Climate change sensitivity of threatened, and largely unprotected, Amazonian fishes

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ABSTRACT

1. Climate change is poised to have fundamental impacts on the freshwater environments of the Amazon River Basin, and protected areas are routinely proposed as a possible management strategy to conserve freshwater fishes. However, there remains a paucity of information regarding the sensitivity of threatened fish species to climate-induced changes in water quantity and quality.

2. An expert-based survey was used to address the following questions: (1) Are currently threatened fish species in Brazil also sensitive to projected effects of climate change? (2) Does the current conservation status of fish species also reflect their degree of sensitivity to climate change? and (3) What are the specific aspects of climate change that are likely to contribute the most to species sensitivity?

3. Survey respondents evaluated 35 species (11 families) representing 50% of the threatened species in the Brazilian Amazon. The results suggest that the majority of threatened Brazilian fish species are considered highly sensitive to climate change impacts.

4. Climate-induced changes in water quality were, on average, considered a greater threat to species persistence than potential changes in water quantity. Survey results also suggest that fishes exhibit high sensitivity to changes in temperature and dissolved oxygen, and moderate to high sensitivity to changes in high-flow (i.e. flood) and low-flow (i.e. drought) regimes.

5. A considerable mismatch was found between species conservation status and sensitivity to climate change, suggesting that perceptions of present-day extinction risk do not necessarily provide insight into future risks associated with climate change.

6. Species sensitivity to climate change showed no relationship to dispersal ability, indicating that protected areas may serve as important refugia for those species unable to keep pace with climate change. Despite this, the number and size of protected areas in Brazil have decreased over the past decade, largely to support the exploitation of hydropower and mining. Strategic conservation planning that involves existing and new protected areas for those species most at risk to climate change is warranted.

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INTRODUCTION

Protected areas (PAs) represent one of many possible strategies to conserve freshwater fishes in the light of future climate change, albeit with a number of recognized challenges (Abell et al., 2007; Lawrence et al., 2011). Protected areas may be less affected by the impacts of climate change and other human activities, thus providing habitat refugia for species in the future (Pittock et al., 2008). For example, the network of PAs in tropical forests can buffer the effects of climate change by decreasing the velocity of future changes in temperature and precipitation (Loarie et al., 2007; Lawrence et al., 2008). For instance, the network of PAs in Brazil has the largest PA network in the world (Bernard et al., 2014), together with some of the largest conservation units (with more than 3 million ha), classified according to Peres (2005) as mega-reserves. In total, approximately 43% of Brazilian Amazon territory are considered protected areas (Veríssimo et al., 2011). With the goal of reducing rates of deforestation, the Brazilian Amazon witnessed rapid growth in the number of PAs established in the 2000s (Veríssimo et al., 2011). As a result many PAs were located in the south-eastern region of the Amazon where numerous human threats already exist. These efforts were effective in slowing the rate of deforestation, and thus reduced carbon dioxide emissions (Soares-Filho et al., 2010). However, the Amazon region is expected to face considerable threats in the future owing to the combined impacts of climate change and continued deforestation (Malhi et al., 2008).

It is predicted that the Amazon River Basin will be especially prone to the ecological impacts of future climate change (Pacifici et al., 2015; Castello and Macedo, 2016). Models indicate that more than one-third of freshwater fish species in the Amazon, Tocantins and Araguaia river basins may be lost if the most pessimistic scenarios of climate change are realized (Xenopoulos et al., 2005). The Intergovernmental Panel on Climate Change (IPCC) recently forecast that the Amazon will face warmer and dryer conditions, with less predictable rainfall and more extreme events (e.g. droughts and floods) in the future (Haylock et al., 2006; Brodie et al., 2012). Amazonian fish communities are largely structured by flood pulse dynamics (Sousa and Freitas, 2008); thus climate-driven changes to the magnitude, duration and timing of ecologically-critical flow events will have direct consequences for the breeding, migration and persistence of fish species (Bunn and Arthington, 2002; Poff et al., 2002; Leigh et al., 2014). In addition, elevated temperature and depressed river discharge will promote conditions of reduced dissolved oxygen, which affects primary productivity (Poff et al., 2002; Leigh et al., 2014) and interacts with species-specific physiological tolerances to determine fish performance and patterns of spatial occupancy (Brauner and Val, 2006; Barletta et al., 2010).

