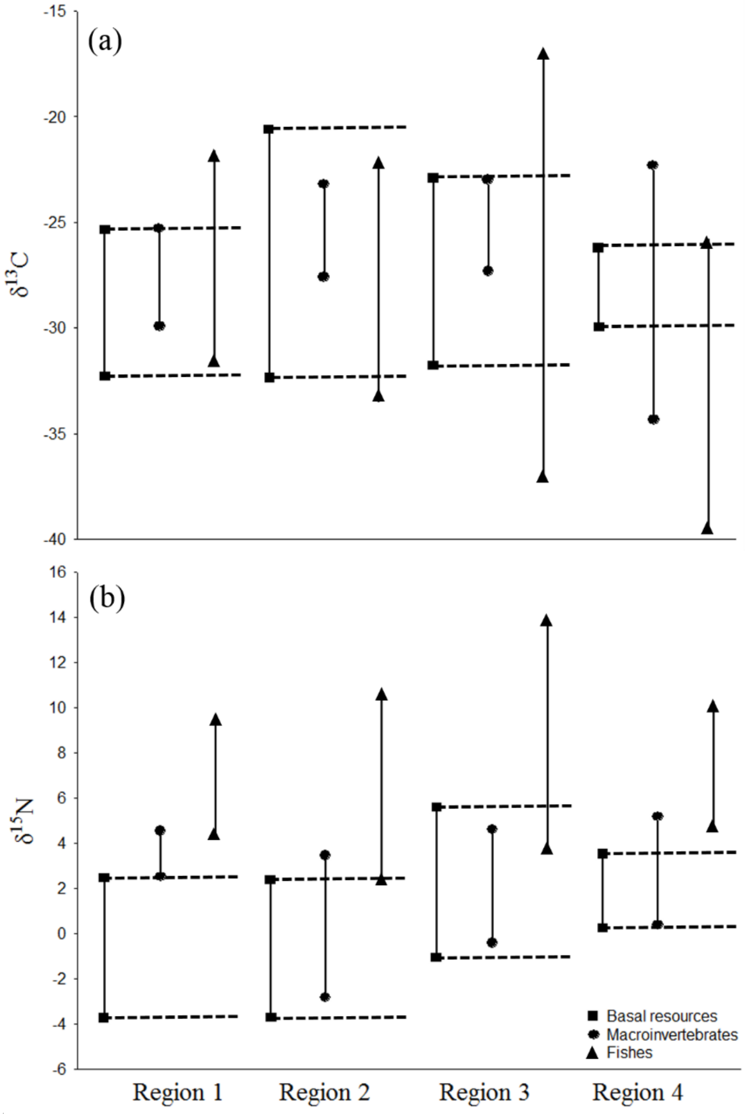
