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Combined exposure to hydroelectric expansion, climate change and forest loss jeopardies amphibians in the Brazilian Amazon

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Abstract

Aim: Human-driven impacts constantly threat amphibians, even in largely protected regions such as the Amazon. The Brazilian Amazon is home to a great diversity of amphibians, several of them currently threatened with extinction. We investigated how climate change, deforestation and establishment of hydroelectric dams could affect the geographic distribution of Amazonian amphibians by 2030 and midcentury.

Location: The Brazilian Amazon.

Methods: We overlapped the geographic distribution of 255 species with the location of hydroelectric dams, models of deforestation and climate change scenarios for the future.

Results: We found that nearly 67% of all species and 54% of species with high degree of endemism within the Legal Brazilian Amazon would lose habitats due to the hydroelectric overlapping. In addition, deforestation is also a potential threat to amphibians, but had a smaller impact compared to the likely changes in climate. The largest potential range loss would be caused by the likely increase in temperature. We found that five amphibian families would have at least half of the species with over 50% of potential distribution range within the Legal Brazilian Amazon limits threatened by climate change between 2030 and 2050.

Main conclusions: Amphibians in the Amazon are highly vulnerable to climate change, which may cause, directly or indirectly, deleterious biological changes for the group. Under modelled scenarios, the Brazilian Government needs to plan for the development of the Amazon prioritizing landscape changes of low environmental impact and economic development to ensure that such changes do not cause major impacts on amphibian species while reducing the emission of greenhouse gases.

KEYWORDS
conservation science, distribution range, extinction risk, habitat loss, land cover, range shift

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1 | INTRODUCTION

The world's tropical biodiversity remains strongly threatened directly or indirectly by human impacts (Newbold et al., 2014). Land use and climate changes along with infrastructure development (e.g., establishment of hydroelectric dams) are major threats to tropical biodiversity (Finer & Jenkins, 2012; Khaliq, Hof, Prinzinger, Bohning-Gaese, & Pfenninger, 2014; Newbold et al., 2014). Among critical impacts are changes in the structure of ecological assemblages (Echeverría-Londoño et al., 2016; Newbold et al., 2016) and in native vegetation structure (Aleman, Blarquez, & Staver, 2016), which cause loss of biodiversity and ecosystem functions. Considering the synergistic effects of land use and climate change, it is essential to understand their potential impacts on biodiversity (Brodie, 2016) and to enable the development of management strategies and conservation policies that safeguard Earth's natural heritage (Titeux et al., 2016).

The Brazilian Amazon currently faces several threats to its conservation. It is the richest rain forest on Earth, and among all its biodiversity, amphibians are one of the vertebrate groups most sensitive to environmental changes (Nori et al., 2015; Wells, 2010). The establishment of hydroelectric dams has been listed as a threat to amphibian populations in the Amazon (IUCN, 2016), and over the next years, a set of new hydroelectric are planned to be built in the region (Castello & Macedo, 2016; Finer & Jenkins, 2012). These new hydroelectric may potentially cause social and environmental impacts (Fearnside, 2016; Prado et al., 2016), such as fragmentation and habitat loss, disruption of populations and local extinctions. In Brazil, the construction of hydroelectric plants has already caused population declines and local extinctions of amphibians (Brandão & Araújo, 2008; Lima et al., 2015; Moraes, Pavan, Barros, & Ribas, 2016) in addition to threatening important, but not well-known evolutionary systems of amphibians such as hybrid zones (Simoes, Lima, & Farias, 2012). The establishment of new hydroelectric plants also has indirect impacts such as deforestation caused by the construction itself, the reservoirs and migration of workers, which are also critical to the survival of amphibians (Finer & Jenkins, 2012).

Satellite monitoring data shown that deforestation have increased in the Amazon over the last five years (Fearnside, 2015a). Deforestation and habitat fragmentation can limit dispersion of amphibian species causing a decrease in gene flow and, as a consequence, loss of genetic diversity (Cushman, 2006; Dixo, Metzger, Morgante, & Zamudio, 2009). Land use changes have also serious impacts on amphibians, especially when forest areas are converted to crops, changing environmental quality, and species richness and abundance of amphibians (Schmutzer, Gray, Burton, & Miller, 2008). Further, land use is an important biogeographic driver to determine the spatial distribution and evolution of amphibian species. Thus, land use change it is a threat, which can jeopardize the conservation of entire lineages of the group (Brum et al., 2013).