Recent decades have witnessed the rapid evolution of assessments on climate change vulnerability to help set priorities and guide conservation efforts, including the identification of protected areas (Williams et al., 2008). Approaches include evaluating vulnerability according to intrinsic traits of species (Foden et al., 2013; Pearson et al., 2014), past changes in geographic distribution (Bush et al., 2014), exposure to extrinsic conditions associated with climatic changes (Foden et al., 2013), and the combination of both intrinsic and extrinsic factors (Gardali et al., 2012; Bush et al., 2014; Case et al., 2015). For instance, Foden et al. (2013) combined information about species sensitivity and exposure to projected climate change for the world’s birds, amphibians and corals to identify taxa and areas that require conservation attention. Similarly, Bush et al. (2014) assessed the vulnerability of Australian Odonata according to past changes in species ranges and projected exposure to future climate change. In data-limited situations, expert knowledge has emerged as a viable approach for assessing species sensitivity to climate change (Moyle et al., 2013; Case et al., 2015). For instance, Moyle et al. (2011, 2013) used experts to evaluate the threatened status of Californian (USA) freshwater fishes according to future threats of climate change.

In Brazil alone there are 310 species classified as threatened according to the most recent national evaluation (normative instruction number 445, www.icmbio.gov.br). Of the many threats to Brazilian fishes, habitat loss and degradation, river fragmentation by dams, invasive species, overexploitation, pollution, and climate change,
are of major concern (Barletta et al., 2010; Nogueira et al., 2010; Castello et al., 2013). The threatened species have at least 25% of their range already affected by at least one of these factors, thus putting into question whether existing protecting areas will be adequate to achieve conservation goals. Despite this growing awareness, management and conservation efforts to protect Brazilian freshwater ecosystems and their constituent fish species remain scarce (Castello et al., 2013; Bernard et al., 2014).

Managing Amazonian freshwater fishes into the future requires a robust understanding of which species will be most sensitive to projected climatic changes, and the factors that will make them more sensitive (Castello and Macedo, 2016). This study sought to evaluate the sensitivity of Amazonian freshwater fishes that are currently threatened (by several factors) to potential climate change impacts. Restricted geographic ranges, small populations, and low tolerance to environmental changes are intrinsic traits that typically make species more sensitive to a given level of exposure to climate change (Williams et al., 2008; Pearson et al., 2014), and are thus considered vulnerable.

An expert-based survey was used to assess sensitivity given the limited published information on the physiological and life-history traits of Amazonian freshwater fishes (Barletta et al., 2010; Baigún et al., 2012; Castello et al., 2013; Ota et al., 2015). Here, the focus was on sensitivity because all species are likely to be exposed to comparable climatic changes owing to similarities in their geographic distributions. The following questions were addressed: (1) are currently threatened fish species also sensitive to projected effects of climate change, specifically those effects associated with changing water quantity and quality? (2) Does the current conservation status of fish species also reflect their degree of sensitivity to climate change? and (3) What are the specific aspects of climate change that contribute the most to species sensitivity? By addressing these questions this paper aims to provide new insight into which threatened Brazilian fish species are at most risk to future climate change, thus identifying the species requiring greater consideration for conservation and discussing the potential role of protected areas.