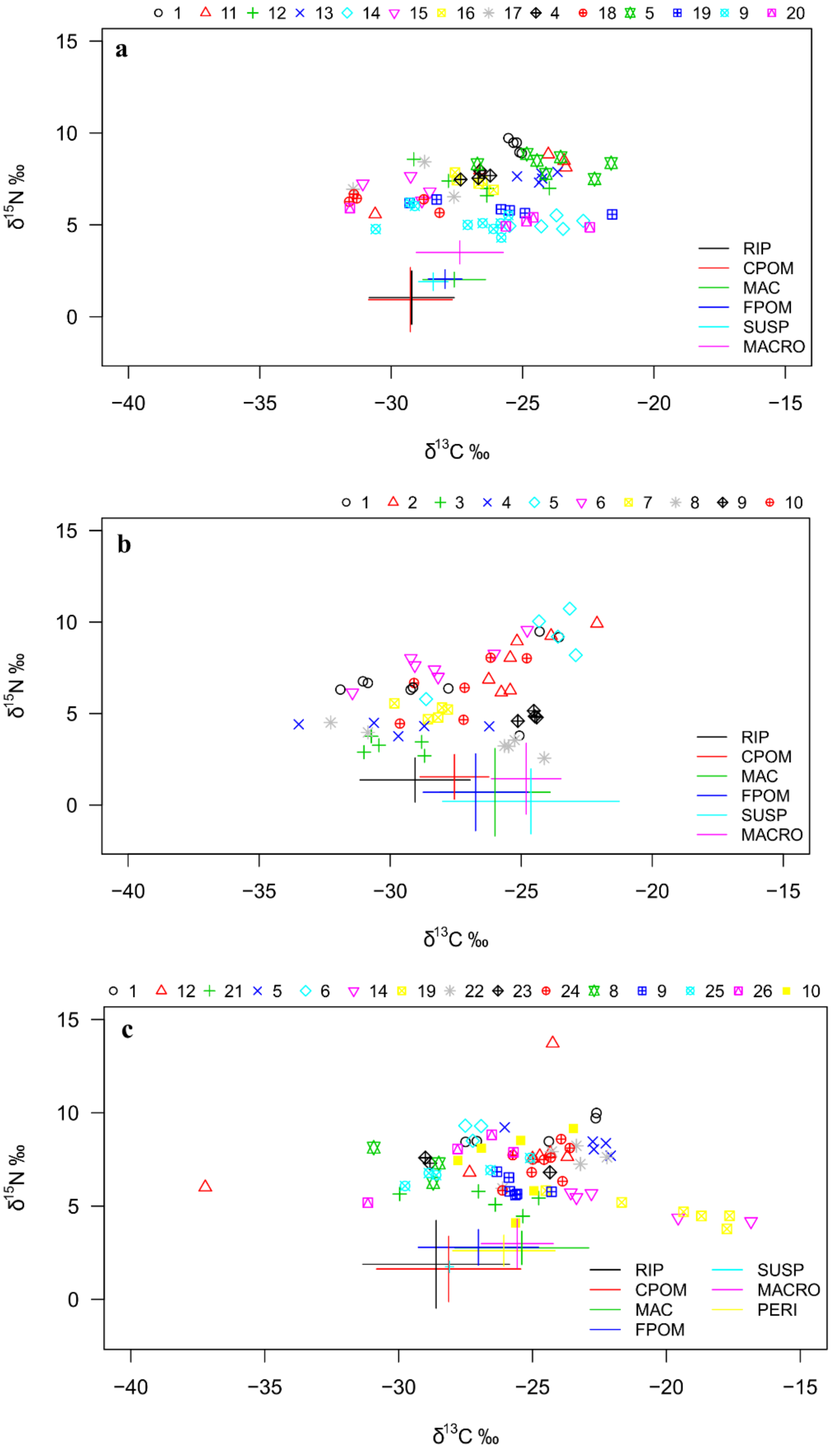