Hydroelectric dams building and land use change also contribute to climate warming (Fearnside, 2015b; Lejeune, Davin, Guillod, & Seneviratne, 2015). All over the world, temperature increases have been related to reduction in species survival, changes in the reproductive characteristics of amphibians and the advance of infectious diseases (Pounds et al., 2006; Reading, 2007; Ron, Duellman, Coloma, & Bustamante, 2003). Despite all these threats, no amphibian extinction has been recorded in the Amazon until now, although an increasing number of studies highlighted the high vulnerability of amphibians to climate change in the Brazilian Atlantic Forest (Lemes & Loyola, 2013; Lemes, Melo, & Loyola, 2014; Loyola, Lemes, Brum, Provete, & Duarte, 2014) and in the Amazon.

Here, we quantified how the expansion of hydropower, forest loss and climate change affect the distribution of Amazonian amphibians. By considering different threats to amphibians, we also assessed the direct and indirect effects of these changes and inform decision-making for the conservation of this imperilled group.

2 | METHODS

2.1 | Species' data

Data on amphibian distribution were obtained at the International Union for the Conservation Nature website (IUCN version 2015.4; Red List Spatial Data, www.iucnredlist.org). We only selected species that had any portion of their distribution inside the Brazilian Legal Amazon limits, corresponding to a total of 255 species (see Appendix S1). To evaluate species with different degrees of endemism in the Amazon extent, we presented data based on (1) all species and (2) species with >80% of the distribution ranges within the Brazilian Legal Amazon (see Appendix S1). For Anurans, we only included species that were also reported for the Amazon biome (Toledo & Batista, 2012). These extent of occurrence maps are usually used in an initial approach in areas with high biodiversity levels and low information of presence and absence of species (Lemes, Faleiro, Tessarolo, & Loyola, 2011), which is the case of the Brazilian Amazon. Furthermore, these data are a good representation of the distribution of amphibian species and have a good accuracy in large-scale analyses (Ficetola et al., 2014). These range maps have also been extensively used in conservation and applied studies as they were generated and/or validated by experts in each taxonomic group (Lemes & Loyola, 2013; Loyola et al., 2014; Nori et al., 2015; Sales, Neves, De Marco, & Loyola, 2017). However, we need to interpret results obtained from range maps carefully, as they have inherent commission and omission errors in species distributions, especially in tropical areas of South America (Ficetola et al., 2014; Sales et al., 2017).

2.2 | Hydroelectric data

We obtained information on the location points of 3,176 hydroelectric plants for the Brazilian territory at the National Electric Energy Agency of Brazil website (ANEEL; Georeferenced Information System of the Electric Sector, 2016, sigel.aneel.gov.br). From these total, 474 were large hydroelectric plants (LHP, >30 MW) and 2,702 were small hydroelectric plants (SHP, >1 MW <30 MW). We only

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included in the analysis three categories of hydroelectric: (1) planned, (2) under construction and (3) in operation within the Legal Brazilian Amazon corresponding to a total of 520 hydroelectric plants (131 LHP and 389 SHP) (Figure 1a).

2.3 | Land use data

We obtained current (2012) and projected (2030 and 2050) land use maps at 500 m of resolution from Soares-Filho et al. (2016). This dataset was derived from a suite of models and a wide geographic dataset information (e.g., maps of suitable land for mechanized agricultural expansion and data of land titling and information of priority conservation and exploration areas, see maps.csr.ufmg.br) to model scenarios of land use and land use change (for more details, see Soares-Filho et al. [2016]). To use these maps, we considered only the forested areas as potential habitat; deforested areas such as urban or grazing zones were not considered in the analysis.

2.4 | Climatic data

We obtained data on mean annual temperature for current (1950–2000) from the WorldClim database (version 1.4; www.worldclim.org) and for projections for the future (2030 and 2050) from the Consortium of International Agricultural Research Centre's website (CGIAR; ccafs-climate.org).

The current mean annual temperature is the result of the interpolation of global monthly climate data (for further details, see Hijmans, Cameron, Parra, Jones, and Jarvis [2005]). To create the interpolation, Hijmans et al. (2005) used data from 24,542 weather stations around the world. The WorldClim data resolution for this study was 5 min. Data on future climate projections were derived