**METHODS**

The frameworks published by Galbraith and Price (2009) and Moyle et al. (2013) were modified to assess sensitivity of threatened Brazilian fishes to climate change; this ensured a repeatable and transparent process for eliciting expert knowledge. A group of 44 experts were identified who had recently participated in the evaluation that resulted in the Brazilian Red List of freshwater fishes. The experts are professors and researchers, each with more than 10 years experience in working with the taxonomy and/or ecology of Amazonian fishes. They were contacted by e-mail and had 40 days to answer the survey. Half of them (22 experts) completed the survey.

**Threatened species**

In December 2014, the Brazilian Ministry of the Environment published a national Red List of all vertebrate and selected invertebrate species (http://www.icmbio.gov.br/portal/biodiversidade/fauna-brasileira/lista-de-especies.html). This list was the outcome of numerous workshops where specialists evaluated almost 4000 freshwater species according to the IUCN Red List criteria. This study evaluated 71 fish species occurring in the Amazon River Basin that are considered threatened according to the Brazilian Red List (Appendix S1, Supplementary material). The present-day threats to these species include habitat loss and fragmentation by land conversion, dams, and other human activities. It is worth noting that the Brazilian Ministry of the Environment (2014) (normative instruction number 445, www.icmbio.gov.br) did not include large-bodied fish species that are exploited in fisheries, such as the giant catfishes (Pimelodidae), owing to their wide distribution in the Amazon basin.

**Survey methods**

An online survey was developed and administered using Qualtrics software, version 2.4 (© 2015, Provo, UT). An online survey was chosen rather than in-person interviews because experts were widely distributed across Brazil. All survey participants were involved with the species evaluation conducted by the Brazilian Ministry of
the Environment, so they were aware of species threats and gaps in knowledge. Experts were asked to evaluate as many species as they considered having sufficient knowledge. The survey comprised seven multi-part questions on each species, addressing basic ecology, current threats and the degree of sensitivity to projected climate change. The survey instrument is presented in the Appendix S2 and summarized below.

**Species range**

Fish species with small geographic ranges are more likely to be sensitive to environmental change because they exhibit narrower habitat requirements (Eaton and Scheller, 1996; Nogueira et al., 2010). To estimate range size, experts were asked to classify the species’ current distribution according to: (1) species limited to a portion of one Amazon sub-basin; (2) species that occur in just one sub-basin; (3) species that occur in two sub-basins; and (4) species that occur in three or more sub-basins.

**Species dispersal ability**

Dispersal ability is considered paramount to whether fish species will shift their distribution in response to climate change (Poff et al., 2002; Freitas et al., 2013). The experts were asked to classify species dispersal ability (of adult fish only) into one of five categories that included: (1) very low dispersal rate (<2 km year\(^{-1}\)); (2) low dispersal rate (2–5 km year\(^{-1}\)); (3) moderate dispersal rate (5–10 km year\(^{-1}\)); (4) high dispersal rate (10–50 km year\(^{-1}\)) and; (5) very high dispersal rate (>50 km year\(^{-1}\)).

**Present impacts other than climate change**

Fish species threatened by other environmental stressors may be more vulnerable to the effects of climate change (Olden et al., 2010; Moyle et al., 2013). The experts were asked to classify present environmental stressors to the focal fish species (following the recent review by Castello et al., 2013) that included: (1) dams and water diversions; (2) timber logging; (3) pollution; (4) mining; (5) urbanization; (6) invasive species; (7) overharvesting; and (8) no stressor other than climate change.

Physiological and/or behavioural tolerances to climate change impact

Fish species demonstrate different degrees of tolerance to climate-associated changes to the environment (Eaton and Scheller, 1996; Ficke et al., 2007). The experts were asked to classify the tolerance of species as: (1) very low; (2) low; (3) moderate; or (4) high, to changes in timing, magnitude and duration of the high-flow season (flood) and the low-flow season (hydrological drought), and to dissolved oxygen concentration and water temperature. In addition, the experts were asked to state their degree of certainty for each response as high, moderate or low.

