Water diversion in Brazil threatens biodiversity

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Abstract Construction of water diversions is a common response to the increasing demands for freshwater, often resulting in benefits to communities but with the risk of multiple environmental, economic, and social impacts. Water-diversion projects can favor massive introductions and accelerate biotic homogenization. This study provides empirical evidence on the consequences of a proposed law intended to divert water from two large and historically isolated river basins in Brazil: Tocantins to São Francisco. Compositional similarity (CS) and β -diversity were quantified encompassing aquatic organisms: mollusks, zooplankton, crustaceans, insects, fishes, amphibians, reptiles, mammals, and plants. For CS we (i) considered only native species, and (ii) simulated the introduction of non-natives and assumed the extinction of threatened species due to this water-diversion project. We highlight the environmental risks of such large-scale projects, which are expected to cause impacts on biodiversity linked to bioinvasion and homogenization, and we recommend alternatives in order to solve water-demand conflicts.

Keywords Animal conservation · Biological conservation · Biological invasions · Biotic interchange · Environmental impacts · Inter-basin water transfer

INTRODUCTION

Human demand for water for domestic consumption, agriculture, and navigation development has historically

led nations to propose actions that can prove unsustainable over long periods (Bagla 2014; Brito and Magalhães 2017). Construction of water-diversion schemes is a common response to the increasing demand for freshwater (Liu et al. 2015; Zhang et al. 2015). This ancient human practice connects one river basin to another through artificial canals, often resulting in positive benefits to communities, but with generally ignored risks to the environmental, economic and social spheres in both the short and the long term (Moreira-Filho and Buckup 2005; Zhang et al. 2018). Water diversions can cause significant hydrological deficits and major changes in the dynamics of the river flow in the donor basin, in addition to habitat destruction, collapse of fisheries, spread of parasites, transmission of diseases, loss of genetic variability between populations, biological invasions, species extinction, and water pollution (Liang et al. 2012; Vitule et al. 2015; Merciai et al. 2017; Qin et al. 2018). Here, together with habitat alteration caused by water-diversion projects, another major ecological effect was highlighted, the concomitant indiscriminate and unplanned biotic interchange between basins. Artificial canals allow the dispersal of isolated taxa or populations between historically separated basins, resulting in multiple introductions of different organisms that otherwise would only very rarely overcome geological barriers (Zhan et al. 2015; Gallardo and Aldridge 2018).

Major water-diversion projects have been implemented around the world, such as China's South-to-North diversion and South Africa's Orange-Fish-Sundays project (Woodford et al. 2013; Zhan et al. 2015). In addition to water diversions that are already in operation, there are plans to connect countless other river basins worldwide. For example, in North America around 30 water-diversion projects are planned (Shumilova et al. 2018). Similarly, water-diversion projects in Brazil have been developed in

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various regions of the country without appropriate consideration of environmental issues, the importance of which are not recognized owing to a lack of political motivation (Andrade et al. 2011; Vitule et al. 2015).

Negative impacts resulting from the interchange of water between river basins are already apparent, with the introduction of non-native species (notably fishes) one of the most evident impacts (e.g., Moreira-Filho and Buckup 2005; Ramos et al. 2018). More astonishingly, novel large-scale projects are still being undertaken (Andrade et al. 2011; Shumilova et al. 2018), disregarding mechanisms for preventing biological invasions and ignoring policies that could preserve biodiversity and riverine ecosystem services for future generations.

An old and controversial project is currently being advanced in Brazil with the aim of connecting the Tocantins and São Francisco River basins. The purpose of this large-scale project is to allow navigation between the basins and to increase the water supply in Brazil's semi-arid North-east region. The Tocantins-São Francisco water-diversion project (hereafter TO-SF-WDP) has been opposed by local people in the donor basin and has been questioned by a number of politicians, even including those who are not usually sympathetic about environmental protection measures (Online Reference S1). Here we provide empirical evidence showing that the TO-SF-WDP would constitute a serious setback for environmental policies in Brazil. It would jeopardize aquatic ecosystems in the Amazon and Tocantins River basins, as well as cause additional damage to the São Francisco River (Brazil's third largest river basin), which is one of the most threatened rivers in South America, mostly due to the diversion of its water that is already underway (Moreira-Filho and Buckup 2005; Brito and Magalhães 2017).

