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GEOGRAPHIC DISTRIBUTION OF THE THREATENED PALM *Euterpe edulis* Mart. IN THE ATLANTIC FOREST: IMPLICATIONS FOR CONSERVATION

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Abstract: The combination of species distribution models based on climatic variables, with spatially explicit analyses of habitat loss, may produce valuable assessments of current species distribution in highly disturbed ecosystems. Here, we estimated the potential geographic distribution of the threatened palm *Euterpe edulis* Mart. (Arecaceae), an ecologically and economically important species inhabiting the Atlantic Forest biodiversity hotspot. This palm is shade-tolerant, and its populations are restricted to the interior of forest patches. The geographic distribution of *E. edulis* has been reduced due to deforestation and overexploitation of its palm heart. To quantify the impacts of deforestation on the geographical distribution of this species, we compared the potential distribution, estimated by climatic variables, with the current distribution of forest patches. Potential distribution was quantified using five different algorithms (BIOCLIM, GLM, MaxEnt, Random Forest and SVM). Forest cover in the biome was estimated for the year 2017, using a recently-released map with 30 m resolution. A total of 111 records were kept to model climatic suitability of *E. edulis*, varying from 6 to 1500 m a.s.l and spanning almost the entire latitudinal gradient covered by the Atlantic Forest (from 7.72º S to 29.65º S). Based on climatic suitability alone, *ca.* 93 million hectares, or 66% of the area of the Atlantic Forest, would be suitable for the occurrence of *E. edulis*. However, 76% of this climatically suitable area was deforested. Therefore, currently, only *ca.* 15% of the biome retains forest patches that are climatically suitable for *E. edulis*. Our analyses show that *E. edulis* has suffered a dramatic loss of potential distribution area in the Atlantic Forest due to widespread deforestation. Our results provided updated information on the distribution of *E. edulis*, and may be used to identify which forested and deforested areas could receive priority in future conservation and restoration efforts.

Keywords: climatic suitability; deforestation; habitat loss; palm heart; species distribution modelling.

INTRODUCTION

Species distribution modelling has increasingly been used to identify areas with suitable environmental conditions for the occurrence of different species, allowing to estimate their potential distribution (Elith & Leathwick 2009). Correlative species distribution models are built by quantifying environmental variables (usually, climatic variables) at points of geographic occurrence of the species. Then, models generate predictions of potential distribution at broader geographic areas based on their environmental conditions (Elith & Leathwick 2009). When using climatic variables only, these models may indicate as "suitable" some areas that no longer have available habitats for species with specific habitat requirements, especially in disturbed ecosystems which have suffered extensive habitat loss, such as the world's biodiversity hotspots (Myers *et al.*

2000). It is well-known that habitat loss is a leading cause of species extinction (Newbold *et al.* 2015), in part because it reduces the actual distribution area of species (*e.g.*, Almeida-Gomes *et al.* 2013). Therefore, the combination of species distribution models based on climatic variables, with spatially explicit analyses of habitat loss, may produce better assessments of species potential distribution, especially for threatened species with specific habitat requirements (Guisan *et al.* 2013).

One threatened species inhabiting a biodiversity hotspot is the palm *Euterpe edulis* Mart. (Arecaceae), which occurs in the Brazilian Atlantic Forest, a top-ranked global hotspot (Laurance 2009). The Atlantic Forest has undergone extensive human exploitation over centuries, resulting in widespread habitat loss and fragmentation (Rezende *et al.* 2018). Current estimates of remaining forest cover in this biome range from 11 to 28%, with only 9% of this remaining forest inside protected reserves (Ribeiro *et al.* 2009, Rezende *et al.* 2018). Deforestation has greatly reduced the distribution of *E. edulis*, as this species is shade-tolerant and restricted to the interior of forest patches, and thus generally absent in large open areas (Henderson *et al.* 1995, Gatti *et al.* 2011). This species has a large ecological importance in the Atlantic Forest, because its fruits are considered a keystone resource consumed by a large variety of animals (Galetti *et al.* 1999, Genini *et al.* 2009). *Euterpe edulis* geographic distribution has dramatically shrunk not only due to deforestation, but also due to overexploitation of its palm heart (Henderson *et al.* 1995). As a result, many populations were extinct or severely reduced, with most large populations now restricted to protected areas (Galetti & Aleixo 1998, Silva-Matos *et al.* 1999). Accordingly, this palm tree is currently considered a threatened species in Brazil (category “Vulnerable”; Martinelli & Moraes 2013).