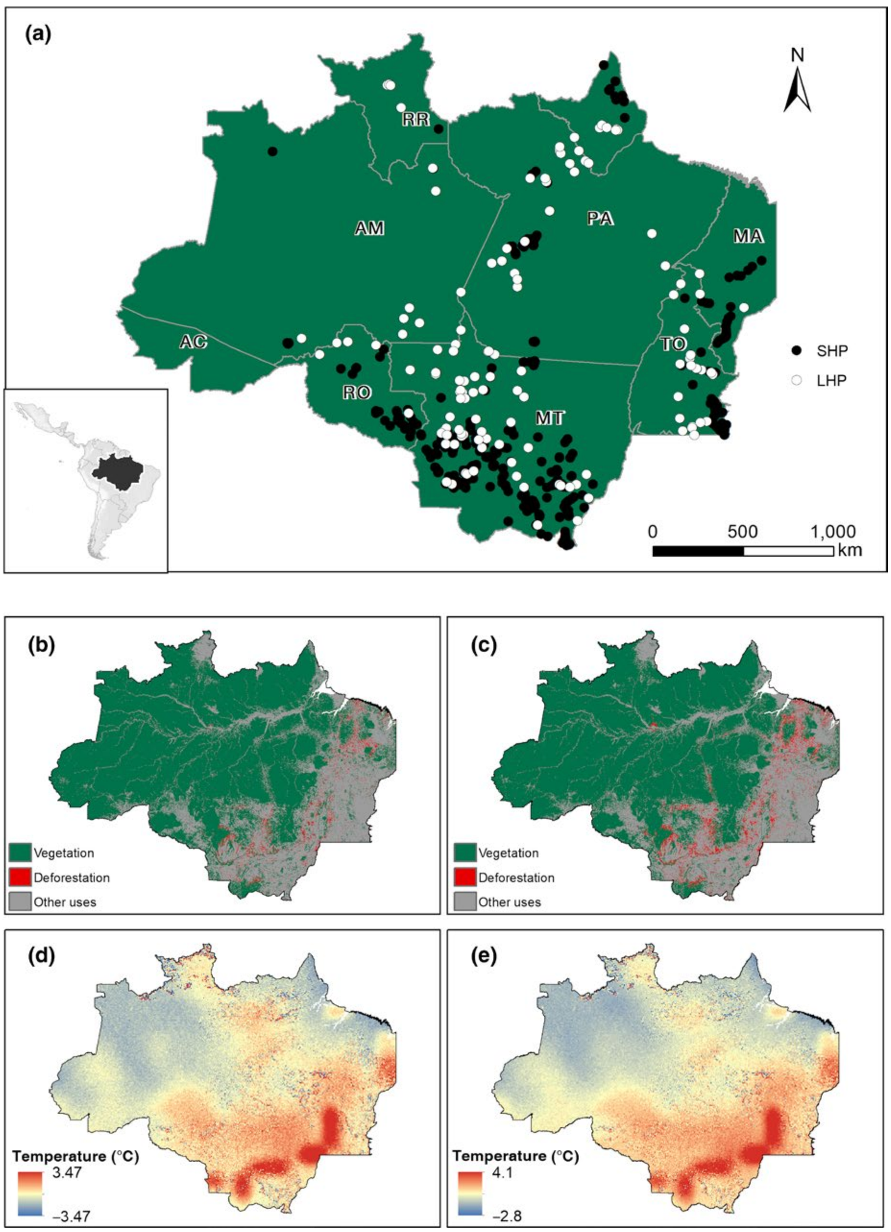

FIGURE 1 (a–e) Location of the study area. (a) Legal Brazilian Amazon geographic limits and hydroelectric points (black and white circles represent small (SHP) and large (LHP) hydroelectric plants, respectively); (b,c) deforestation scenarios for the Amazon according to Soares-Filho et al. (2016), for 2030 and 2050, respectively; (d,e) difference in the mean annual temperature between the present and climatic scenarios for 2030 and 2050, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

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from three alternative models (GISS, MIROC and MRI) for 2030 and 2050 at a spatial resolution of 5 min of latitude/longitude based on a high-emission greenhouse gases scenario proposed by Intergovernmental Panel on Climate Change (IPCC) (Representative Concentration Pathway; RCP 8.5). According to this scenario, emissions of greenhouse gas continue to rise throughout the 21st century. Although global circulation models (GCMs) can show low accuracy for fairly populated regions, we ran analysis using three of the most accurate GCM that showed low uncertainties based on low standard deviations (Figure S1).

2.5 | Species' vulnerability analysis

To evaluate the threats of hydroelectric plants, we overlapped the location points to each species' ranges and calculated the number and density of hydroelectric dams within each species' range in the Legal Brazilian Amazon limits. To assess the species vulnerability to land use changes, we identified the current forest cover within each species' range (within the Legal Amazon extent) according to land use model for the current period (Soares-Filho et al., 2016). We considered as species ranges only cells containing areas of forest cover. For each species' range cell, we identified the forest cover change in future for each period (2030 and 2050) and considered vulnerable cells that might be deforested in future. In order to assess amphibian vulnerability to climate change, we computed for the entire species' range (not only species range within the Amazon extent) the maximum value of temperature at which species is currently exposed. As data on species' physiological limits are scarce, the maximum values of temperature could represent a good proxy to species tolerances (Foden et al., 2013).

