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ORIGINAL ARTICLE

Species distribution models of rare tree species as an evaluation tool for synergistic human impacts in the Amazon rainforest

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Abstract In the present work, we have considered the vulnerability of some rare tree species to human disturbances in a high biodiversity tropical region. In this context, we aimed to evaluate the combined effect of deforestation and artificial flooding of the large Jirau hydroelectric reservoir on potential distribution areas of 13 locally rare tree species in the southwestern Brazilian Amazon. We performed species distribution modeling (SDM) by using the environmental distance algorithm. Based on these models, we found new sites and subsequently applied rapid ecological assessment to collect further species occurrence data. Additional SDMs were carried out using MaxEnt to determine the potential distribution areas of these rare species. We found that artificial flooding and deforestation caused combined losses of potential distribution areas of rare tree species between 8 and 39% of the total area. The most vulnerable species were *Semaphyllanthe megistocaula* (K. Krause) L. Andersson (Rubiaceae) (39%), *Chrysophyllum colombianum* (Aubrév.) T.D. Penn. (Sapotaceae) (34%), *Lacunaria jenmanii* (Oliv.) Ducke (Quiinaceae) (32%), *Brosimum parinarioides* Ducke (Moraceae) (32%) and *Xylopia benthamii* R.E. Fr. (Annonaceae) (30%). These results indicate an additive effect of human disturbances such that artificial flooding, when combined with deforestation, has an overall effect by orders of magnitude. SDMs can be effectively used as a predictive tool in the assessment of human impacts on rare tree species in tropical forests. The results also showed different vulnerability among the rare species, and these results may indicate that some species are more seriously threatened by the extreme loss of potential distribution areas.

Keywords Deforestation · Environmental licensing · Hydroelectric dams · MaxEnt · Madeira river basin

1 Introduction

Most taxa in biological communities are unusual or rare; thus, relative to common species, rare groups are proportionately important with respect to patterns of diversity (Lennon et al. 2004; Cunningham and Lindenmayer 2005). Most notably, tropical forests are mostly comprised of rare species (Pitman et al. 2001; Steege et al. 2013). However, many such populations are still inadequately identified because they have low abundance and uncertain geographic distribution, making it difficult to locate fertile individuals. This is a complicating factor for the development of conservation strategies for this group (Steege et al. 2013). Generally, rare species inhabit unusual niches based on specific environmental requirements, low capacity of competition and dependence on dispersal ability (Markham 2014). Rarity may be caused by several factors, but it is most often characterized by low abundance and restricted geographic distribution of the population (Rabinowitz 1981; Kunin and Gaston 1993; Gaston 1994). At the same time, however, rare species and their biotic and abiotic

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interactions are important in determining the richness, structure and dynamics of communities (Flather and Sieg 2007). Hence, this large group is essential for the development of actions to protect and sustain biodiversity.

Monitoring of rare populations is important for conservation actions because of their contribution toward identifying areas that need more protection (Guisan et al. 2005; Giulietti et al. 2009). In this context, the Amazon forest is undergoing accelerated fragmentation by the overexploitation of its natural resources, and in response, the scientific community has been actively studying and reporting on biodiversity losses and the risk of species extinction (Benítez-Malvido and Martínez-Ramos 2003; Ferraz et al. 2005; Fearnside 2005; Hubbell et al. 2008; Laurance et al. 2011; Ferreira et al. 2014). Agriculture, logging, construction of roads, power lines, gas pipelines and hydroelectric dams are among the main modifying human activities affecting the Amazon natural landscape, and these human incursions are having extremely negative effects (Laurance et al. 2009). In the Amazon, rare tree species are identified as a group vulnerable to human impacts, and future scenarios foretell sharp population declines (Steege et al. 2015). Lately, monitoring human impacts on Brazilian Amazon native vegetation, such as those caused by hydroelectric dams, has been improving with studies on species distribution predictors in the impacted areas. However, this kind of monitoring is still limited to more restricted spatial scales, with a distance of up to 5 km from the direct area of influence of these projects (Moser et al. 2014). Furthermore, most environmental impact studies carried out in Amazonian countries such as Brazil only take into account the simplest forest inventory data on the composition and abundance of species in the directly impacted area (IBAMA 2016), without considering the additive and, thus, compounded effects of human disturbances that threaten tropical biodiversity at larger spatial scales (Laurance and Useche 2009), e.g., artificial flooding combined with deforestation, as discussed in the present work.