Despite the large ecological importance of *E. edulis* and its classification as a threatened species, it is unclear both how much of the area of the Atlantic Forest is climatically suitable for this species, and how much of this climatically suitable area has been lost by deforestation. Here, we quantified the potential distribution of *E. edulis* in the Atlantic Forest, considering not only climatic variables but also the spatial distribution of remaining forest patches. This combined approach provided useful information to guide conservation and reforestation actions, by revealing (i) the extent of reduction in the species distribution area due to deforestation; (ii) which remaining forest patches are climatically more suitable for *E. edulis*; and (iii) which deforested areas should receive priority for reforestation aiming at reintroduce and/or restore *E. edulis* populations.

MATERIAL AND METHODS

Study species

Euterpe edulis occurs in the Atlantic forests of Brazil, Argentina and Paraguay, and in gallery forests of the Brazilian Cerrado (Henderson *et al.* 1995). In the Brazilian Atlantic Forest, this species has a wide latitudinal distribution, from Rio Grande do Norte to Rio Grande do Sul states, and from seal level up to around 1000-1400 m a.s.l. (Henderson *et al.* 1995, Souza *et al.* 2018). *Euterpe edulis* occurs in different vegetation types within the Atlantic Forest, including Ombrophylous, Deciduous, and Restinga forests (Henderson 1995, Gatti *et al.* 2011). This palm is shade-tolerant and restricted to forest areas, probably due to the higher humidity and lower radiation levels compared to open areas, as the species has recalcitrant seeds, weak stomatal control, and low seedling growth at high irradiance levels (Andrade 2001, Gatti *et al.* 2011, 2014).

Occurrence records

We restricted our analyses to the Brazilian Atlantic Forest, which contains most of the distribution area of *E. edulis*. We obtained *E. edulis* occurrence records from the Global Biodiversity Information Facility (https://www.gbif.org/), using the package ‘dismo’ (Hijmans *et al.* 2017) in R 3.3.1 (R Core Team 2016). From a total of 740 available records, 321 were located within the limits of the Atlantic Forest. To maximize the independence of occurrence records, we kept only records located more than 10 km away using the package ‘spThin’ (Aiello-Lammens *et al.* 2019) in R.

Environmental variables

To model climatic suitability, we obtained bioclimatic variables from WordClim 1.4 (Hijmans *et al.* 2005), representing current (~1960-1990) conditions at 30 arc-seconds (~1 km) resolution. To select variables for modelling, we extracted the values for all 19 bioclimatic variables at 1000 points randomly distributed within the study area, defined as the limits of the Atlantic Forest plus a surrounding buffer of 200 km. We kept six variables for modelling: maximum temperature of warmest month, temperature annual range, mean temperature of wettest quarter, annual precipitation, precipitation of wettest quarter and precipitation of coldest quarter. We chose these variables due to their relatively low degree of pairwise correlation (all Pearson r's < 0.65), and because they included seasonality, average, and extreme conditions of both precipitation and temperature, as in previous studies (Souza *et al.* 2011, Teixeira *et al.* 2014).

Current forest cover was obtained from MapBiomas collection 3.1, at a resolution of 30 m for the year 2017 (http://mapbiomas.org). We transformed the original map into a binary layer (forest - non-forest), reclassifying as "forest" all pixels originally in classes 1, 2 or 3 ("forest", "natural forest" and "forest formation"). We upscaled the binary forest map to the same resolution of the climatic suitability maps (~1 km), to allow direct comparisons. Forest cover was not included as a layer in the models, which were based on climatic variables alone. By analyzing forest cover only *a posteriori*, we were able to assess more directly how deforestation reduced the climatically suitable areas for *E. edulis*, and how climatic suitability varied both within and outside forest remnants.