Figure 1. Isotopic signature range for δ^{13}C (a) and δ^{15}N (b) of basal resources, macroinvertebrates and fishes. Dashed

line represents variation of each stable isotope for basal resources.



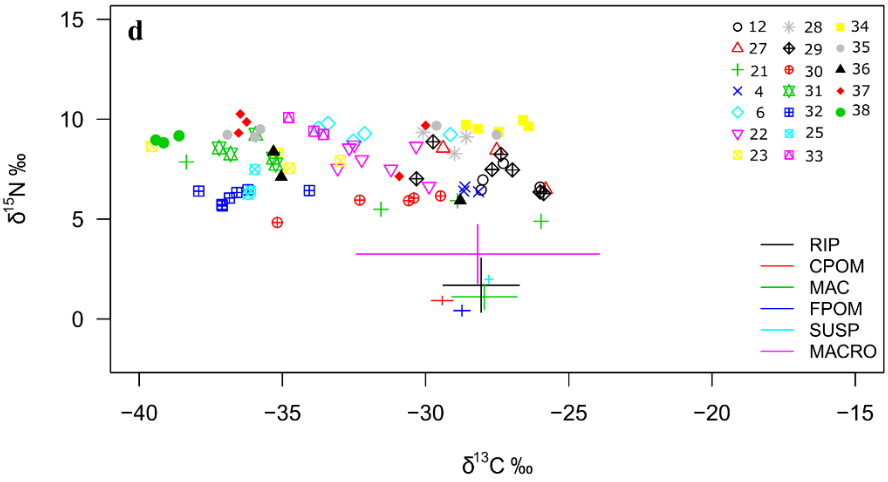


Figure 2. Representation of the trophic structure of fish assemblages for each region along the Pandeiros River, ***a*** Region 1, ***b*** Region 2, ***c*** Region 3, ***d*** Region 4. The numbers in figures represent each species in the fish community. Symbols: *(1) Acestrorhynchus lacustris; (2) Bryconops affinis; (3) Cichlasoma sanctifranciscense; (4) Hemigrammus marginatus; (5) Hoplias intermedius; (6) Hoplias malabaricus; (7) Hoplosternum littorale; (8) Metynnis maculatus; (9) Myleus micans; (10) Trachelyopterus galeatus; (11) Astyanax fasciatus; (12) Astyanax lacustris; (13) Centromochlus bockmanni; (14) Hypostomus aff. margaritifer; (15) Characidium zebra; (16) Corydoras sp.; (17) Eigenmannia virescens; (18) Hisonotus sp.; (19) Hypostomus sp1; (20) Steindachnerina elegans; (21) Curimatella lepidura; (22) Leporinus piau; (23) Leporinus reinhardti; (24) Leporinus taeniatus; (25) Prochilodus costatus; (26) Tetragonopterus chalceus; (27) Brycon orthotaenia; (28) Lophiosilurus alexandri; (29) Orthospinus franciscensis; (30) Phenacogaster franciscoensis; (31) Pimelodus maculatus; (32) Prochilodus argenteus; (33) Pseudoplatystoma corruscans; (34) Pygocentrus piraya; (35) Salminus franciscanus; (36) Schizodon knerii; (37) Serrassalmus brandtii; (38) Triportheus guentheri*. The crosses represents the variation of each resources (leaves of riparian vegetation (RIP), fine particulate organic matter (FPOM), coarse particulate organic matter (CPOM), organic matter in suspension (SUSP), macrophytes (MAC), periphyton (PERI) and macroinvertebrates (MACRO)) for each stable isotope (δ^{13}C and δ^{15}N).

The trophic niche metrics varied between regions of the Pandeiros River (Tab. 4), and indicated that region 4 is the most distinct isotopic niche occupied, particularly due to the lower δ^{13}C values (Fig. 3). However, region 3 presented the highest values of total area (TA), carbon (CR) and nitrogen (NR). Despite overlapping between regions 1, 2 and 3, region 2 presented slightly higher SEAc and thetas value (Tab 4).

Table 4. Isotopic niche metrics for each region along the Pandeiros River. *S* = number of fish species, TA = total area, SEAc = standard ellipse area, CR = carbon range ($\delta^{13}C$), NR = nitrogen range ($\delta^{15}N$), Theta (θ) = angle of ellipse inclination in radians.

Region	Trophic metrics					
	S	TA	SEAc	CR	NR	θ
1	14	40.47	11.09	10.01	5.41	0.092
2	10	55.27	16.84	11.38	8.17	0.532
3	15	101.54	16.82	20.38	9.99	-0.121
4	19	63.05	17.91	13.75	5.43	-0.048

