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Vulnerability of turtles to deforestation in the Brazilian Amazon: Indicating priority areas for conservation

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ABSTRACT

The loss of forest cover has been considered to be an important factor in the decline of turtle populations. We used Species Distribution Models (SDM) to identify the potential distribution areas of several turtle species in the Brazilian Amazon and to calculate amount of area possibly lost to deforestation (vulnerability). We then used the software Zonation to prioritize areas for turtle conservation. We assigned higher conservation weight to terrestrial, semi-aquatic and threatened turtles and forced the exclusion of deforested areas. Different scenarios were run to assess the effectiveness of PAs in protecting turtles. Priority areas for turtle conservation are located in central-northern Amazon. These regions usually do not encompass high deforestation areas. Areas that turtles are most vulnerable to deforestation are located in central-northeastern Amazon, but only three species lost more potential distribution area to current and predicted deforestation than the percentage of total deforestation in the Brazilian Amazon. *Phrynops geoffroanus*, *Podocnemis unifilis*, *Mesoclemmys gibba* and *Kinosternon scorpioides* had a highest proportion of their potential distribution area lost due to deforestation. Many priority sites for turtle conservation are located outside of PAs, even when considering only the top 17% of priority sites. Although we did not explicitly take into consideration the social importance of turtles as a food resource in our analysis, our results highlight the most important regions for investing in conservation of turtles in the Brazilian Amazon. These results have significant practical implications for conservation.

1. Introduction

Forest ecosystems have been quickly fragmented in the Amazon basin, mainly due to development policies related to the expansion of infrastructure and agriculture (Laurance et al., 2004; Fearnside, 2005; Soares-Filho et al., 2006). The creation of Protected Areas (PAs) is one of the key conservation strategies used in the Amazon to avoid biodiversity loss (Ferreira et al., 2005; Nepstad et al., 2006), and may be the best option to prevent human impacts (Gaston et al., 2008; Soares-Filho et al., 2010) and conserve viable populations (Rodrigues et al., 2004; Loucks et al., 2008). However, a previous gap analysis revealed that areas reserved for biodiversity conservation may be inadequate (Scott et al., 2001). The choice of priority areas for conservation should incorporate the complementary principle (Rodrigues et al., 2003), which prioritizes sites that complement each other in relation to biodiversity composition rather than those that have high richness, since such sites may have redundant species composition (Margules and Pressey, 2000; Bonn and Gaston, 2005).

In general, aquatic species are only indirectly included in the creation of PAs (Roux et al., 2008). This holds true for Amazon, where the spatial location of PAs was mainly established to protect terrestrial taxa from overharvesting and to decrease deforestation (Peres and Terborgh, 1995; Veríssimo et al., 2011). The protection of large terrestrial areas based on biogeographic units was considered to be adequate to conserve the diversity of freshwater ecosystems and their related fauna in the Amazon (Peres and Terborgh, 1995; Peres, 2005). However, significant gaps in the protection of aquatic species have been recently identified in the biome, including freshwater turtles (Fagundes et al., 2016) and stream-dwelling fish fauna (Frederico et al., 2018). Those studies question the ability of large PAs to conserve aquatic

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elements of biodiversity. Castello et al. (2013) had already highlighted the importance of shifting the Amazon conservation paradigm to encompass the freshwater ecosystems, since they comprise a large area of the Amazon basin and are highly sensitive to anthropogenic impacts occurring in both freshwater and terrestrial habitats.

Turtles are considered useful organisms to include in spatial prioritization planning and for examining broader impacts of habitat loss on ecosystems, as all species require both wetlands and terrestrial environments to complete their life cycle (Klemens, 2000). Moreover, the group is among the most threatened vertebrate taxa and its worldwide decline is largely attributed to wetland loss and habitat fragmentation due to anthropogenic land-use (Reese and Welsh Jr., 1998) and exploitation (Gibbons et al., 2000). In the Amazon, seven turtle species have been classified in some threat category by the IUCN's (International Union for Conservation of Nature) Tortoise and Freshwater Turtle Specialist Group (TFTSG) (Turtle Taxonomy Working Group et al., 2017. In that region, turtles are an important food resource for indigenous and riverine populations (Fachín-Terán et al., 1996; Vogt, 2008), but are also affected by anthropogenic impacts at landscape level (Rhodin et al., 2009; Berry and Iverson, 2011; Magnusson and Vogt, 2014; Mittermeier et al., 2015). The landscape predictor that plays the greatest role in the decline of turtles is vegetation loss (Quesnelle et al., 2013), but turtles are particularly dependent on habitat connectivity to maintain their populations (Semlitsch and Jensen, 2001; Rizkalla and Swihart, 2006; Sterrett et al., 2011; Quesnelle et al., 2013).