For each cell overlapping amphibian species range, we first calculated an average future temperature based on three climate models for each period (2030 and 2050). We only computed future temperatures within cells of species range if any part was covered by forest land use. We considered that species would potentially be exposed to climate change in those cells where future climate temperature exceeds the maximum current temperature at which a species is already exposed (for a similar approach, see Ribeiro, Sales, De Marco, and Loyola [2016]).

Finally, we overlapped the climatic exposition and the forest loss maps to identify areas where species may potentially be exposed to both threats simultaneously. As we only assessed the proportion of the area affected by threats inside the limits of the Legal Brazilian Amazon, we resized the values to be relative of the entire species' distribution range. All analyses and figures were performed and built in ArcGis10.4 (ESRI, 2015) and R version 3.3.1 (R Core Team, 2016) using the raster package (Hijmans, 2016).

3 | RESULTS

The 255 species studied correspond to 19 families of Amazonian amphibians, and 13% of species has unknown status or is classified into some category of threat (IUCN, 2016). From this total 63 species from 13 families presented high degree of endemism in the Amazon extent, with >80% of their distributions within the Brazilian Legal Amazon. For the entire Brazilian Amazon, 520 hydroelectric plants are predicted, and most of these constructions are planned to be built near the Arch of Deforestation, on the east and south regions of the Amazon (Figure 1a).

From the total of 255 species of Amazonian amphibians and 63 with >80% of their distribution range within the Brazilian Legal Amazon, 170 species (67%) and 34 (54%) overlapped their distributions with hydroelectric plants, respectively (Table 1). Among the families with species with higher degree of endemism that would be less threatened are Bufonidae (1 sp.), Eleutherodactylidae (1 sp.), Pipidae (1 sp.), Siphonopidae (1 sp.) and Typhlonectidae (1 sp.). On the other hand, Dendrobatidae (4 spp.), Leptodactylidae (5 spp.) and Microhylidae (5 spp.) would have more than 50% of their highly endemic species within the Legal Amazon limits threatened by hydroelectric plants (Table 1). The family Hylidae should be the one with higher density of hydroelectric plants in relation to the distribution range of species with high degree of endemism within the Legal Brazilian Amazon (Table 1).

Overall, Bufonidae, Hylidae, Leptodactylidae, Microhylidae and Siphonopidae are the families that should be most threatened with the construction of hydroelectric plants (Figure 2). Species of those families might be already suffering loss of area due to the construction and operation of at least 162 hydroelectric power plants (Appendix S1). If all the planned hydroelectric plants were built, there would be 520 constructions overlapping those families' territories.

The species *Hypsiboas leucocheilus* and *Pristimantis variabilis* from the Hylidae and Craugastoridae families, respectively, showed the higher densities of hydroelectric plants, considering their small distribution ranges within the Legal Brazilian Amazon (Appendix S1).

According to land use change models, between 2030 and 2050, 200 species will likely to lose area due to deforestation. Among those species, *Oreobates heterodactylus* and *Elachistocleis carvalhoi*, both with higher degree of endemism, will potentially lose over 10% of their distribution areas within the Legal Brazilian Amazon (Appendix S1). From all amphibian species, 37 with higher endemism in the Legal Amazon would reduce their distributions' range due to land use change in 2030 and 2050 (Table 2). Even though deforestation is a local change, it is possible that the potential loss of amphibians' range will increase due to this threat (Figure 3).

The greatest potential loss of distribution area was caused by climate change (Figure 3; Appendix S1). We found that five amphibian families would have at least half of their species with over 50% of distribution area potentially threatened by the climatic changes between 2030 and 2050 (Appendix S1). The amphibian species would have on average 19.1% and 29.9% of area within the Legal Brazilian Amazon limits potentially exposed to increasing temperatures in 2030 and 2050, respectively. Considering only species with high endemism in the Amazon extent, 55 (87.3%) would lose area due to increases in temperature in 2050 (Appendix S1). The mid-west portion

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TABLE 1 Total number of (1) all amphibian species and (2) species with high degree of endemism (>80% of distribution range with the Amazon extent) affected by hydroelectric plants in the Legal Brazilian Amazon for each family of amphibians. Mean density (range) of hydroelectric plants reported by 10,000 km^2