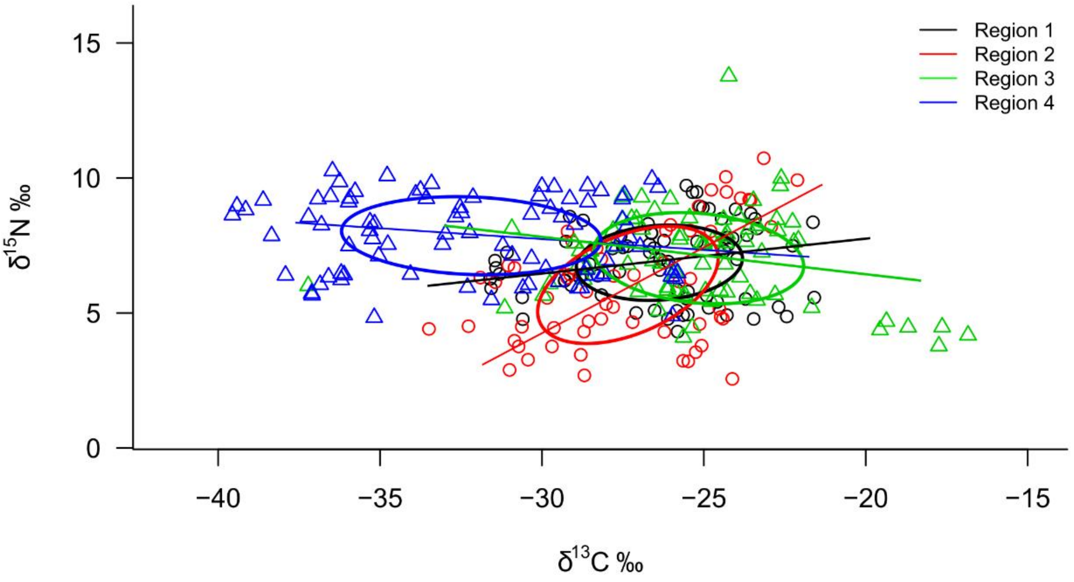
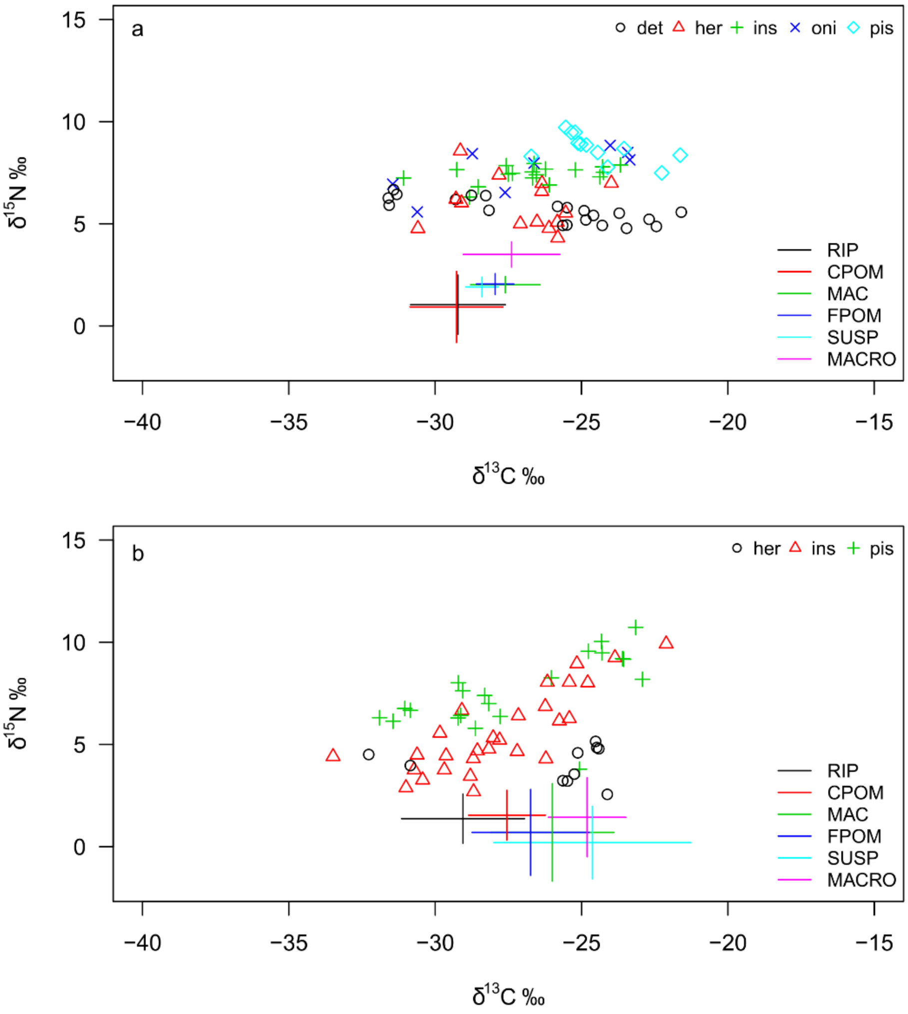