Modelling algorithms

As climatic suitability estimates may vary according to the modelling algorithm used (Elith & Leathwick 2009), we combined results from five algorithms: BIOCLIM, GLM, MaxEnt, Random Forest and SVM. For BIOCLIM, we used the presence (occurrence) points only. For MaxEnt, we used the presence points plus 10,000 "background" points randomly chosen within the study area. For the other three models (GLM, Random Forest and SVM), we used 1110 pseudo-absence values (10 for each presence record), chosen from pixels located within the study area but outside the climatic domain favorable for *E. edulis* as estimated from BIOCLIM (following Lobo & Tognelli 2011). Algorithms were implemented in R, using the packages 'dismo' (Hijmans *et al.* 2017), 'randomForest' (Liaw & Wiener 2002) and 'raster' (Hijmans 2017). For every model, we used 10-fold cross-validation, repeated 10 times for each algorithm, splitting occurrence data into training (90% of occurrences) and test (10%; Elith & Leathwick 2009). For each run of each algorithm, we calculated the true skill statistic (TSS) and the area under the curve (AUC), to evaluate models, and the maximum training sensitivity plus specificity threshold, to convert continuous projections into binary maps. For each algorithm, we produced two ensemble maps, one continuous and one binary, by overlapping the projections of models that had TSS > 0.70 and AUC > 0.85. The continuous ensemble map was obtained by averaging standardized values (varying from 0 to 1) of each map pixel across model runs, whereas the binary map was obtained by the majority ensemble rule (Araújo & New 2008). Finally, we used the same approach to combine the five ensemble maps (produced by the five algorithms), obtaining one continuous consensus map and one binary consensus map, which were used in further analyses.

RESULTS

A total of 111 records were kept to model climatic suitability of *E. edulis*, spanning almost the entire latitudinal gradient covered by the Atlantic Forest (from 7.72º S to 29.65º S; Figure 1). These records varied from 6 to 1500 m a.s.l. The climatic suitability models had excellent performance (average AUC and TSS values: consensus model = 0.96 and 0.90; BIOCLIM = 0.94 and 0.86; GLM = 0.94 and 0.84; MaxEnt = 0.97 and 0.90; Random Forest = 0.98 and 0.95; SVM = 0.99 and 0.93). Climatic suitability predicted by the continuous consensus model varied extensively across the biome (from 0.03 to 0.85), with higher values near the Atlantic coast and lower values towards the interior (inland) areas, except for some areas in the southern portion of the biome (Figure 1).

Forest remnants currently occupy *ca.* 24% of the area of the Atlantic Forest (Figure 2a). Some areas of high climatic suitability for *E. edulis* are still forested, especially near the Atlantic coast (Figure 2b). However, many areas of relatively high climatic suitability were lost due to deforestation, especially areas in southern Brazil (interior of Paraná state), in southeastern Bahia and northeastern Espírito Santo, and in the northeastern portion of the biome (Figure 2c).