**Statistical analysis**

A composite measure of climate change sensitivity for each species was calculated using the following protocol. First, each question (with the exception of species range and current threats) was arranged on an ordinal scale from the lowest to the highest perceived sensitivity and then standardized from 0 to 1, where 0 represented low sensitivity and 1 represented high sensitivity to climate-related threat (Appendix S3). This ensured that all the questions had equal weighting. For species with multiple entries, the average score obtained before standardization was used. High inter-respondent agreement supported this decision (described below). Second, the overall sensitivity score of each species to climate change was represented by the sum of the standardized scores for dispersal ability (DA), flood (F), drought (D), temperature (T) and dissolved oxygen (DO) (DA + F + D + T + DO = overall sensitivity). This resulted in a composite measure ranging from 0 to 5, where 0 represents lowest overall sensitivity and 5 represents highest overall sensitivity to climate change impacts (Appendix S3). Range size was not included because all the threatened species evaluated have small range sizes.

The level of inter-respondent agreement for species with multiple entries was quantified using Fleiss’ Kappa index (Conger, 1980). Fleiss’ kappa ranges from 0 to 1 (indicating no agreement) to 1 (indicating complete agreement), and was calculated to estimate the concordance among the entries. Pearson correlation coefficients were used to assess
the relationship between overall sensitivity and the degree of expert certainty. During the species evaluation, the Brazilian government did not take into account the potential climate change impacts. Thus, a Kruskall–Wallis non-parametric analysis of variance was performed to determine whether there was a relationship between the current threatened status assigned by the Brazilian government and the species’ sensitivity to climate change. The frequency distribution of sensitivity scores to different water quantity and quality parameters were examined to identify the primary threats associated with climate change. Ordinary least squares (OLS) regression was applied to quantify the relationship between dispersal ability and sensitivity (tolerance to water quality and quantity parameters). All the analyses were performed in the R programming language (R Core Team, 2012).

RESULTS

Survey respondents evaluated 35 species (11 families) representing 50% of the threatened species in the Brazilian Amazon (Figure 1, Appendix S1). The majority of threatened Brazilian Amazon fish species are considered highly sensitive to climate change impacts according to the expert survey (Figure 2). Almost
half of these species had multiple entries with statistically significant concordance among the experts’ answers (Fleiss’ Kappa: mean = 0.42, \( P < 0.05 \), \( n = 17 \), Table 1). Little correlation was found between species’ overall sensitivity scores and the degree of certainty reported by the respondents (Pearson’s correlation \( R = -0.113, \ P = 0.521, n = 35 \)).

Species overall sensitivity to climate change impacts showed little concordance with current threatened status assigned by the Brazilian government (Kruskal–Wallis, \( K = 0.64, \ P = 0.72, \ df = 2 \); Figure 3). Notably, the potential effects of climate change were not incorporated into the government evaluation. Survey respondents identified dams and diversions, pollution and urban development as the leading non-climate threats to fishes (Figure 4).

Climate-induced changes in water quality were, on average, considered a greater threat to species persistence compared with potential changes in water quantity. Survey results suggest that fishes exhibit high sensitivity to changes in temperature and dissolved oxygen, and moderate to high sensitivity to changes in high-flow (i.e. flood) and low-flow (i.e. drought) regimes (Figure 5).

Table 1. Concordance in survey responses as measured by inter-rate reliability analysis (Fleiss’ kappa) for each fish species receiving multiple entries. Question number corresponds to survey presented in Appendix S2, Supplementary material

<table>
<thead>
<tr>
<th>Species</th>
<th>kappa</th>
<th>Entries</th>
<th>Questions</th>
<th>( P )</th>
</tr>
</thead>
<tbody>
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<td>Baryancistrus niveatus</td>
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<td>5</td>
<td>0.000</td>
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<td>Hypancistrus zebra</td>
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<td>0.000</td>
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<td>25</td>
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</table>

Figure 2. Overall sensitivity to climate change for 35 threatened freshwater fish species in the Brazilian Amazon.