Species distribution modeling (SDM) has been widely applied across a range of biogeographical analyses, and advances in these techniques provide valuable information to evaluate anthropogenic effects on patterns of biodiversity (Guisan and Thuiller 2005). Some of the most promising applications of these models relate to poorly known tropical landscapes where biogeographical data are scarce due to cryptic habits, locally restricted distributions or low sampling effort (Raxworthy et al. 2003). However, different modeling techniques can give very different predictions (Pearson et al. 2007). Hence, the choice of an appropriate modeling algorithm is important and recent analyses supported the use of MaxEnt (Phillips et al. 2006) when sample sizes are very small (Pearson et al. 2007).

The lack of knowledge about biogeographical data of rare species in southwestern Brazilian Amazon is still worse if we consider that anthropic impacts have been particularly significant in recent decades, including deforestation for intensive farming activities (Alves et al. 1999; Ferraz et al. 2005) and for the construction of large hydroelectric power plants on the Madeira River (Finer and Jenkins 2012). We predict that these anthropogenic impacts will cause significant loss of potential distribution areas of locally rare tree species in the Amazon region of southwestern Brazil. Furthermore, we will evaluate MaxEnt algorithm as a predictive tool in the assessment of these human impacts on rare tree species in tropical forests on a greater landscape scale (10–200 km). In this context, the present study aimed to evaluate the combined effect of artificial flooding of the large Jirau hydroelectric reservoir and deforestation on potential distribution areas of 13 locally rare tree species in the Amazon region of southwestern Brazil. To accomplish this, we used species distribution models as an evaluation tool of these impacts on the potential distribution areas of these rare native species.

2 Material and methods

Study area – The study was carried out in the southwestern Brazilian Amazon comprising an area of 9422.92 km^2 in the upper Madeira river basin (9°9′35″–9°50′25″S and 64°35′21″–65°28′8″W), Porto Velho, Rondonia State. This area received both direct and indirect influence of the Jirau hydroelectric reservoir flooding. This dam was designed as a “run-of-the-river” hydroelectric type that requires little water storage and has a reduced reservoir size compared to traditional hydroelectric dams. The Jirau hydroelectric reservoir operates since 2013, and the water level varies between 82.5 and 90 m during the year, flooding an area of approximately 361.6 km^2 at its maximum level. This flooding is approximately 5–10 m above the pre-damming levels of the river and causes both permanent and temporary flooding in forest areas surrounding the reservoir.

The study area has a history of land use and deforestation, mainly due to farms associated with cattle grazing that were founded as a result of the construction and subsequent pavement of the BR-364 highway during the 1980s (Ferraz et al. 2005). The area on the left side of the Madeira River is more conserved and includes significant forest landscapes in the Mapinguari National Park.

The climate in the study area is tropical humid and hyperthermic (Cochrane and Cochrane 2010), with the highest average annual temperature ranging from 31 to 33 °C, the lowest annual temperature ranging from 20 to 22 °C and the annual precipitation ranging from 1700 to

2000 mm (INMET 2016). The elevation in the region varies between 70 and 358 m asl.

The predominant soils in the area are red–yellow Latosols (or Oxisols in US taxonomy), principally in the areas of open ombrophilous forest, and Gleysols, more common in forest arboreal "Campinarana" transition zones (Cochrane and Cochrane 2010), where seasonal flooding occurs, caused by rising water tables. Fluvisols sensu (Quesada et al. 2011) also occur and are most common on the banks of the large rivers in Amazonia, such as the Madeira River.

The predominant vegetation type of the region is lowland open rainforest (IBGE 2012), mostly characterized as open-canopy "terra firme" forest by the lack of flooding during the rainy period (Pires and Prance 1985). Other vegetation types in the region include patches of woody "Campinarana," a seasonal low-stature forest subject to flooding during the rainy season caused by the rise of the water table, as well as narrow strips of "várzea" forests, which are areas seasonally inundated by the rise of the Madeira River and its tributaries.