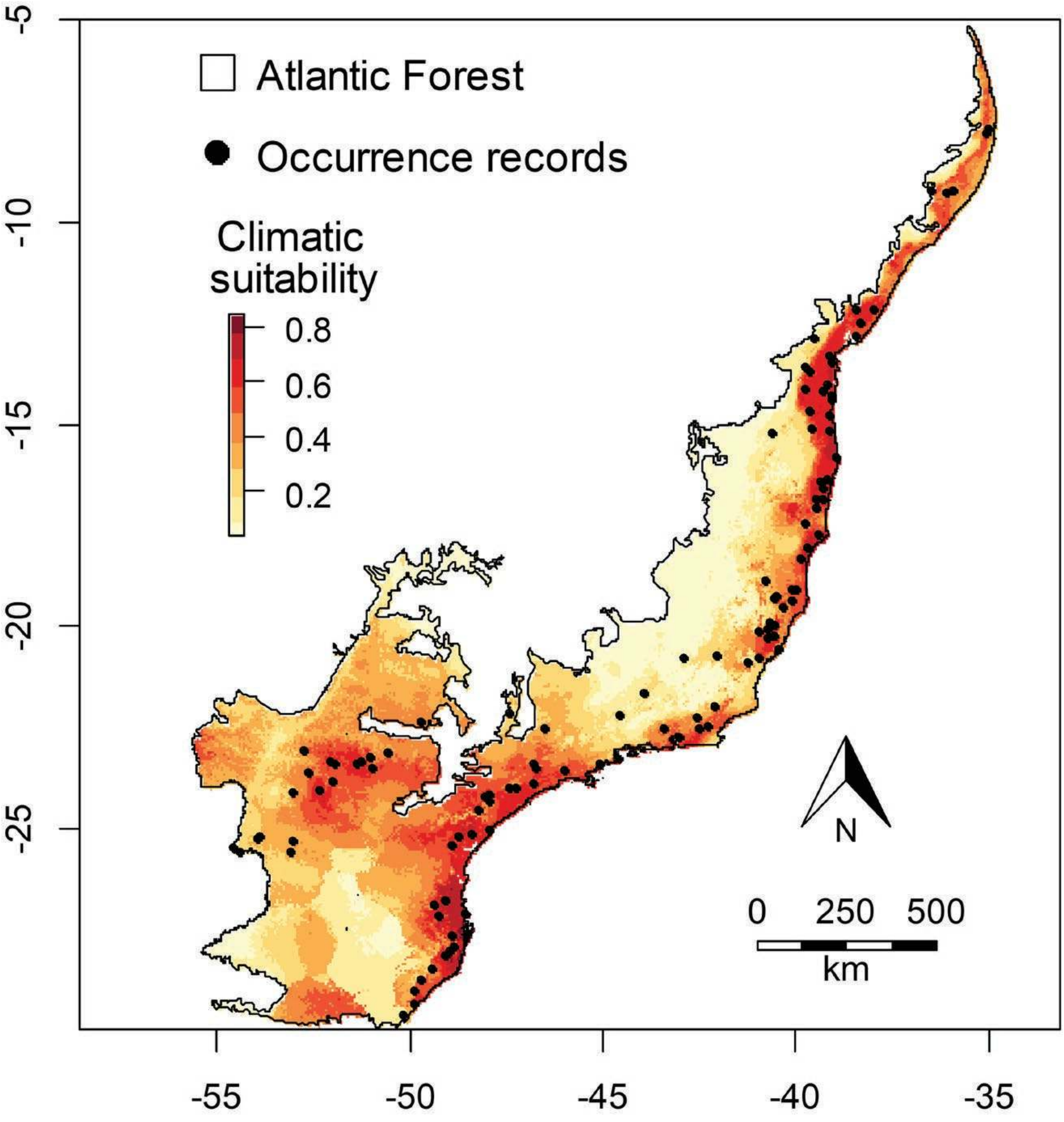

Figure 1. Occurrence points of *Euterpe edulis* Mart. (Arecaceae) and its climatic suitability in the Atlantic Forest, Brazil.

The binary consensus climatic suitability map for *E. edulis* indicated that *ca.* 93 million hectares (Mha), or 66% of the area of the Atlantic Forest, were climatically suitable for the species (Figure 3a). However, *ca.* 71 Mha (or 76%) of this climatically suitable area was lost by deforestation (Figure 3b). Therefore, only *ca.* 15% of the total biome area retained forest remnants in 2017 that were climatically suitable for *E. edulis.*

DISCUSSION

Our analyses confirm that *E. edulis* occurs across a relatively broad geographic area spanning wide latitudinal and altitudinal ranges (Henderson *et al.* 1995), and additionally reveal large variation in climatic suitability across this area. The most suitable areas are concentrated along the Brazilian coast and in the interior of Paraná state in southern