Figure 3. Representation of the trophic structure of the fish community on the Pandeiros River. Standard ellipse areas (SEA, circles) represent the core isotopic niche space of each fish assemblage along the Pandeiros River. The solid lines represent the theta value for each region.

The use of carbon resources did not show any specialization by feeding guilds, since each guild could explore a wide range of carbon. However, the detritivorous guild in region 3 had the highest $\delta^{13}C$ value, and the insectivorous guild in region 4 had the lowest $\delta^{13}C$ value (Fig. 4). In general, the species in the piscivorous guild were the most $\delta^{15}N$ enriched.

However, regions 2 and 3 showed individuals belonging to other feeding guilds (insectivorous and herbivorous) with high values of δ^{15}N. In contrast, the detritivorous and herbivorous guilds were always less δ^{15}N enriched (Fig. 4).



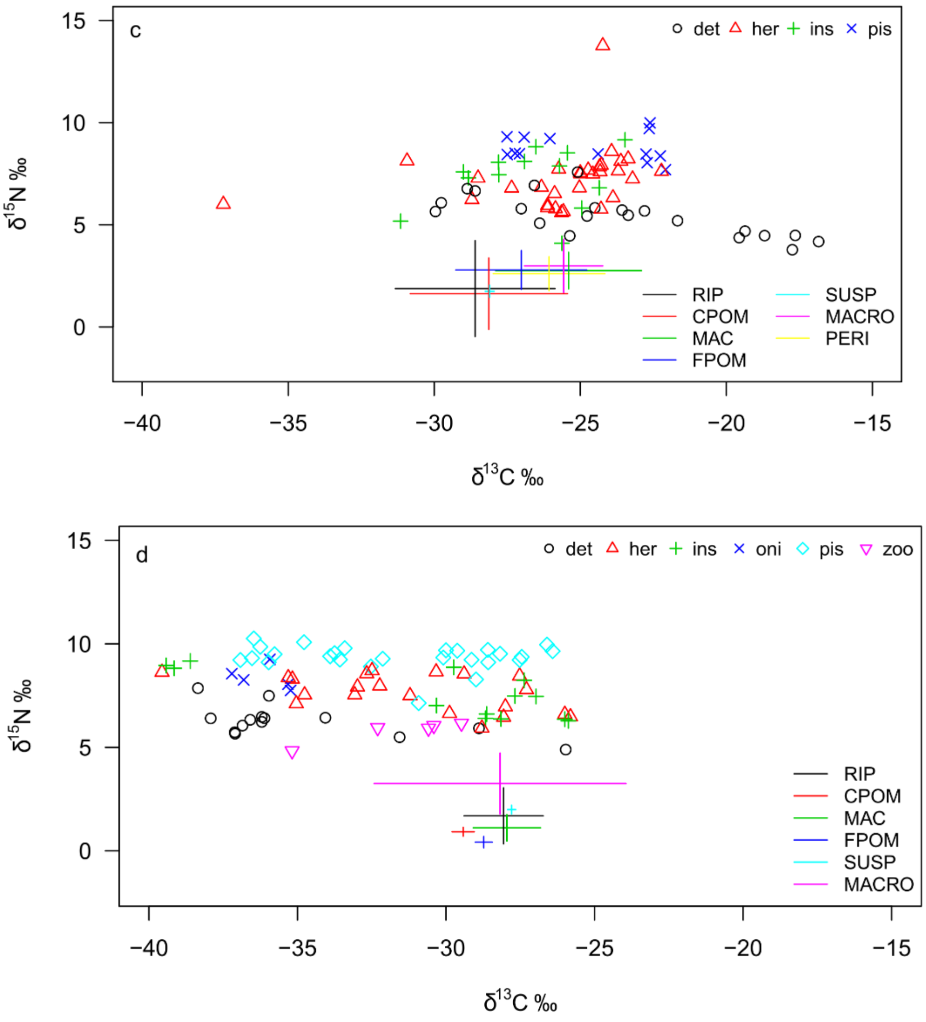


Figure 4. Representation of the trophic structure of the fish assemblages for each region along the Pandeiros River, separated by feeding guilds; (***a***) Region 1, (***b***) Region 2, (***c***) Region 3, (***d***) Region 4.

The most represented guilds by biomass in the four regions were the piscivorous, herbivorous, detritivorous and insectivorous guilds (Fig. 5). The piscivorous guild was most represented in region 4, with approximately 55% of the total biomass sampled during the study. In this region, this guild was mainly represented by the species *P. piraya*, *S. franciscanus*, and *H. malabaricus*. The guild with the highest representation in a single region was the insectivorous guild in region 2, with about 68% of the total biomass. This mainly consisted of the species *H. littorale* and *T. galeatus*, which accounted for approximately 65% of the biomass of the guild. The region under influence of the dam was the only one in which species belonging to all five trophic guilds were not found. In region 2, only piscivorous, herbivorous and insectivorous trophic guilds were represented (Fig. 5).

