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Efficiency of protected areas in Amazon and Atlantic Forest conservation: A spatio-temporal view

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A B S T R A C T

The Amazon and Atlantic Forest are considered the world's most biodiverse biomes. Human and climate change impacts are the principal drivers of species loss in both biomes, more severely in the Atlantic Forest. In response to species loss, the main conservation action is the creation of protected areas (PAs). Current knowledge and research on the PA network's conservation efficiency is scarce, and existing studies have mainly considered a past temporal view. In this study, we tested the efficiency of the current PA network to maintain climatically stable areas (CSAs) across the Amazon and Atlantic Forest. To this, we used an ecological niche modeling approach to biome and paleoclimatic simulations. We propose three categories of conservation priority areas for both biomes, considering CSAs, PAs and intact forest remnants. The biomes vary in their respective PA networks' protection efficiency. Regarding protect CSAs, the Amazon PA network is four times more efficient than the Atlantic Forest PA network. New conservation efforts in these two forest biomes require different approaches. We discussed the conservation actions that should be taken in each biome to increase the efficiency of the PA network, considering both the creation and expansion of PAs as well as restoration programs.

1. Introduction

Historically, the Amazon and the Atlantic Forest were continuous. Currently, however, they are separated by a dry vegetation belt formed by the Cerrado, Chaco, Caatinga and relicts of Seasonally Dry Tropical Forests (Prado, 2000; Hoorn et al., 2010; Dryflor, 2016). The Amazon is located in the northern-northwestern portion of South America, whereas the Atlantic Forest is the predominant vegetation covering most of the continent's eastern coast (Fig. 1). These biomes have high rates of endemism, species richness and diversity, but they are both suffering from severe forest loss (Laurance et al. 2009; Ribeiro et al. 2009). The Amazon harbors approximately 60% of rainforests remaining worldwide, making it one of the most important biomes for preserving biodiversity, the water cycle and global climate (Salati and Vose, 1984; Fearnside, 1999). Expansion of agriculture and livestock, mainly in the southern and eastern regions (Morton et al. 2006; DeFries et al. 2008), has accelerated the loss of Amazon forest cover (Soares-Filho et al. 2006).

The fragmentation scenario of Atlantic Forest is even more drastic. Approximately 100 million people (c.a. 70% of Brazilian population) live in large cities within this forest domain (Martinelli et al., 2013). Furthermore, massive industrialization and agricultural expansion have fragmented the forested area (Scarano and Ceotto, 2015). Currently, only 11.6% of its original forest cover remains (Ribeiro et al., 2009), distributed in a mosaic of small disconnected fragments (Joly et al., 2014) that often do not exceed 50 ha (Ribeiro et al., 2011). The Atlantic Forest is listed among 25 global priority conservation hotspots (Myers et al., 2000; Mittermeier et al., 2004).

Climate change is a driver of biodiversity loss (Root et al., 2003; Araújo et al., 2004; Bellard et al., 2012). It may cause spatial displacement of species ranges since species tend to shift toward environmentally suitable areas over time (Eldredge et al., 2005), as demonstrated by some Atlantic Forest tree species (Colombo and Joly, 2010). Due to this threat in a future climate scenario, the Atlantic Forest is considered as one of the three hotspots most vulnerable to global warming (Bellard et al., 2014).

The combined impacts of habitat fragmentation and climate change on Amazon and Atlantic Forest biodiversity highlight the need to

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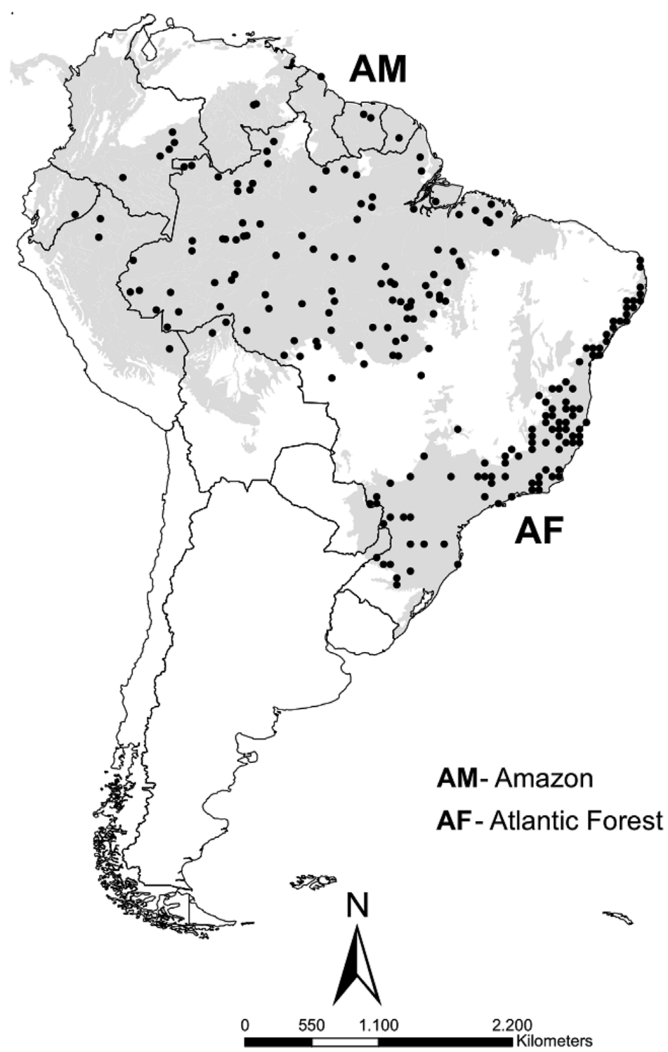