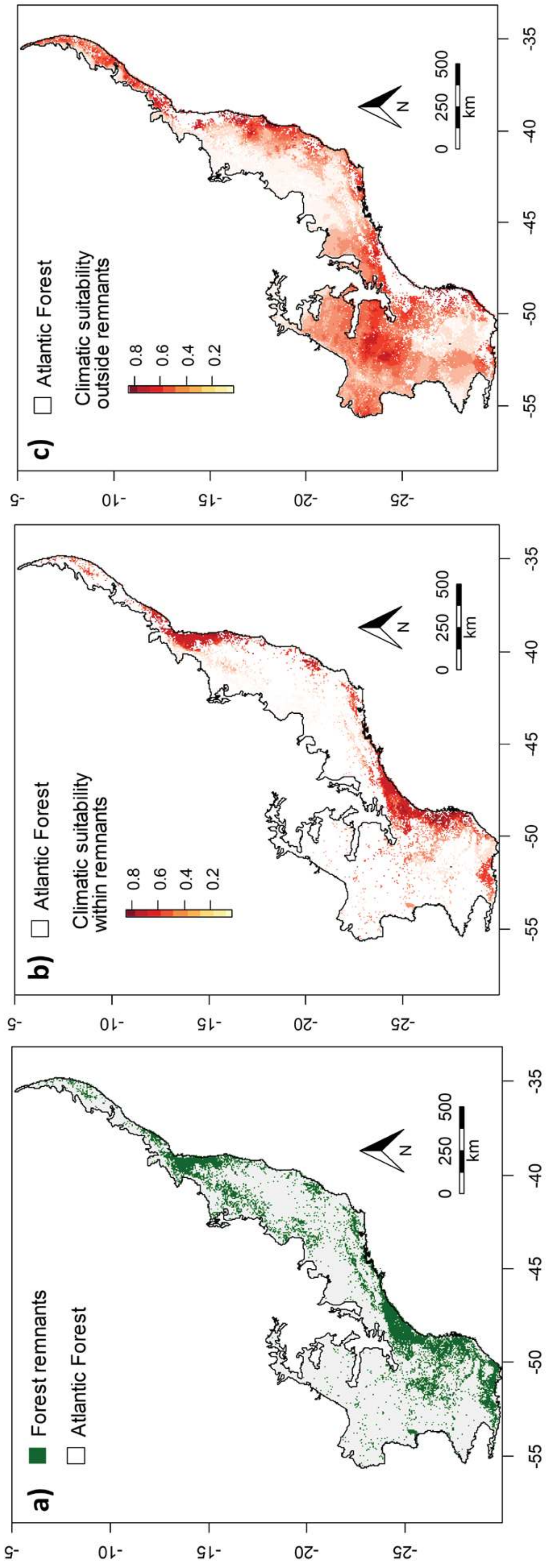

Figure 2. a) Distribution of Atlantic Forest remnants in Brazil for the year 2017; b) climatic suitability of *Euterpe edulis* Mart. (Arecaceae) within forest remnants; c) climatic suitability outside forest remnants.