Figure 3. Overall sensitivity to climate change for freshwater fish species according to present-day threatened status given by the Brazilian Government. Boxplots show the 25th, 50th and 75th percentiles; whiskers show the 10th and 90th percentiles, with circles representing outliers.

Figure 4. Number of freshwater fish species considered under threat from non-climate related factors by one and more than one impact.
Fish species demonstrated considerable variability in their tolerances to climate change impacts (Figure 5). The overall sensitivity scores varied from 2.9 (Scobinancistrus pariolispos) to 4.8 (Sternarchorhynchus jaimei and Sternarchorhynchus kokraimoro) (Table 2). Sternarchorhynchus jaimei and S. kokraimoro are considered highly sensitive to changes in water quality and quantity parameters, whereas Sternarchorhynchus pariolispos showed the lowest overall sensitivity to climate change impacts, owing to moderate tolerance to changes in water quality and quantity (Table 2).

Among the species with high overall sensitivity to climate change, five are categorized as critically endangered: Apteronotus lindalvae, Baryancistrus niveatus, Hypancistrus zebra, Microglanis robustus and Sternarchorhynchus higuchii. Another two species Leporinus pitingai and Crenicichla cyclostoma are highly sensitive to projected climate-induced changes in both water quality and quantity parameters, but demonstrate moderate to high dispersal ability thus reducing their overall sensitivity (Table 1). Survey experts reported considerable variability in fish dispersal ability, which was not associated with sensitivity to projected climate-induced changes in water quantity and quality ($R = 0.04$, $F = 0.95$, $P = 0.33$).

**DISCUSSION**

Approximately half the threatened fish species evaluated in the Brazilian Amazon are considered sensitive to climate change impacts according to the expert survey. Altered hydrological regimes have direct consequences for Amazonian fish biodiversity given that feeding and reproductive strategies of many species are dependent on flooding dynamics (Alho et al., 2015), and thus are a major determinant of fish community composition (Sousa and Freitas, 2008). In the past decade alone, the Amazon River basin has been subjected to two severe supra-seasonal droughts (2005 and 2010) and one record flood in 2009 (Marengo et al., 2012). Increasing frequency of these extreme events will have important implications for freshwater biodiversity in the Amazon. According to Freitas et al. (2013) the environmental impacts
associated with climate change could lead to the loss of at least 7% of fish species.

A major constraint to using PAs to protect freshwater fishes is that riverine ecological integrity is subject to human disturbances that occur outside the boundaries. This is one of the main criticisms of applying the terrestrial protected area approach to freshwater ecosystems (Abell et al., 2007, 2011). Evidence from the USA suggests that the National Park System, a network of reserves established for the conservation of terrestrial features, adequately represents freshwater fish diversity (Lawrence et al., 2011). However, this is unlikely to be the case in the Amazon. In fact, the majority of Amazonian threatened fish species are not well represented (in terms of their range) in the present PA network (Figure 1, www.icmbio.br). This is not unexpected given that the primary reason for the original expansion of PAs in the Amazon was to slow the rate of deforestation, and by some estimates it has been successful in accomplishing this goal (Soares-Filho et al., 2010; Veríssimo et al., 2011).

Land-cover changes in the Amazon River Basin have direct consequences for freshwater ecosystems. The expansion of protected areas in the Brazilian Amazon between 2004 and 2006 led to a 37% reduction in deforestation rates (Soares-Filho et al., 2010). These are favourable trends given that deforestation has been linked to reduced precipitation, and in some catchments such as the Tocantins and Araguaia Rivers, deforestation has already altered the regional water balance (Coe et al., 2009). In catchments where less than 25% of the land surface has been deforested, changes in