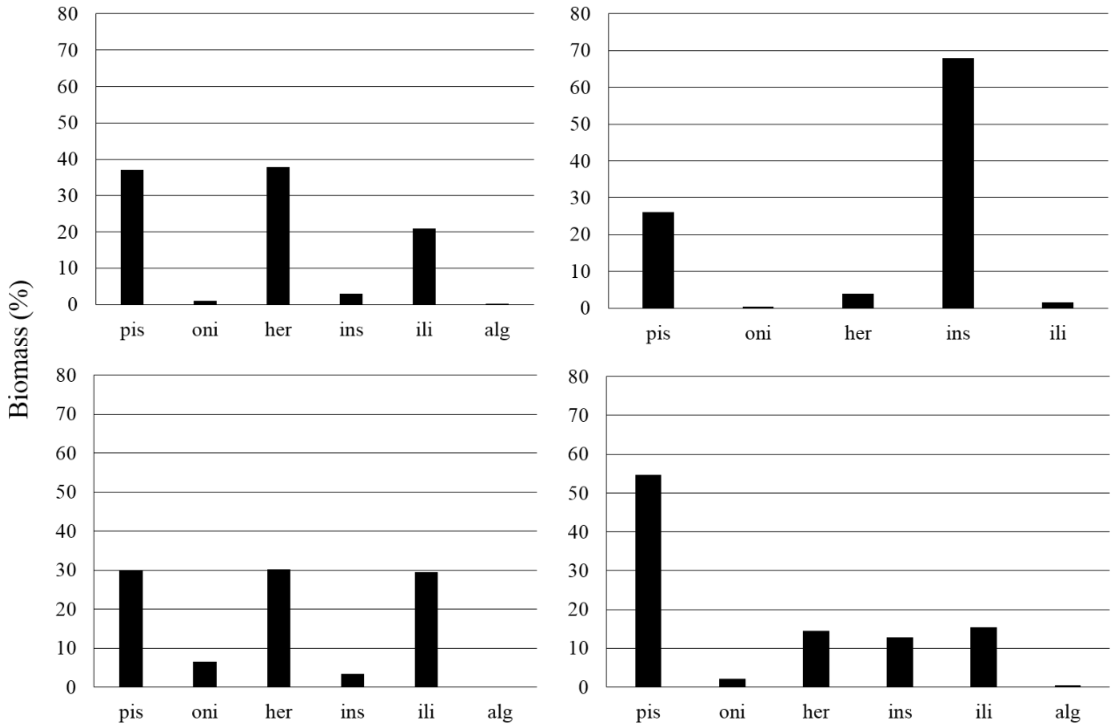


Figure 5. Relative biomass for each feeding guilds (piscivorous (pis), omnivorous (oni), herbivorous (her), insectivorous (ins), detritivorous/iliophagous (ili), algivorous (alg) in a four region along Pandeiros River ((***a***) Region 1, (***b***) Region 2, (***c***) Region 3, (***d***) Region 4).

Discussion

Land use impacts and changes influence the range of $\delta^{13}C$ and $\delta^{15}N$ signatures from basal resources due different inputs of chemicals, organic fertilizers and sewage (Allan 2004, De Carvalho et al. 2015, De Carvalho et al. 2017). Therefore, signatures with higher values of nitrogen and/or greater $\delta^{13}C$ ranges would be expected in regions subject to such impacts. However, the isotopic range ($\delta^{13}C$ and $\delta^{15}N$) from basal resources on the Pandeiros River did not show differences between regions along the longitudinal gradient. This suggests that the isotopic baseline on the Pandeiros River is similar along the stretch studied, and the human impact on natural carbon and nitrogen availability along the river is not significant.

The range of $\delta^{13}C$ signatures identified from the resources sampled did not cover the range of $\delta^{13}C$ assimilated by fish, indicating that fish in this region have consumed basal resources that were not sampled. In tropical riverine ecosystems there are a complex variety of possible resources available to fish communities, which ranges from seeds to small vertebrates, and opportunistic feeding is more common than specialization (Lima et al. 1995). Furthermore, omnivory is one of the most abundant foraging modes in tropical freshwater fishes (Winemiller & Jepsen 1998), and it is possible that we have not captured all basal resources. Region 4 is located