	All species		Species with high degree of endemism in the Amazon	
Family	No. Species/ hydroelectric	Mean hydroelectric density (range)	No. Species/ hydroelectric	Mean hydroelectric density (range)
Allophrynidae	1/1	0.55	0/0	0
Aromobatidae	15/8	0.81 (0.22–1.90)	11/5	0.92 (0.22–1.90)
Bufonidae	21/11	1.78 (0.07–7.43)	5/1	0.35
Caeciliidae	2/2	0.25 (0.12–0.39)	0/0	0
Centrolenidae	2/0	0	0/0	0
Craugastoridae	28/11	61.72 (0.10–673.44)	4/2	0.41 (0.24–0.57)
Dendrobatidae	19/12	1.48 (0.16–9.94)	6/4	0.40 (0.16–0.64)
Eleutherodactylidae	2/2	0.55 (0.45–0.64)	1/1	0.45
Hemiphractidae	2/0	0	0/0	0
Hylidae	85/60	668.61 (0.03–40,000.00)	17/8	5,000.48 (0.22–40,000.00)
Leptodactylidae	49/40	3.93 (0.02–18.26)	7/5	1.63 (0.48–5.37)
Microhylidae	15/12	1.42 (0.03–6.85)	6/5	0.46 (0.03–0.81)
Odontophrynidae	1/0	0	1/0	0
Pipidae	3/3	0.50 (0.32–0.78)	1/1	0.32
Plethodontidae	2/1	0.09	1/0	0
Ranidae	1/1	0.75	0/0	0
Rhinatrematidae	1/1	2.49	0/0	0
Siphonopidae	3/3	3.10 (0.81–6.85)	1/1	0.81
Typhlonectidae	3/2	0.46 (0.33–0.58)	2/1	0.58

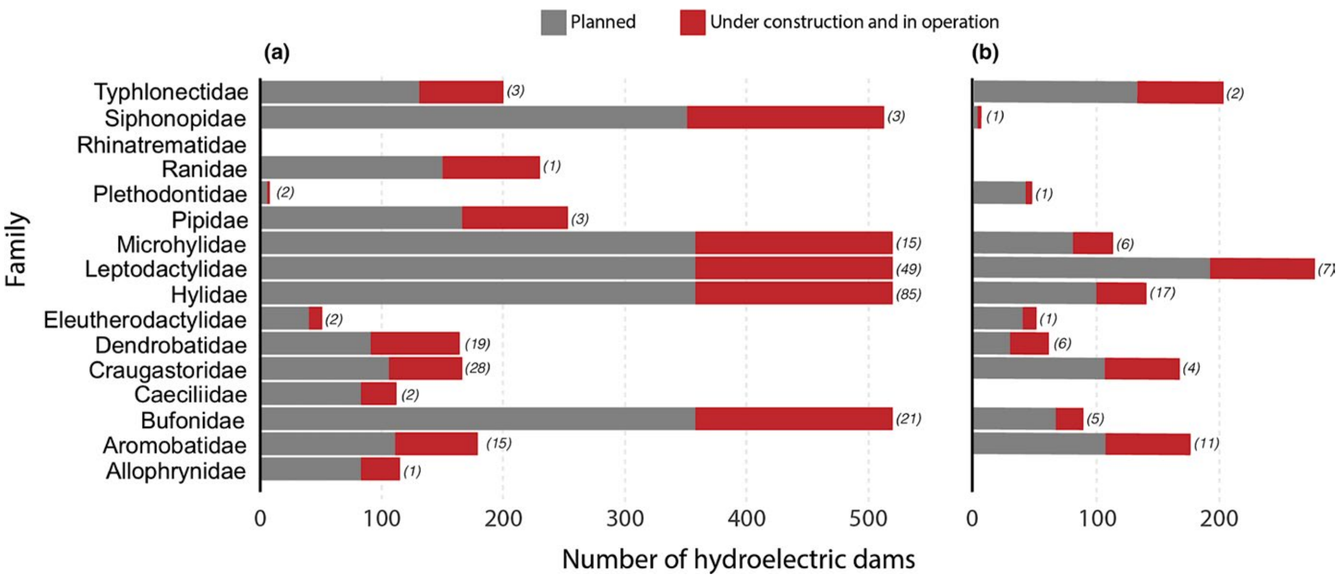

FIGURE 2 (a,b) Overlap of planned (grey) and under construction and in operation (red) hydroelectric plants over the distribution of amphibian families with (a) all species and (b) species with >80% of their distribution range within the Legal Brazilian Amazon. The number of amphibian species per family is shown in parentheses [Colour figure can be viewed at wileyonlinelibrary.com]

of the Brazilian Legal Amazon presents an area that is more prone to impacts by climatic exposure and land use combined with concentration of distribution of amphibian species with higher degree of endemism in the Legal Brazilian Amazon (Figure 4a,b).