### Table 2. Rank of sensitivity to climate change of 35 threatened fish species in the Brazilian Amazon. Sensitivity scores indicate only the tolerance to changes in water quantity and quality and overall sensitivity (water quality and quantity, and dispersal ability). The sensitivity rank is based on the overall sensitivity to climate change impacts. Threat of extinction categories officially adopted by the Brazilian Government in December 2014

<table>
<thead>
<tr>
<th>Family</th>
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<th>Threat category</th>
<th>Sensitivity score</th>
<th>Overall sensitivity</th>
<th>Rank of sensitivity</th>
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<td>2.66</td>
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<td>23</td>
</tr>
<tr>
<td>Apteranotidae</td>
<td>Sternaorchorhynchus villasboasi</td>
<td>VU</td>
<td>2.62</td>
<td>3.37</td>
<td>24</td>
</tr>
<tr>
<td>Cichlidae</td>
<td>Teleocichla cinderella</td>
<td>EN</td>
<td>2.55</td>
<td>3.30</td>
<td>25</td>
</tr>
<tr>
<td>Doradidae</td>
<td>Rhynchocephus xingui</td>
<td>EN</td>
<td>2.44</td>
<td>3.17</td>
<td>26</td>
</tr>
<tr>
<td>Anostomidae</td>
<td>Leporinus pitingui</td>
<td>CR</td>
<td>2.66</td>
<td>3.16</td>
<td>27</td>
</tr>
<tr>
<td>Cichlidae</td>
<td>Crenicichla cyclostoma</td>
<td>CR</td>
<td>2.66</td>
<td>2.91</td>
<td>28</td>
</tr>
<tr>
<td>Apteranotidae</td>
<td>Sternaorchorhynchus marekeae</td>
<td>VU</td>
<td>2.16</td>
<td>2.91</td>
<td>28</td>
</tr>
<tr>
<td>Loricariidae</td>
<td>Scobinacinclus pariolispos</td>
<td>VU</td>
<td>2.33</td>
<td>2.83</td>
<td>29</td>
</tr>
</tbody>
</table>

CR – critically endangered, EN – endangered, VU - vulnerable
regional hydrological cycles may be too small to be detected (Coe et al., 2009).

The results of this study indicate that nearly 80% of the (evaluated) Amazonian threatened fish species of Brazil are considered highly sensitive to climate-induced changes in flood timing, magnitude and duration. Many larger-bodied fish species demonstrate a periodic reproductive strategy where recruitment occurs during the early flood season when wetland and off-channel habitats enlarge, become enriched with nutrients, and primary and secondary productivity spike (Beesley et al., 2012; Alho et al., 2015). Enhanced lateral connectivity during these times facilitates the dispersal of native species, but at the same time may promote the spread of non-native species (Leigh et al., 2014; Reich and Lake, 2015). Hydrological changes during the wet season may especially affect species with seasonal reproductive strategies by causing a mismatch between flood dynamics and reproductive activity and cues (Olden, 2016).

The survey showed that most species (nearly 90%) are considered highly sensitive to climate-induced changes in hydrological drought regimes. Extreme drought has a number of well-recognized consequences for freshwater fishes, including the fragmentation of floodplain lakes from rivers, decreased lake surface area, and the concentration of fish in confined refugia leading to increased competition and predation (Magoullick and Kobza, 2003; Alho et al., 2015). For example, the 2005 extreme drought in the Brazilian Amazon led to early and severe disconnection among lakes and rivers, and many species were trapped in shrinking lakes, later dying due to hypoxia, extreme water temperatures or predation (Tomasella et al., 2013). Freitas et al. (2013) observed that the beta diversity in six floodplain lakes along the Solimões River decreased after the extreme drought in the Amazon in 2005. They concluded that these extreme events could lead to both local and regional loss of fish, especially those species in low abundance and demonstrating niche specialization.

During an intense drought in 1997, Thomé-Souza and Chao (2004) reported a significant decrease in the biomass and richness of benthic fish fauna in the Negro and Branco rivers. The authors attributed these decreases to the redistribution of some species to deeper waters (refugia) to avoid the shallow, warmer and hypoxic waters and elevated rates of predation (Thomé-Souza and Chao, 2004).