PROPOSED LAW (PL) 6569/2013

The proposed law (PL) 6569/2013 is intended to divert water from the Tocantins River (Amazon River Basin) to the Preto River (São Francisco River Basin) (Fig. 1). The TO-SF-WDP would create a waterway for navigation between the basins and deliver water to the already-diverted São Francisco River (Online Reference S2). The project includes plans for constructing ~ 200 km of canals in a network totaling 733 km that would cross several "conservation units" (protected areas), mostly in the states of Tocantins and Bahia. The proposed law was initiated under previous presidential administrations; it was approved in November 2017 by the Chamber of Deputies and was archived in June 2018 by the Senate (Online Reference S3). The archiving was mainly motivated by the absence of studies and technical support justifying the

supposition that the TO-SF-WDP would preserve the donor basin. However, the archiving does not guarantee that this PL will be forgotten or that new water-diversion projects will not be proposed, given that politicians are ignoring this decision and promising that the transposition project will be carried out (e.g., Online References S4 and S5).

PUTTING BIODIVERSITY AT RISK

The main impact expected from the proposed TO-SF-WDP is the introduction of non-native organisms from one basin to another and the many potential negative effects that the introduced species can have on the receiving basin's biota and ecosystem services. Organisms may be carried passively by river flow from the Tocantins to the São Francisco basin (aquatic invertebrates, eggs and juvenile of fish, aquatic plants, and algae), or they may disperse actively in both directions (crustaceans, fishes, and reptiles). Displacement of aquatic plants (floating mats or plant fragments) through the network may also play a fundamental role in dispersing many organisms that colonize these plants (Marsden and Ladago 2017). Additionally, because part of the rationale for the TO-SF-WDP is to ensure navigation between the basins, encrusted aquatic organisms may be carried by boats and barges, as is commonly reported in other cases of biological invasion (Table S1). The Amazon River Basin has a long history of international navigation, and ballast water may enhance introductions, as occurred with the invasive Asian clam *Corbicula fluminea* (Müller, 1774) (Table S1), and an Asian midge (Chironomidae) species (Amora et al. 2015).

Globally, introduction of non-native species is considered to be one of the primary causes of species extinction (Clavero and García-Berthou 2005; Sax and Gaines 2008; Bellard et al. 2016), as well as ecosystem disruption (Lövei et al. 2012). Species introductions represent an important phenomenon that needs to be studied and prevented, in particular because of the large catalog of negative impacts (Simberloff and Vitule 2014). Biological invasions are of paramount concern for conservationists and a huge challenge in megadiverse countries, where introductions of non-native species and environmental degradation of rivers are accelerating the biotic homogenization process (e.g., Lövei et al. 2012; Winemiller et al. 2016). The outcome of biotic homogenization is a consistent decrease over time in the genetic, taxonomic, or functional distinctiveness of biotas, which occurs across a variety of ecosystems and taxonomic groups (Olden et al. 2004). Connecting distinct drainage basins through large-scale projects greatly facilitates biotic homogenization, as is the case of the planned Nicaragua Canal, which would certainly cause a biotic upheaval in the freshwater fish fauna of the affected basins,

Fig. 1 Tocantins River Basin (yellow) and São Francisco River Basin (green), which are planned to be connected by a water-diversion project

whose current compositional similarity is only one-third (Härer et al. 2017).

The Tocantins River is a tributary of the Amazon River Basin and hosts valuable biodiversity, corresponding to an important area of endemism, particularly for fish: around 400 species are present, of which 50% are endemic to the basin—the highest percentage among all Amazonian tributaries (Winemiller et al. 2016). As a consequence, the Tocantins River shares only a few species with the São Francisco River (see Methods section and Table S2), with a low compositional similarity (CS) for native assemblages of mollusks, zooplankton, crustaceans, aquatic insects, freshwater fishes, amphibians, reptiles, aquatic mammals, and aquatic plants (Fig. 2—values in black). Furthermore, the likely introduction of non-native species and extinction of all currently threatened species owing to the construction of the TO-SF-WDP (Fig. 2—values in red), will cause the CS for all taxonomic groups between these basins to increase even more. This scenario will be significantly more catastrophic for aquatic mammals (Fig. 2 h), since all species recorded are threatened with extinction. In addition, the β -diversities (Sørensen dissimilarity index— β_{sor}) of mollusks ($\beta_{\text{sor}} = 0.86$), zooplankton ($\beta_{\text{sor}} = 0.71$), crustaceans ($\beta_{\text{sor}} = 0.65$), aquatic insects ($\beta_{\text{sor}} = 0.92$), freshwater fishes ($\beta_{\text{sor}} = 0.99$), amphibians ($\beta_{\text{sor}} = 0.94$), reptiles ($\beta_{\text{sor}} = 0.60$), and aquatic plants ($\beta_{\text{sor}} = 0.79$) show strong species turnover between basins (see details on

Methods—Supplementary Material S1). These results indicate that taxonomic homogenization is an anticipated outcome, leading to the loss of a long history of evolution across each taxonomic group by vicariance.