4 | DISCUSSION

Our study evaluated the threats caused by environmental and landscape changes over Brazilian Amazonian amphibians

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TABLE 2 Total number of amphibian species and species with high degree of endemism (>80% of distribution range with the Amazon extent) affected by future threats in the Amazon (deforestation and climate change) for each family of amphibians

Family	Number of all species	Number of species affected by		Number of species with high degree of endemism	Number of species affected by	
		Land use change 2030/2050	Climate change 2030/2050		Land use change 2030/2050	Climate change 2030/2050
Allophrynidae	1	1/1	1/1	0	0	0
Aromobatidae	15	7/9	14/14	11	4/6	10/10
Bufonidae	21	10/12	18/19	5	1/2	3/4
Caeciliidae	2	2/2	2/2	0	0	0
Centrolenidae	2	0/0	2/2	0	0	0
Craugastoridae	28	3/4	27/28	4	3/3	4/4
Dendrobatidae	19	9/9	18/18	6	3/3	5/5
Eleutherodactylidae	2	1/1	2/2	1	1/1	1/1
Hemiphractidae	2	0/0	2/2	0	0	0
Hylidae	85	48/55	79/81	17	6/6	13/13
Leptodactylidae	49	33/35	48/49	7	6/6	7/7
Microhylidae	15	10/12	15/15	6	5/6	6/6
Odontophrynidae	1	0/0	1/1	1	0/0	1/1
Pipidae	3	3/3	3/3	1	1/1	1/1
Plethodontidae	2	2/2	2/2	1	1/1	1/1
Ranidae	1	1/1	1/1	0	0	0
Rhinatrematidae	1	0/0	0/1	0	0	0
Siphonopidae	3	3/3	3/3	1	1/1	1/1
Typhlonectidae	3	2/2	2/2	2	1/1	1/1
Total	255	135/157	240/246	63	33/37	54/55

throughout the next three decades. We showed the potential synergistic threat of the hydroelectric plants implementation, the loss of forest cover and temperature rise on the diversity of Amazonian amphibians. The installation of hydroelectric plants and land use changes generates the release of greenhouse gases, contributing to global temperature changes. The complex simultaneous action of several factors, environmental and anthropic, should be considered as an important driver for the conservation of amphibians (Sodhi et al., 2008; Whitfield et al., 2007). We considered Brazilian Government planning to use the potential of the Amazon basin to increase energy production by 60% until 2030 (MME, 2007) and the growth in hydroelectric numbers in the Brazilian Amazon (Castello & Macedo, 2016). Further, the potential loss of species is certainly underrated because of the low taxonomic knowledge and patterns of intraspecific diversity in tropical regions (Diniz, Loyola, Raia, Mooers, & Bini, 2013; Fouquet et al., 2007; Simoes et al., 2014).

The increase in the number of hydroelectric plants in the Brazilian Legal Amazon also brings an indirect concern, the increase in deforestation. The establishment of new hydroelectric plants has the potential to increase the deforestation rates due to the formation of the reservoir and construction of new roads and transmission lines (Fearnside, 2008; Finer & Jenkins, 2012). These interventions are well documented as important factors in the deforestation of tropical forests (Chen, Powers, de Carvalho, & Mora, 2015; Laurance, Goosem, & Laurance, 2009). We showed that, despite localized, deforestation advances over the distribution area of amphibians, having agriculture and livestock as the main drivers, which have been observed previously (Almeida et al., 2016). The conversion of forests to pastures is an important factor and influences the number and diversity of amphibians (Bernarde & Macedo, 2008; da Silva, Candeira, & Rossa-Feres, 2012) because it has an effect over the availability of food and reproductive sites, and it can cause microclimatic alterations as well as a decrease in the dispersion, that limit the survival of some amphibian species. Land use change and the long-term deforestation create an extinction debt on native species which could increase species losses in the Amazon (Rosa, Smith, Wearn, Purves, & Ewers, 2016).

Our work also highlights that, among the species with the highest degree of endemism in the Amazon region, the *H. leucocheilus* is the most threatened by the construction of hydroelectric plants. However, this result should be interpreted with caution, as this species was previously within the genus *Hyla* and has only been moved to the resurrected genus *Hypsiboas* recently (Faivovich et al., 2005); thus, there is little information on its extent of occurrence (Caramaschi, 2004). Among all species