Floods and droughts have direct influence on water quality, and the results described here show that the majority of species demonstrate high sensitivity to climate-induced changes to temperature and dissolved oxygen. The water temperature of Amazonian streams and rivers ranges between 24 °C and 32 °C (Barletta et al., 2010; pers. obs.), and the regional fish fauna is well adapted to these high temperatures. Tropical species, however, are stenotherms, having a smaller required temperature range compared with most temperate fishes; thus they have low tolerance to extremes in temperature. Low concentrations of dissolved oxygen occur in the Amazon basin (Barletta et al., 2010), and many species have evolutionary and behavioural adaptations to cope with these conditions (Brauner and Val, 2006). However, strong and persistent oxygen depletion may be more common in the future, and could lead to chronic stress for many fish species. According to Loarie et al. (2009), due to the size of protected areas in tropical and subtropical moist broadleaf forests, the rate of climate change impacts could be lower when compared with other regions of the world. Thus, Amazonian fish species could be sheltered, at least in part, if the Brazilian government maintains the current network of PAs in the Amazon. However, it is still unclear whether protected areas afford protection to freshwater fishes, particularly in the future when fishes will be shifting their distributions in response to climate change.

Unfortunately, the Brazilian government continues to fall short in the protection of biodiversity (Ferreira et al., 2014; Loyola, 2014). Since 2008, around 3.4% of Brazilian conservation units were reduced in size or degazetted, and in the Amazon nearly 42% of PAs were downgraded, downsized or degazetted (Bernard et al., 2014). The loss of protected areas often paves the way for additional hydropower and mining developments (Bernard et al., 2014; Ferreira et al., 2014). Moreover, developing Amazonian countries are
experiencing high rates of dam construction (Finer and Jenkins, 2012), constituting one of the most serious threats to the region (Castello and Macedo, 2016).

The present and future impacts from climate change cannot be understated. A considerable mismatch was found between the conservation status of a species and its sensitivity to climate change – a phenomenon also reported for fishes in California by Moyle et al. (2013). This suggests that perceptions of present-day extinction risk do not necessarily provide insight into future risks associated with climate change. Taking into account the current and future (climate change) impacts in the Amazon basin and the ecological characteristics such as small range size and low dispersal ability, it is possible to predict those species most likely to face elevated risk of extinction (Table 2).

Evidence suggests that dispersal ability is a primary predictor of how the ranges of fish species have shifted in response to past climate change (Heino et al., 2009; Comte et al., 2014). For example, Comte et al. (2014) found that high dispersal was a critical attribute enabling fish to colonize higher altitudes in order to track suitable thermal conditions. The analysis here revealed that fish species identified as highly sensitive to climate change (specifically, alterations in water quantity and quality) demonstrated variable dispersal abilities. This suggests that regardless of sensitivity, species may vary considerably in their ability to track changes in the climatic conditions. Indeed, species dispersal ability is considered paramount in the ultimate effectiveness of PA networks to conserve species (Hannah et al., 2007; Hannah, 2008). This is particularly true in freshwater ecosystems where fish are dispersing through dendritic channel networks that drain upstream catchments and connect critical habitats downstream (Abell et al., 2007). Strategies that incorporate longitudinal connectivity in conservation, including the management of current PAs and the identification of future ones, are critical (Hermoso et al., 2011). This challenge is especially pressing given that climate change is likely to reduce hydrological connectivity within rivers and fish dispersal may ultimately determine their ability to respond (Jaeger et al., 2014). Therefore, better knowledge is needed of which areas are the most important to protect to ensure that catchment functionality is maintained (Pittock et al., 2008). This is especially true in areas, such as the Brazilian Amazon, where the majority of the PAs were created for the purposes of conserving terrestrial assets.

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