Data collection and species distribution models – We initially evaluated 25 rare tree species, according to a previous study carried out in the region (Moser et al. 2014), by using the RAPELD method, a modification of the Gentry method for biodiversity surveys, which combines the rapid assessment protocol (RAP) with long-term ecological research (LTER) (Magnusson et al. 2005). The occurrence records were collected using the GPS model GPSMap 60csx (Garmin®, Oregon, USA), precision <10 m. We followed the local rarity classification according to Rabinowitz (1981). In this case, as the rarity criterion, we adopted the maximum abundance of three individuals in the entire inventory (less than one individual per hectare) with geographic distribution restricted to the Amazon biome (Table S1). Botanical material was deposited in the Herbaria of Embrapa Genetic Resources and Biotechnology (Embrapa Recursos Genéticos e Biotecnologia Herbário CEN) and the Federal University of Acre (UFAC). The scientific names followed the criteria of the Brazilian Flora Checklist (Flora do Brasil 2020 2017).

Using data from the previous study of Moser et al. (2014), we performed species distribution modeling (SDM) by using the environmental distance algorithm, following the methodology of Siqueira et al. (2009), for rare species based on the georeferenced occurrence points of the species available in the forest community database in the region (Moser et al. 2014). The SDMs were performed with openModeller software (Muñoz et al. 2011), with fifteen environmental variables, eleven of which were determined by satellite images of the normalized difference vegetation index (NDVI). The other four were obtained by layers derived from digital elevation models (DEM), including elevation, aspect, slope and moisture topographic index (TWI), which were provided by TOPODATA (Valeriano and Rossetti 2012). The NDVI measured 11 months of vegetation spectral reflectance, as obtained between January and November 2013 from moderate-resolution imaging spectroradiometer (MODIS) with spatial resolution of 30 m (USGS 2015). Climate has also been named as an important predictor. However, climate is a predictor in broader spatial scales (Coronado et al. 2009; Toledo et al. 2011). The models were processed with LANDSAT8 2014 images (OLI sensor) in three scenes with natural composition and spatial resolution of 30 m (USGS 2015).

Based on these models, we found new sites for 13 rare tree species (Table S1) from the initial list of 25 species and subsequently applied rapid ecological assessment (REA) (Sayre et al. 2003) to collect further species occurrence data in addition to those of Moser et al. (2014). The survey of species was performed on points within the different vegetation types (IBGE 2012) in the study area. Species were sampled within a radius of 20 m in a 360° sweep around each point (Sayre et al. 2003). Results from the previous SDM and new REA runs resulted in the collection of 119 new presence data for these 13 species. The occurrence records were collected using the GPS model GPSMap 60csx (Garmin®, Oregon, USA), precision <10 m. These 13 species included *Moronobea coccinea* Aubl. (Clusiaceae), *Xylopia benthamii* R.E. Fr. (Annonaceae), *Vochysia biloba* Ducke (Vochysiaceae), *Buchenavia congesta* Ducke (Combretaceae), *Annona neoinsignis* H. Rainer (Annonaceae), *Semaphyllanthe megistocaula* (K. Krause) L. Andersson (Rubiaceae), *Nealchornea yapurensis* Huber (Euphorbiaceae), *Brosimum parinarioides* Ducke (Moraceae), *Rauvolfia sprucei* Müll. Arg. (Apocynaceae), *Chaunochiton kappleri* (Sagot ex Engl.) Ducke (Olacaceae), *Lacunaria jenmanii* (Oliv.) Ducke (Quiinaceae), *Qualea tessmannii* Mildbr. (Vochysiaceae) and *Chrysophyllum colombianum* (Aubrév.) T.D. Penn. (Sapotaceae).

We carried out soil collection at one point within each occurrence datum at depths of 0–20 cm, totaling 211 simple samples. The samples were dried at room temperature and then arranged for physicochemical analyses in accordance with Embrapa (1979).