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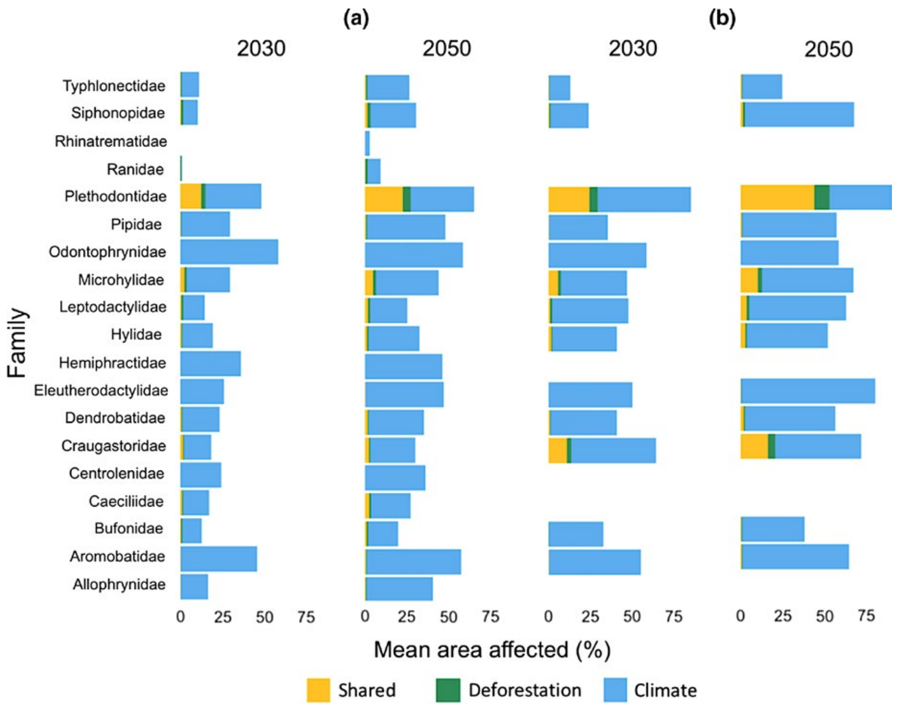

FIGURE 3 (a,b) Future threats for amphibians in the Brazilian Amazon. Chart bar showing for each amphibian family the mean percentage of the distribution range within the Legal Brazilian Amazon that would be affected by climate change, deforestation and both threats combined. (a) All species and (b) species with >80% of their distribution range within the Legal Brazilian Amazon, in 2030 and 2050 [Colour figure can be viewed at wileyonlinelibrary.com]

studied, *P. variabilis* is the second with highest density of hydroelectric plants within its distribution inside the Legal Brazilian Amazon. To protect amphibian species, the Brazilian Government needs to evaluate new alternatives for the generation of energy in the Amazon, besides expanding the efforts to reduce deforestation in the region.

We found that the exposure to temperature rise represents the greatest threat to the distribution area of Amazonian amphibians, because it happens at a scale higher than deforestation or the effects of the hydroelectric plants. Studies characterize the Amazon as an area of high vulnerability to climatic changes for amphibians (Foden et al., 2013) and other groups (Ribeiro et al., 2016), especially because of the great diversity of species that occur in this biome. It is important to consider the direct and indirect effects of temperature rise in various aspects of the amphibians' lives (Carey & Alexander, 2003). Studies observed that global warming can harm amphibians' physiology, causing an increase in the susceptibility to infections (Raffel, Rohr, Kiesecker, & Hudson, 2006), as well as higher mortality rate and decrease in fertility (Reading, 2007). Taking into account the limits of physiological tolerance of the species, especially the temperature, is a key point for the conservation of species in the current scenario of climate changes (Seebacher & Franklin, 2012). Considering the possibility of extreme thermal events occurring in future, the low thermal tolerance (Gutierrez-Pesquera et al., 2016) and limited dispersion capacity of amphibians (Sinsch, 1991), studies focusing on the conservation of these groups should become priority.

However, as we calculated climate change exposition based on the number of the cells within the distribution range where climate temperature exceeds the maximum current temperature of the species' distribution, we are not considering that species can track appropriate conditions in space and shift their distributions (Bellard, Bertelsmeier, Leadley, Thuiller, & Courchamp, 2012). Also, predictions of gains in amphibian species as a result of potential climate change shifts in species distributions were already documented (Blaustein et al., 2010).

It is important to highlight that we are only evaluating species that have distributional ranges within the limits of the Legal Brazilian Amazon. For example, the Ranidae and Rhinatrematidae families, both with one species in our study area, will have a low potential climatic threat in 2030; however, by 2050, more than 80% of the family range of Rhinatrematidae may have its area affected by climate change. Even with this potential threat, these particular species of these families are not listed in any status of threat and have no major threats highlighted by the IUCN (Gaucher, MacCulloch, Wilkinson, & Wake, 2004; La Marca, Azevedo-Ramos, Coloma, Ron, & Hardy, 2010).

All these changes in landscape should be part of the planning of the region, aiming to avoid large losses in the local biodiversity and to reduce the release of greenhouse gases and consequently the temperature rise. Global warming is a large-scale threat, especially in the Amazon, and that is why Brazil must retake leadership (Loyola, 2014) when it comes to environmental issues. Diversification of energy sources should be a key factor in ensuring that Brazil can expand its energetic production (Corrêa da Silva, de Marchi Neto, & Silva Seifert, 2016; Herreras Martínez et al., 2015) without contributing to forest loss and climate warming. Such expansion should prioritize renewable sources of energy, such as solar or wind; review investments in large hydroelectric plants; and manage measures that can reduce the impact of large constructions and reduce deforestation rates and climatic changes in the region.