Deforestation affects migration patterns and habitat use in different ways depending on the natural history of species (Pearman, 1997; Becker et al., 2007). In this context, terrestrial and semi-aquatic turtles are more affected by forest loss and habitat fragmentation than the aquatic species, because they move between ecosystems through forests rather than open areas to reduce thermal stress (Bowne, 2008) and exposure to natural predation and human exploitation (Buhlmann and Gibbons, 2001). Semi-aquatic turtles are species that use terrestrial habitats to obtain complementary resources such as food, rehydration and mating and nesting sites (Buhlmann and Gibbons, 2001; Grgurovic and Sievert, 2005; Beaudry et al., 2009). Furthermore, even exclusively aquatic turtles depend on the landscape matrix composition and might be vulnerable to forest cover changes, as they inhabit a variety of wetland types (Joyal et al., 2001) and eventually use uplands to move among aquatic habitats (Marchand and Litvaitis, 2004). The vegetation density may be particularly important in determining how far those species will travel to nest in riverbanks (Quesnelle et al., 2013), the quality of wetlands (Trebitz et al., 2007; DeCatanzaro et al., 2009), water temperature, depth heterogeneity and the amount of sediments (Walser and Bart, 1999). All those characteristics may constitute important threats to the group.

Despite habitat loss and habitat degradation are reported as important threats to turtle species in the Amazon (Rhodin et al., 2009; Berry and Iverson, 2011; Magnusson and Vogt, 2014; Mittermeier et al., 2015), no study has yet evaluated the vulnerability of an Amazon turtle to deforestation. Vulnerability is the extent which a species or population is threatened and is usually divided into three components: exposure, sensitivity, and adaptive capacity (Dawson et al., 2011). Our objective here was to evaluate the exposure of turtle species to deforestation in the Brazilian Amazon to indicate geographic locations where species are most vulnerable to forest loss. We focused on the exposure component because it is easily estimated by measuring the overlap between a distribution of a species distribution and a threat. Both sensitivity to threat and adaptive capacity to new conditions are difficult to predict without a large amount of knowledge on the ecology of individual species (Dawson et al., 2011). Thus, for the majority of individual species, vulnerability to anthropogenic impacts can be suggested only in general terms (Kozlowski, 2008).

Lack of information about the distribution of organisms (Diniz et al., 2010) is an important limitation for conservation planning (Peres, 2005), especially in tropical regions (Myers et al., 2000). Species distribution models (SDMs) can be an important tool to fill gaps in knowledge about species' distributions (Raxworthy et al., 2003; Costa et al., 2010) because they identify suitable habitat for populations of a species (Guisan and Thuiller, 2005; Peterson et al., 2011). These models are advantageous for identifying sites that species are most vulnerable to particular threats and for selecting priority areas for conservation. Spatial prioritization is critical for broad-scale conservation actions. Thus, in addition to the evaluation of the vulnerability of turtles to deforestation, this paper also aims to assess the efficiency of existing protected area (PA) networks in representing the distribution of turtle species in the Brazilian Amazon. The selection of priority areas was based on the habitat requirements of the species in each basin, the current location of PAs and deforested areas.

2. Material and methods

2.1. Species distribution modeling (SDM)

We used Species Distribution Modeling (SDM) to provide an estimate of turtle distribution (Guisan and Thuiller, 2005; Peterson et al., 2011) because observed records for most turtle species in the Amazon are limited to a few localities within their ranges (Souza, 2004, 2005; Brito et al., 2012). We ran maximum entropy algorithm using the MaxEnt software (Phillips et al., 2006) because it had the best evaluation values among the statistical methods previously used to estimate the distribution of Amazon turtles (Fagundes et al., 2016) and has been extensively evaluated and considered to be consistent over a large range of modeling scenarios (Pearson et al., 2007; de Siqueira et al., 2009). This approach correlates the environment at the locations of known records with the environment across the entire study area (Peterson et al., 2011).

To analyze the statistical relationship between species' occurrences and environmental predictors, we compiled occurrence records for 17 Amazon turtles (15 freshwater species and two terrestrial species) and used 42 environmental variables: 37 climatic predictors, three variables that reflect terrain shifts and two predictors that characterize the aquatic environment (Appendix A). Only one occurrence record of each species in each cell was considered (spatially unique records) to help avoid effects of sampling bias (Kadmon et al., 2004). We performed a principal components analysis (PCA) of the 42 environmental variables to decrease collinearity among them and to avoid model overfitting. Then, we used the PCA scores (12 axes - responsible for $>$ 95% of the variation) as environmental layers in the SDM procedures (Peres-Neto et al., 2005; Dormann et al., 2012; Fagundes et al., 2016). We divided occurrence data of species that had $>$ 15 spatially unique records into 80–20% training–test subsets. We used the training subset to fit the SDMs and the test subset to evaluate the predictions. For species that had $<$ 15 spatially unique records, we fit and tested the SDMs with the same dataset. We used 10,000 random points as background data. The models had a resolution of 4 km^2 and were created and evaluated for the entire Amazon basin.

Species distribution models based on presence-only data are expected to be good predictors of species suitability at a macroscale (Guisan and Thuiller, 2005) and are widely used in spatial conservation prioritization (Faleiro et al., 2013; Lemes and Loyola, 2013; Frederico et al., 2018). Nevertheless, the conversion of those models into potential distribution is based on the assumption that all predicted areas are accessible for the species during their evolutionary history (Barve et al., 2011). The coverage of SDMs to the entire Amazon basin and the possibility of dispersal along the rivers for the majority of turtle species favor the acceptance of this assumption. To convert the continuous suitability into a binary distribution model we used a threshold derived from the ROC curve. By plotting the sensitivity against 1-specificity for all existing thresholds, the method identifies the value at which the omission and commission errors intersect and minimize them (Pearce