in the floodplain, in the confluence between the Pandeiros and São Francisco Rivers. Hence, these missing $\delta^{13}C$ values, may be explained by feeding that occurred outside the Pandeiros River, particularly for migratory fishes (*Leporinus reinhardti*, *Prochilodus* spp.). For this reason, the range of basal resource may be different from those sampled in the Pandeiros River. However, most of the individuals sampled were juveniles that have probably not yet migrated to another region in the São Francisco basin.

Extreme seasonal events are characterized by long periods with low levels of dissolved oxygen, which occurs particularly in the floodplain (region 4). This can facilitate the production of methane, which has been recognized as a source of carbon for aquatic food webs (Sanseverino et al. 2012). The lowest $\delta^{13}C$ values were observed in that region, and some individuals presented -38.35‰ (*Curimatella lepidura* carbon mean -31.19‰), -39.42 ‰ (*Triportheus guenteri* carbon mean -39.06‰) and -39.56‰ (*Leporinus reinhardti* carbon mean -35.62‰). These low $\delta^{13}C$ values are thought to come from biogenic CH_4 (Bastviken et al. 2003). We identified another three species from that region that also had low values: *P. maculatus* (-36.1 ‰), *P. argenteus* (-36.55 ‰), and *P. costatus* (-36.09 ‰). All of these species with lower carbon signatures were zooplanctivorous, detritivorous or omnivorous (with tendency towards invertivory). Such species feed on particulate and dissolved organic matter oxidized by MOB (methane oxidizing bacteria), or rely on pelagic (zooplanctivorous) or benthic organisms (invertivorous). These are all possible ways in which methane can be incorporated into food webs in tropical rivers (Bastviken et al. 2003, Sanseverino et al. 2012).