Fig. 1. Amazon and Atlantic Forest geographical delimitation (modified from Olson et al. (2001) and Lima et al. (2017), respectively) and the occurrence points used to build the ENMs.

increase conservation actions such as the creation of protected areas (PAs). However, these strategies are only marginally effective for local biodiversity conservation (Colyvan et al., 1999; Rylands and Brandon, 2005; Jenkins and Joppa, 2009). In this scenario of high rates of habitat loss, fragmentation and climate change, innovative and more effective biodiversity conservation strategies with the potential for worldwide application are needed. Approaches being discussed include the Reserve Selection method, which aims to maximize biodiversity within PAs (Margules and Pressey, 2000). However, the shift of species distribution over time could decrease the efficiency of PAs (Araújo et al., 2004). Thus, to ensure conservation efficiency and the maintenance of species over time, the design of PAs must consider a climate change scenario (Araújo et al., 2011).

The most common Reserve Selection Method uses information about species distribution and assumes that PAs should encompass areas with greater species diversity and, in some cases, long-term species persistence (Cabeza and Moilanen, 2001). However, species distribution patterns are dynamic over time, while PAs protect populations in a static space and for a limited period. These aspects increase the risk of PAs not adequately protecting endangered species in the long term if climate change results in range shifts (Araújo et al., 2002). Consequently, other methods have been developed to ensure the efficiency of PAs within climate change scenarios, such as the Habitat Suitability and Reserves Connectivity Methods (Onal and Briers, 2002; Cabeza, 2003; Cabeza et al., 2004). These methods use a niche modeling approach to infer the dynamics of species distribution within a climate change scenario. Distribution patterns for many species are predicted for various climate scenarios, and an overlap of these distributions shows a geographical pattern of species richness. Identifying the areas with a high richness ratio in all climate scenarios ensures the most suitable placement of PAs (Araújo et al., 2004; Loyola et al., 2012).

Although various methods for predicting PA efficiency exist, the knowledge concerning Amazon and Atlantic Forest PA efficiency is limited to a few papers that tested the conservation of high richness areas under the current climate and/or future climate change. For example, studies reported a loss of phylogenetic diversity of frog species inside Atlantic Forest PAs under a global warming scenario (Lemes et al., 2014; Loyola et al., 2014). Similarly, Ferro et al. (2014) observed a loss of Arctiidae (moths) within Atlantic Forest PAs. In contrast, the Amazon PAs were shown to be effective in preserving areas with higher species richness of freshwater turtles (Fagundes et al., 2016) and mammals (Avezedo-Ramos et al., 2006) under current climate and habitat fragmentation conditions.

Another approach to testing PA efficiency is to contrast protected areas' delimitation with that of Climatically Stable Areas (CSAs). Terribile et al. (2012) proposed that PAs should be delineated to coincide with long-term CSAs, which are suitable for species occurrence in past, present and (if possible) future climate conditions. CSAs ensure the survival of different species by providing them with suitable habitats over time (Carnaval et al., 2009). CSA, in combination with the presence of large-sized seed dispersers, was important for maintain genetic diversity of *Euterpe edulis*, a key palm tree within Atlantic Forest biome (Carvalho et al., 2017). Therefore, PAs that cover CSAs offer species long-term protection, regardless of the species' dispersion ability and distribution shifts (Collevatti et al., 2013).

The Atlantic Forest CSAs (sometimes reported as refuges) have been proposed based on biome delimitation and for different taxa (Carnaval and Moritz, 2008; Carnaval et al., 2009; Carvalho and Del Lama, 2015). Several Amazon CSAs have also been proposed, varying according to taxonomic group (Haffer, 1969; Vanzolini and Williams, 1981; Prance, 1982; Brown, 1987; Haffer and Prance, 2001). However, there is no consensus on where these CSAs occur or on whether Amazon CSAs actually exist (Colinvaux et al., 2000; Bush and Oliveira, 2006). So far, no studies have tested the efficiency of PAs to conserve Amazon and Atlantic Forest CSAs, despite this knowledge this being of primary importance given the high rates of species richness and high intraspecific genetic variability in these areas (see Haffer, 1969; Carnaval and Moritz, 2008; Terribile et al., 2012; Collevatti et al., 2013).

In this paper, we aim to quantify the efficiency of PAs in the conservation of Amazon and Atlantic Forest CSAs. We use ecological niche modeling techniques to simulate the biomes and their paleoclimate in three different temporal climate change conditions — Last Glacial Maximum (LGM; 21ka), Holocene (6ka) and current — to propose conservation priority areas in both biomes. These Pleistocene climatic scenarios were used because it is recognized by changing in the geographical delimitation of studied biomes through time (Carnaval et al., 2009; 2009; Sobral-Souza et al. 2015a,b). Based on the difference between Atlantic Forest and Amazon fragmentation scenarios and the size of remaining forests (cited above), we hypothesize that Amazon PAs are more efficient than Atlantic Forest PAs in the conservation of CSAs.

2. Methods

2.1. Inferring the potential distribution of Amazon and Atlantic Forest over time

We used an Ecological Niche Modeling (ENM) framework to infer the current distribution and the palaeodistribution (21ka and 6ka) of the Amazon and Atlantic Forest. The ENM technique estimates the association between environmental variables (usually climate) and