The Tocantins River currently has few non-native aquatic species, in contrast to the São Francisco River, which has a long history of non-native species introductions and invasions (Table S2) because of intense environmental degradation driven by anthropogenic activities. Additionally, the Tocantins and São Francisco Rivers run through different biomes, physiographic regions, and climate zones (Tocantins: *Cerrado* and rainforest; São Francisco: *Cerrado* and *Caatinga* semi-arid vegetation). Thus, it is not possible to envisage which basin or ecoregion will be more affected by the biological invasions and their negative impacts or socioeconomic consequences for human populations. Information about some freshwater groups (e.g., aquatic insects and aquatic plants) is still scarce and difficult to assess, which makes the TO-SF-WDP even riskier.

Although the Tocantins River still has many endemic species, both river basins are extensively impacted by multiple disturbances, especially changes in land cover and river hydrology (e.g., construction of many dams), along with habitat conversion and degradation (Winemiller et al. 2016; Pelicice et al. 2017). Social conflicts are expected as a result of the water diversion, given that hydropower and

Fig. 2 Number of native species recorded in the Tocantins River Basin (yellow circle) and São Francisco River Basin (green circle), and the compositional similarity (CS—blue intersection): (i) considering only native assemblages (values in black), and (ii) taking into account the introduction of non-native species and assumes that all currently threatened species will become extinct due to the construction of the TO-SF-WDP (values in red), for each taxonomic group: **a** Mollusks, **b** Zooplankton, **c** Crustaceans, **d** Aquatic insects (genus level), **e** Freshwater fishes, **f** Amphibians, **g** Reptiles, **h** Aquatic mammals, **i** Aquatic plants (genus level). Data sources and methods are given in the Supplementary Material

agribusiness activities have developed significantly in the Tocantins River Basin while water availability is limited (i.e., highly seasonal, with six dry months). Furthermore, lack of effective wildlife-management strategies, lead to illegal hunting (Kemenes and Pezzuti 2007). This is the case of trade traffic of *Podocnemis* spp. turtles (Pantoja-Lima et al. 2014), which is expected to expand in the TO-SF-WDP network because these species are highly appreciated for human consumption in Amazonia and other regions of the country. The sum of these factors indicates that the TO-SF-WDP would cause profound changes in both basins, including irreversible impacts affecting biodiversity patterns, ecosystem functioning, and the provision of ecosystem services that are important for conservation of aquatic resources, water supply, food production, and public health (Moreira-Filho and Buckup 2005; Vitule et al. 2015; Brito and Magalhães 2017).

In summary, projects such as the TO-SF-WDP represent a huge challenge at a time when biodiversity in megadiverse nations is increasingly threatened and in need to strong conservation measures (Scarano et al. 2012; Frehse

et al. 2016; Pelicice et al. 2017; Alves et al. 2018; Bockmann et al. 2018; Azevedo-Santos et al. 2019; Bezerra et al. 2019). This is a good example of sharing the multiple and complex costs associated with misguided policies and large-scale degradation (i.e., the São Francisco River) with a distinct and moderately disturbed neighbor (i.e., the Tocantins River), leading to negative consequences for both.

BETTER POTENTIAL ALTERNATIVES

In view of the high environmental risk associated with water diversions (Zhang et al. 2018) and the lack of adequate information to guide conservation strategies and monitoring programs, authorities should consider other alternatives. The most important recommendation is avoiding the construction of new water-diversion projects whenever possible, however if it is unavoidable, at least the construction of barriers to movement (e.g., acoustic, electrical, or physical) should be also proposed, aiming to

contain the spread of aquatic organisms between basins (Clarkson 2004; Rahel 2013; Rahel and Smith 2018).

In the case of the TO-SF-WDP, transport functions can be served by improvement of rail connections, and, if the demand is sufficient (Matera 2012), improved air transport infrastructure can also be justified. Railways offer a still impacting alternative, but likely less than water-diversion projects. This can either be done through improvement of existing railways (e.g., EF-151, Online Reference S6) or through the construction of new lines (sensu Laurance and Balmford 2013), providing transportation for both passengers and freight. As with all projects, railway construction or improvement should be preceded by multidisciplinary assessments that include explicit and honest consideration of negative impacts on biodiversity.

Water scarcity in North-east Brazil is an important rationale for the TO-SF-WDP, as is frequently the case for water diversions worldwide. One alternative rather than water-diversion projects is water reuse (Hespanhol 2002), a practice already adopted in many countries (Miller 2006). For this practice, there are methods available for treating reused water for human consumption (Warsinger et al. 2016). In addition, innovative methods have been

implanted in some semi-arid regions of the world, such as water harvesting from thin air, which has low cost and maintenance (Davtalab et al. 2013; Online Reference S7). Another alternative is rainwater harvesting, where water is captured (often from rooftops) and stored in cisterns (e.g., Gomes and Heller 2016). Rainwater harvesting systems are already in use in Brazil's North-east region; however, they could be further implemented in the area that would receive water from the diversion project if the federal or state governments were to provide subsidies for massive application of this method. The combination of rainwater harvesting and water reuse could supply much of the demand for water for domestic use in the area served by the proposed water-diversion project.