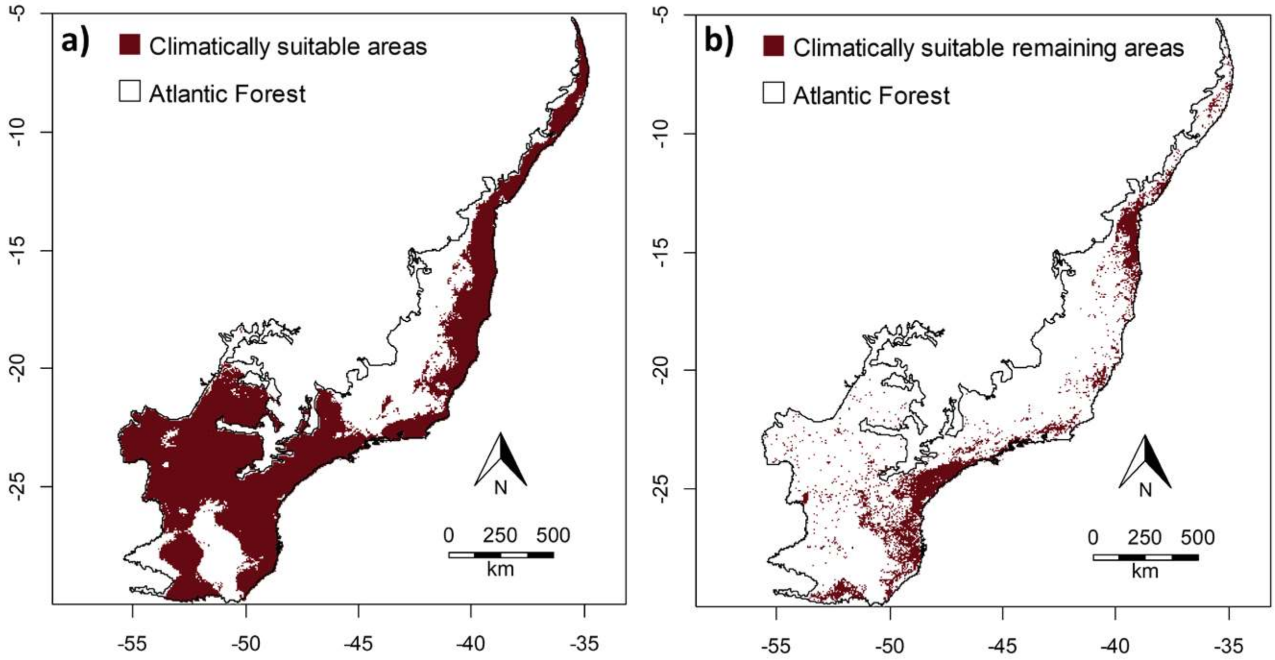

Figure 3. Total (a) and forested (b) climatically suitable area for *Euterpe edulis* Mart. (Arecaceae) in the Atlantic Forest, Brazil. Map "a" is the binary version of Figure 1, with each pixel classified as either climatically suitable or unsuitable for the species. Map "b" was produced by overlapping Figure 3a with forest remnants distribution in 2017 (Figure 2a), thus depicting only the climatic suitable areas located within forest remnants.

Brazil (Figure 1), largely coincident with the distribution of the Dense and Mixed Ombrophilous forests, respectively (IBGE 1993). Conversely, climatic suitability is much lower in inland areas of southeastern Brazil (especially in Minas Gerais state), which are mostly dominated by Deciduous and Semideciduous Seasonal forests. This pattern of variation in climatic suitability is probably linked to the physiological requirements of *E. edulis* for germination and growth, especially a low tolerance to dry conditions (Andrade 2001, Gatti *et al.* 2014), which are relatively more common in Seasonal forests than in Ombrophilous forests (IBGE 1993). In addition, the low tolerance of *E. edulis* to low temperatures could explain the absence of this species above 1500 m altitude (Gatti *et al.* 2008, Roberto & Habermann 2010, Souza *et al.* 2018).

Euterpe edulis has suffered a dramatic loss (~76%) of potential distribution area in the Atlantic Forest. Currently, only 15% of the biome is both forested and has suitable climatic conditions for this species. However, the actual scenario is probably even worse for two reasons. First, most of the remaining forest fragments are small (< 50 ha) and isolated (Ribeiro *et al.* 2009), therefore probably supporting only small populations of *E. edulis*. Secondly, this species is still systematically exploited for its palm heart, an illegal activity that kills exploited individuals, since *E. edulis* is a single-stem palm that does not have resprouting ability after cutting (Martinelli & Moraes 2013). Taken together, these factors are likely to reduce significantly the long-term persistence of *E. edulis* populations (Henderson 1995, Ribeiro *et al.*, 2009, Rezende *et al.* 2018). Therefore, our analyses provide further evidence to corroborate the classification of *E. edulis* as a threatened species (Martinelli & Moraes 2013).

Considering the forest-dependency of *E. edulis* and that the large populations of the species are now mostly restricted to well-preserved forest patches (Martinelli & Moraes 2013), it is essential to protect those forest patches. We suggest focusing conservation efforts first on the few large and climatically suitable forest patches (see Figure 2b). Some of these patches are certainly located outside existing reserves, as only 9% of the remaining forests are currently protected (Ribeiro *et al.* 2009). Conservation of such large, climatically suitable patches may be vital to ensure preservation of large populations in the long term.

In addition, restoration efforts are also needed to increase habitat (*i.e.*, forest) range for *E. edulis* and other forest-dependent species of the Atlantic Forest. Fortunately, large reforestation actions are already being conducted or are planned for the Atlantic Forest (*e.g.*, https://www.pactomataatlantica.org.br/). These actions could greatly benefit *E. edulis*, especially if conducted in areas with higher climatic suitability for this species. This is the case of many inland areas in the Paraná state, for example, which originally harbored large patches of Ombrophilous forests (IBGE 1993), which were climatically suitable for *E. edulis*, but have been extensively deforested (Ribeiro *et al.* 2009, Rezende *et al.* 2018).

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