The measures of trophic structure utilized in this study have become widely adopted in trophic community ecology studies based on stable isotopes (Jepsen & Winemiller 2002, Jackson et al. 2011, De Carvalho et al. 2017). These measures facilitate the improved understanding of the relationship between basal resources and their consumers, making it possible to compare the relationship between areas under different human impacts (Silva et al. 2007, De Carvalho et al. 2015, 2017). In this study, the CR, TA and theta values were markedly different between regions.

Regions 3 and 4, located downstream of the dam, had higher CR and TA values. Those regions possessed some species with a great variation of signatures, for example, one of the individuals of *Leporinus piau* analyzed had -24.23‰ $\delta^{13}C$ and 13.77‰ $\delta^{15}N$. These values contribute to increase the TA of the region and indicate that the region, connected to the São Francisco main stream, supports species with different approaches to exploit the resources, receiving individuals that can forage other areas (Bearhop et al. 2004). The higher CR and TA values characterize an assemblage with large niche width, high trophic diversity and multiple basal resources (Layman et al. 2007). It also indicates that the lower Pandeiros River can exchange individuals with others areas of the basin, increasing the diversity of isotopic signatures.

The theta value can be used as an alternative to interpret the SEA, especially when ellipse area values were similar (Reid et al. 2016). In our study, despite the similar area and great overlap among the ellipses, the different angle of inclination (theta value) pointed to differences in food web structures in each region. Vertically distributed communities, like those under the influence of the dam (region 2), tend to be composed of simpler species assemblages, with a narrower use of resources. The strong environmental filter imposed by reservoirs has been extensively described in the literature, and reductions in species richness and fish diversity are expected, as some species are locally eliminated and others become dominant and numerous (Agostinho et al., 2008). However, a progressive change in the trophic community in region 2 towards that observed in regions 1 or 3 is expected to result from removing the dam.

We observed that piscivorous, detritivorous and herbivorous guilds were of greatest importance in all regions. In general, fish characterized as herbivores and detritivore/iliophagous are in the same trophic position (according to the variation in $\delta^{15}N$) as primary consumers, although they possibly utilize different carbon sources (Jepsen & Winemiller 2002, Post 2002). However, the signatures of the herbivores have a greater amplitude in the use of the two isotopes studied. As proposed by Vannote et al. (1980), a higher proportion of piscivorous fishes is expected to be found in lower parts of a longitudinal gradient in a river, and this aspect has been documented by several studies (Hoeinghaus et al. 2007, Ibanez et al. 2007). We could identify similar patterns along the Pandeiros River where piscivorous and detritivorous fishes were dominant in the lower reaches (region 3 and 4). However, we have also found a great biomass of piscivorous and detritivorous fishes upstream of the dam. Yet, only predators (e. g. *Salminus franciscanus*) and detritivores (e. g. *Prochilous* spp.) found in the lower reaches of the river were represented by migratory species. Predators and detritivores in the upper basin were sedentary species like *Hoplias* spp.

and *Hypostomus* spp, suggesting that fragmentation by the dam separates the assemblages upstream and downstream into two different functional and taxonomic regions.

The findings presented here demonstrate how the trophic structure based on stable isotopes can change along a small regulated tropical river. Although the input of organic matter did not change in terms of $\delta^{13}C$ and $\delta^{15}N$, the region under influence of the dam and the floodplain region showed marked differences in the exploited resources. In addition, although the guild composition did not change among the lotic regions, the contribution of migratory species changed along the river due to the fragmentation imposed by the dam. Considering the possibility of removing the Pandeiros dam, the data collected present an opportunity to follow the changes in resource assimilation and guild composition after such removal. After restoring the natural dynamic of the Pandeiros River, changes in the region under influence of the dam, and upstream of the current reservoir due to the colonization by migratory species are expected, and must be monitored.

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