FINAL REMARKS

Decisions on inter-basin water diversion are being made without sufficient reference to expected environmental and social impacts related to biodiversity and biological invasions. Warnings from the scientific community are being circumvented to allow implementation of questionable

Table 1 Examples of water diversion in Brazil

Water diversion	Reason	Situation	References
Piumhi River (Grande River Basin) to Sujo River (São Francisco Basin)	Dam	C	Moreira-Filho and Buckup (2005)
Paraíba do Sul River (Paraíba do Sul Basin) to Guandu River (Guandu River Basin)	Water supply	C	Castro and Ferreirinha (2012); Acselrad et al. (2015)
Itapanhaú River (Itapanhaú River Basin) to Biritiba reservoir (Tietê River Basin)	Water supply	P	LabSid (2015)
Capivari stream (Capivari Basin) to Piacó stream (Piacó Basin)	Water supply	C	Morgantini (2017)
Claro River (Claro River Basin) to Saudade stream (Uberaba River Basin)	Water supply	C	Santos and Naves (2016)
Capivari River (Capivari River Basin) to Cachoeira River (Cachoeira River Basin)	Dam	C	Branco (2008)
São Francisco River (São Francisco River Basin) to Paraíba do Norte River (Paraíba River Basin)	Water supply	C	Ramos et al. (2018)
São Francisco River (São Francisco River Basin) to Piranhas-Açu River (Piranhas-Açu River Basin)	Water supply	C	Andrade et al. (2011)
São Francisco River (São Francisco River Basin) to Apodi River (Apodi River Basin)	Water supply	C	Andrade et al. (2011)
São Francisco River (São Francisco River Basin) to Jaguaribe River (Jaguaribe River Basin)	Water supply	C	Andrade et al. (2011)
Doce River (Doce River Basin) to Riacho River (Riacho River Basin)	Water supply	C	Coelho (2006)
Paraíba do Sul to Cantareira	Water supply	U	Andrade et al. (2011); Vitule et al. (2015)
Tocantins River (Amazon River Basin) to Preto River (São Francisco River Basin)	Navigation, water supply	P	This study
Piracicaba River (Piracicaba River Basin) to upper Tietê River (upper Tietê River Basin)	Water supply	C	Andrade et al. (2011)
Cravo River (Cravo River Basin) to Ligeirinho reservoir (Ligeirinho River Basin)	Water supply	U	Bernardi (2014)
Caí River (Caí River Basin) to Sinos River (Sinos River Basin)	Water supply	C	Online Reference S8

Situation: C concluded, P planned (under evaluation), U unknown

economic-development projects (Vitule et al. 2015; Brito and Magalhães 2017). PL 6569/2013 is not an isolated case in Brazil (Table 1). Several large-scale projects have been developed or planned in the last decade, as is the case of the São Francisco River water-diversion mentioned previously: a problematic project characterized by environmental problems and delays (Brito and Magalhães 2017). Severe water scarcity in the city of São Paulo has also led local authorities to propose diversions (Vitule et al. 2015) to bring water from several other basins (Paraíba do Sul, Ribeira de Iguape, and Itapanhaú), and recently even the transposition of the Amazon River has been suggested by politicians (Online Reference S9). Water diversions are well accepted by Brazilian authorities because they are striking and have popular appeal. Consequently, new water diversions will appear as water demands increase.

It is also important to remember that Brazil is signatory to the Convention on Biological Diversity in which Aichi Biodiversity Target No. 9 specifies that “By 2020, invasive alien species and pathways are identified and prioritized, priority species are controlled or eradicated, and measures are in place to manage pathways to prevent their introduction and establishment” (Online Reference S10). We recommend that Brazil’s leaders heed warnings from the local and international scientific communities questioning PL 6569/2013 and other harmful projects with high environmental risks and costs. Authorities must always treat such projects with complete transparency, discussing both positive and negative impacts with all sectors of society, including academia. Decision makers must recognize the value of biodiversity and give more credit to science-based knowledge (Azevedo-Santos et al. 2017) before formulating policy largely based on populism and particular interests. Construction of water diversions is an environmentally and economically risky activity, as we show. The entire region’s natural and cultural heritage may be decimated, and freshwater ecosystems that humans and other aquatic organisms alike rely on can be compromised, certainly resulting in a global impact for humanity.

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