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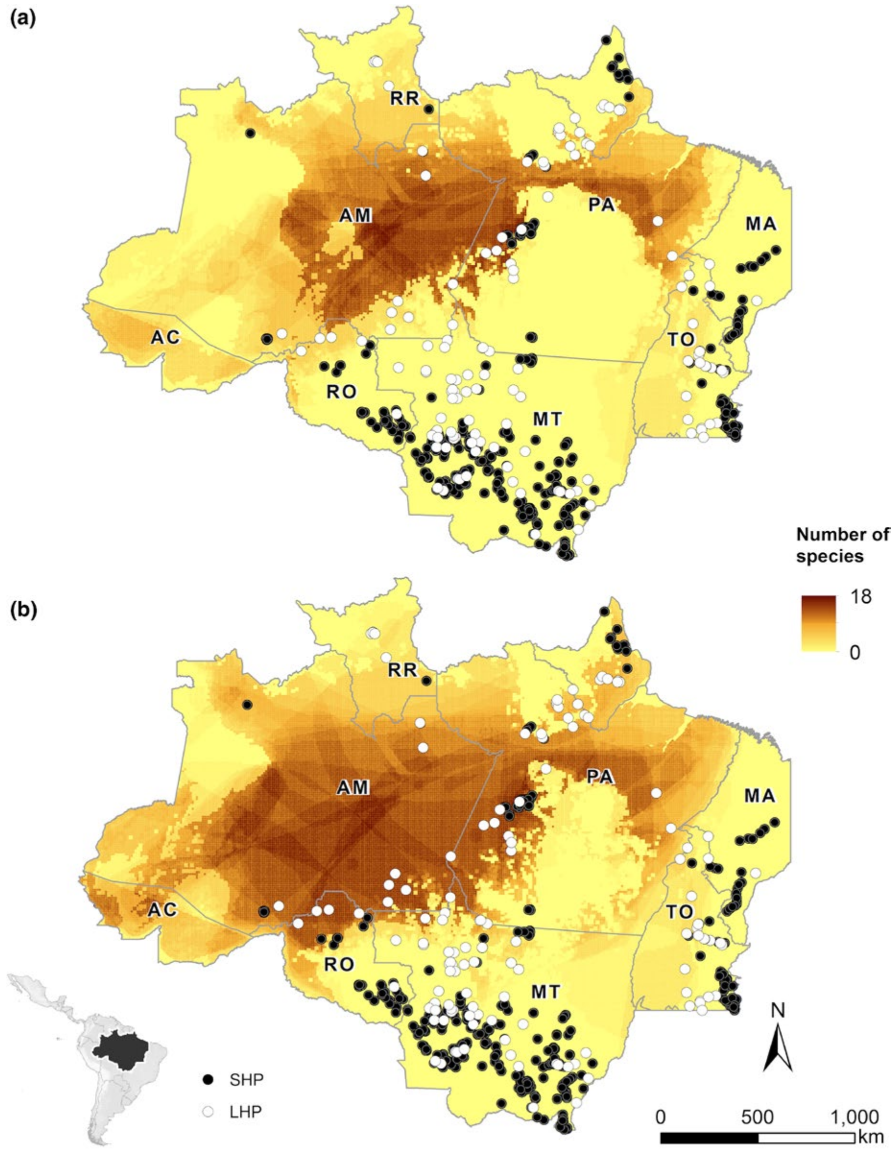

FIGURE 4 Map showing the spatial distribution of the upper quartile (75%) of species with >80% of their distribution range within the Legal Brazilian Amazon affected by (a) climate change and (b) climate change and deforestation combined. Black and white circles represent the location of small (SHP) and large (LHP) hydroelectric plants, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

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DATA ACCESSIBILITY

Species occurrence data are freely available at IUCN Red List website (http://www.iucnredlist.org). Hydroelectric plants data are available at the National Electric Energy Agency of Brazil website (http://sigel.aneel.gov.br/sigel.html). Climate data are available at WorldClim (http://www.worldclim.org).

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BIOSKETCH

Yuri B. S. Silva focuses on various biological aspects of Amazonian amphibians.

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Author contributions: Y.B.S.S., F.M. and R.L. conceived the ideas; Y.B.S.S., B.R.R., F.T.B., B.S. and R.L. collected the data; Y.B.S.S., F.M., B.R.R., F.T.B. and R.L. analysed the data; and all authors contributed to the writing.

SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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