Additional and final SDMs were carried out using a maximum-entropy approach (MaxEnt version 3.4.1 download URL https://biodiversityinformatics.amnh.org/open_source/maxent/) (Phillips et al. 2006). This SDM used such soil variables as texture and soil fertility in accordance with the literature reporting the influence of environmental factors on plant species distribution in the Amazon (Steege et al. 2006; Zuquim et al. 2012; Moser et al. 2014). Climate has also named as an important predictor. However, climate variables are predictors in broader spatial scales (Coronado et al. 2009). The variation of vegetation phenology throughout the year (Saatchi et al. 2008; Figueiredo et al. 2014) was considered by using NDVI satellite data. Therefore, 13 environmental variables were selected after Pearson correlation analysis: altitude, sand, clay, silt, sum of bases, slope and NDVI data of February, January, May, March, November, October and September. The correlation threshold was $p > 0.8$.

MaxEnt is a presence-only SDM algorithm that can produce robust distribution estimates even with small sample sizes (Pearson et al. 2007; Wisz et al. 2008). MaxEnt also generally predicted a larger proportion of the study area as being present, thus making the approach suited to the identification of new distributional areas in poorly known regions. The logistic output of MaxEnt generates a map with values ranging from 0 to 1. The models used 75% of the samples for training and 25% for tests. We compared the area of suitable habitat by using three of the threshold selection methods available in MaxEnt: minimum training presence, maximum training plus sensitivity and fixed cumulative value 1. Models were validated by true skill statistic—TSS and area under the curve of the receiver operating characteristics (AUC). TSS ranges from -1 to $+1$, where $+1$ indicates perfect agreement and values of zero or less indicate a performance no better than random (Allouche et al. 2006). The value of the AUC is between 0.5 and 1.0. If the value is 0.5, the scores for two groups do not differ, while a score of 1.0 indicates no overlap in the distributions of the group scores (Fielding and Bell 1997).

The soil variables, including sand, silt and clay, as well as sum of bases, were interpolated by ordinary kriging, transforming the data points on gradients of spatial values with a resolution of 30 m. For this procedure, 211 soil samples were collected during the recording of new occurrences of rare species, as noted above. Ordinary kriging is a statistical technique that uses a semi-variogram function, defined as the variance of the difference between field values at two locations and across realizations of the field (Cressie 1993), to consider values in areas not sampled (Goovaerts 1999). Ordinary kriging also considered soil analyses conducted in the same area in previous surveys (Moser et al. 2014) and was performed with ESRI® ArcGis, version 10.1.

In this study, we focus on artificial flooding and deforestation, the two main human impacts in southwestern Brazilian Amazon. With respect to deforestation, we considered derivative impacts, such as agriculture, road building, transmission lines and urbanization on the losses of natural areas. The losses of natural areas were determined by LANDSAT8 OLI sensor image classification with three scenes and spatial resolution of 30 m. The images used to determine the area of flooding were taken in August 2014, the largest period of reservoir water intake after hydroelectric construction. Data on deforestation used August 2015 LANDSAT8 OLI sensor images. The classification and processing of the images were done with ESRI® ArcGis, version 10.1.

SDMs were processed with the ESRI® ArcGis, version 10.1, calculate geometry tool in order to provide the potential distribution areas of each species in m^2. The extraction tool made it possible to determine the intersection of each impact on the potential distribution areas of species from the image, followed by calculation of losses of potential distribution areas.

3 Results

The previous SDM based on the environmental distance algorithm helped in different ways in the collection of new records for each species. These new occurrence records were five for *Moronobea coccinea,* seven for *X. benthamii* and *Vochysia biloba* and ten individuals for the other species. The soil maps with clay, sand, silt and sum of bases generated by ordinary kriging and used as environmental variables in the SDM with MaxEnt made it possible to represent the potential gradient texture and fertility of the soil in the study area (Supplementary Material Fig. S1).

The SDM with MaxEnt algorithm generated potential distribution areas of 13 locally rare tree species (Supplementary Material Figs. S2, S3, S4 and S5). The accuracy of the models showed significant performance for values of AUC and TSS (Table 1).

The losses of potential distribution areas caused by deforestation ranged from 4.2 to 18.7%. The species with the highest percentages of potential area losses were *C. colombianum* at 18.7%, *S. megistocaula* at 16.4%, *L. jenmanii* at 14.5% and *B. parinarioides* at 14%. Losses of potential distribution area from artificial flooding were between 3.7% and 22.4%. The greatest losses of potential distribution areas caused by artificial flooding were observed for *S. megistocaula* (22.4%) and *X. benthamii* (19.6%) (Fig. 1).

Importantly, deforestation and artificial flooding resulted in combined losses of potential distribution areas ranging between 8 and 39%. The species identified as the most vulnerable to these combined human impacts were *S. megistocaula* (39%) and *C. colombianum* (34%) *L. jenmanii* (32%), *B. parinarioides* (32%) and *X. benthamii* (30%) (Fig. 1).

4 Discussion

SDM with the environmental distance algorithm based on previous data and new records of occurrence data provided by rapid ecological assessment were essential to increase

Table 1 Species distribution models with MaxEnt validation statistics for locally rare tree species in the upper Madeira river basin, southwestern Brazilian Amazon, Brazil

Species	AUC	TSS	Threshold rule
Annona neoinsignis H. Rainer	0.828	0.803	Minimum training presence
Brosimum parinarioides Ducke	0.925	0.925	Minimum training presence
Buchenavia congesta Ducke	0.931	0.762	Minimum training presence
Chaunochiton kappleri (Sagot ex Engl.) Ducke	0.96	0.924	Minimum training presence
Chrysophyllum colombianum (Aubrév.) T.D. Penn.	0.98	0.984	Minimum training presence
Lacunaria jenmanii (Oliv.) Ducke	0.917	0.976	Minimum training presence
Moronobea coccinea Aubl.	0.853	0.724	Minimum training presence
Nealchornea yapurensis Huber	0.884	0.783	Minimum training presence
Qualea tessmannii Mildbr.	0.71	0.712	Minimum training presence
Rauvolfia sprucei Müll. Arg.	0.886	0.976	Fixed cumulative value
Semaphyllanthe megistocaula (K. Krause) L. Andersson	0.956	0.981	Minimum training presence
Vochysia biloba Ducke	0.792	0.854	Minimum training presence
Xylopia benthamii R.E. Fr.	0.856	0.917	Maximum training plus sensitivity

AUC statistics vary between 0 and 1. TSS statistics vary between −1 and 1

the accuracy of SDM using MaxEnt, as performed in the present work. SDM may provide biogeographical information on little studied and/or rare taxa, but knowledge about the ecology of species is necessary to complement these studies (Raxworthy et al. 2003; Pearson et al. 2007). Furthermore, in southwestern Brazilian Amazonia, large geographic gaps in our knowledge and the small number of herbarium collections available for study for many species impede accurate mapping of plant distributions (Hopkins 2007). Our results provide such geographic information for this region comprising a set of vulnerable and rare tree species.

The high percentage of losses in potential distribution areas by deforestation, which affected 100% of rare species, indicates that this type of human impact is widespread in the region. The Brazilian Amazon has undergone deforestation and forest fragmentation for more than 3 decades, continuously intensifying until the 1990s when government incentives on migration and landholding exploration began to have a curbing effect (Fearnside 2005). Thus, accelerated deforestation occurred in the central region of Rondonia State between the years 1984 and 2002, manifesting as pastures for cattle growers, which became the predominant landscape in the state (Ferraz et al. 2005). Such intensity of man-made landscape on the diversity of species in the Amazon rainforest is necessarily impactful on rare populations. Furthermore, recent analyses suggest that historical and ongoing forest loss may cause population declines of $> 30\%$ in one-quarter to one-half of all Amazonian tree species by 2050 (Steege et al. 2015).

Deforestation has impacted “várzea” forests with losses of potential distribution areas for species such as *B. parinarioides* and *Lacunaria jenmanii*, as well as “terra firme” forests, including such species as *M. coccinea*, *S. megistocaula*, *C. colombianum* and *X. benthamii*. The impacts of deforestation differ both qualitatively and quantitatively in tropical ecosystems and depend on several factors (Laurance et al. 2009), including the vulnerability of species with particular spatial distribution patterns, such as maybe the case for the rare species herein studied.

The impact of Jirau reservoir flooding also resulted in considerable losses of potential areas for species characteristic of “várzea” forests, such as *B. parinarioides*, *L. jenmanii* and *N. yapurensis*, as well as those occurring in “terra firme” forests, such as *S. megistocaula*, *C. colombianum* and *X. benthamii*. These two forest ecosystems exhibit dissimilarity in floristic patterns by such soil factors as texture and fertility (Gama et al. 2005; Haugaasen and Peres 2006) and adaptive physiological traits in “várzea” forests which are subject to flooding and anaerobic soil conditions (Wittmann et al. 2013). Loss of potential distribution areas from artificial flooding for “terra firme” forest species, such as *S. megistocaula, X. benthamii* and *C. colombianum*, draws attention to the scope of such human impacts along different forest ecosystems, as well as the increasing spatial vulnerability of rare species. The “várzea” forests of the upper Madeira River are seen as most vulnerable to the impacts of the Jirau hydroelectric dam (Moser et al. 2014). Although these forest ecosystems are resistant to seasonal natural floods, artificial flooding goes far beyond the typical impact of natural flooding by volume and levels of water (Ferreira and Stohlgren 1999).

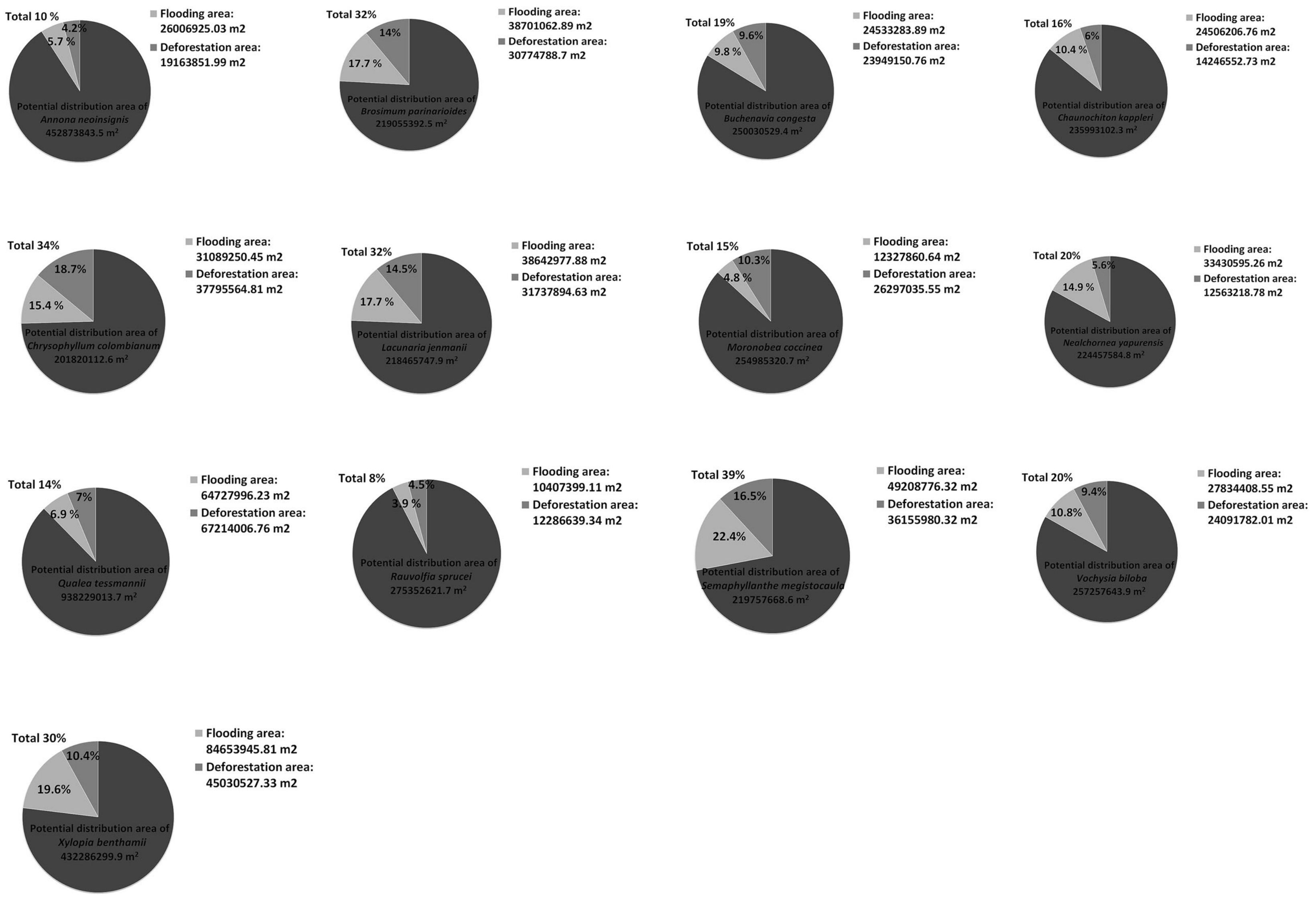

Fig. 1 Size and percentage of potential distribution areas of locally rare tree species in the upper Madeira river basin, southwestern Brazilian Amazon, Brazil, and the losses of these areas resulting from flooding of the Jirau hydroelectric dam and deforestation

The fragmentation caused by human impact, even on a local spatial scale, may have, in turn, major impacts on population dynamics, particularly for those species with low densities (Laurance et al. 1998; Anderson et al. 2000; Laurance et al. 2011). Both deforestation and artificial flooding caused considerable losses of potential distribution areas for rare species in "várzea" and "terra firme" forests. Laurance and Useche (2009) observed that forest fragments are not only reduced and isolated, but they are also lands used by hunters and loggers. Moreover, these forest fragments are subject to fires and other environmental disturbances, with predicted declines in population in response to these impacts in Amazonia (Steege et al. 2015). The greatest loss in potential distribution areas by both flooding and deforestation, when combined, was to *B. parinarioides*, *L. jenmanii, S. megistocaula*, *C. colombianum* and *X. benthamii*. Some species such as *B. parinarioides, L. jenmanii* and *X. benthamii* have occasional and frequent occurrences in other regions of the Amazon (Ribeiro et al. 1999; Flora do Brasil 2020 2017). However, after continuous habitat fragmentation, studies on species vulnerability warn that the initial loss of this habitat has a ripple effect whereby demographic and stochastic decay inevitably follows (Watson 2002). Thus, despite the occasional occurrence of these species in other locations of the Amazon, the observed vulnerability may have repercussions for the entire region. Furthermore, the species *C. colombianum* had a narrow geographic distribution for the Amazonas state (Flora do Brasil 2020 2017) and the species *X. benthamii* has populations restricted to the southern Amazonia. The results also showed different vulnerability among the rare species, and these results may indicate that some species are more seriously threatened by the extreme loss of potential distribution areas.

SDM could be a quicker and less expensive tool to support in situ and ex situ plant conservation practices for endangered and rare species in comparison with methods that require costly and time-consuming field surveys (floristic and phytosociological studies) in regions affected by hydropower dam reservoirs (Guarino et al. 2012). Also, SDM has been a valuable tool for supporting efforts to conserve tropical forests such as determining potential areas of future Amazon deforestation (Souza and De Marco 2014). Hence, as shown in this study, SDM can be effectively used as a predictive tool in the assessment of human impacts on rare tree species in tropical forests, including deforestation and artificial flooding together. Environmental impact studies and other governmental steps to curb such threats, including project licensing, only take into account general impacts that directly influence these projects, thus often restricting analysis to elementary forest inventories (IBAMA 2016). In the case of the Jirau hydroelectric dam, only areas up to 5 km from the Madeira river bank are being monitored to assess the impact of the artificial flooding on vegetation (Moser et al. 2014). On the other hand, the approach to anthropogenic interference, as presented in this paper, evaluates the potential synergism among various types of human disturbances (Laurance and Useche 2009) on vulnerable species, such as rare tree species, on a greater landscape scale (10–200 km), which is crucial in human impact studies.

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