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Spatial conservation planning framework for assessing conservation opportunities in the Atlantic Forest of Brazil

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Abstract

Historic rates of habitat change and growing exploitation of natural resources threaten avian biodiversity in the Brazilian Atlantic Forest, a global biodiversity hotspot. We implemented a twostage framework for conservation planning in the Atlantic Forest. First, we used ecological niche modeling to predict the distributions of 23 endemic bird species using 19 climatic metrics and 12 spectral and radar remote sensing metrics. Second, we utilized the principle of complementarity to prioritize new sites to augment the Atlantic Forest's existing reserves. The best predictors of bird distributions were precipitation metrics (the seasonality of rainfall) and radar remote sensing metrics (QSCAT). The existing protected areas do not include 10% of the habitat of each of the 23 endemic species. We propose a more economical set of protected areas by reducing the extent to which new sites duplicate the biodiversity content of existing protected areas. There is a high concordance between the proposed conservation areas that we designed using computerized algorithms and Important Bird Areas prioritized by BirdLife International. Insofar as deforestation in the Atlantic Forest is similar to land conversion in other biodiversity hotspots, our methodology is applicable to conservation efforts elsewhere in the world.

Keywords

Brazil; Ecological niche models; Endemic birds; Environmental management; Protected areas; Radar

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Appendix A. Supplementary data
Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.apgeog.2014.06.013.

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Introduction

The Brazilian Atlantic Forest is a biodiversity hotspot that contains high levels of diversity and endemism and is under a high degree of threat due to humans (Mittermeier et al. 2005). Prior to European settlement, the Atlantic Forest occupied 16% of Brazil (Tabarelli, Pinto, Silva, Hirota, & Bede, 2003), however, only 11% of the Atlantic Forest currently remains. Most intact fragments are embedded in a mosaic of pastures or cropland and many forest fragments are susceptible to selective logging, fire, and development (Dean, 1995; Ribeiro, Metzger, Martensen, Ponzoni, & Hirota, 2009). Although large tracts of forest have survived in locations that make timber extraction difficult, the risk that the remaining forest will be cleared is intense due to the biome's population of 140 million (Tabarelli, Pinto, Silva, Hirota, & Bede, 2005). Indeed, due to deforestation, over 70% of the Atlantic Forest's 200 endemic bird species are considered threatened (Goerck, 1997; Stotz, Fitzpatrick, Parker, & Moskovits, 1996).

There is broad interest in protecting biodiversity in the Brazilian Atlantic Forest. Biodiversity can be defined as the variation of life forms (genetic, species, taxa) within a given ecosystem, region, or the entire earth. Since measuring all aspects of biodiversity is not currently possible, it may be necessary to select taxa that represent biodiversity in general when designing protected areas. Birds are frequently used as surrogates of biodiversity because they are one of the best-studied vertebrate groups in the Atlantic Forest with numerous, updated, and reliable records (Elith & Leathwick, 2009; Loiselle et al. 2003; Rondinini, Wilson, Boitani, Grantham, & Possingham, 2006). When high-resolution field data are combined with ecological niche models, this approach has proved effective for mapping species' distributions in the tropics and this approach can be used for conservation planning (Guisan & Thuiller, 2005; Saatchi, Buermann, Ter Steege, Mori, & Smith, 2008).

Given the limited resources available for conservation efforts, it is critical that reserves are strategically planned to ensure the most effective protection of biodiversity and the most efficient use of land (Kupfer, 2012). A systematic approach to conservation planning generally prioritizes representativeness, persistence, and complementarity principles in reserve design (Margules & Pressey 2000). A reserve is representative if the species included within the reserve adequately represent the biodiversity of the region. Persistence is achieved if the reserve protects species from threats and preserves important natural and ecological processes, maintaining the viability of the reserve over time (Sarkar et al. 2006). Complementarity refers to the inclusion of habitat that contains species not already included in the reserve. Achieving these conservation planning goals requires methods for measuring levels of biodiversity within a region and developing concrete targets for systematic conservation planning based on these fundamental principles (Margules & Pressey 2000; Sarkar et al. 2006).

It has been proposed that new reserves and corridors be established to link large mature forest fragments with smaller fragments in the Atlantic forest (Damschen, Haddad, Orrock, Tewksbury, & Levey, 2006; Metzger et al. 2009; Ribeiro et al. 2009). However, there is uncertainty regarding where reserves and connectivity corridors should be placed in order to best preserve biodiversity in the region (Dobson, Bradshaw, & Baker, 1997). Our objectives

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were to develop a habitat restoration plan for the Atlantic Forest by identifying the most effective and highest priority conservation needs in the Atlantic Forest of Brazil. First, we use ecological niche models to predict habitat suitability for 23 endemic bird species serving as surrogates for biodiversity in the region. In particular, we use climate and remote sensing data derived from spaceborne spectral and radar sensors to model suitable habitat for forest birds in the Atlantic Forest. Second, we assess the current reserve system and use a complementarity-based site selection to prioritize habitat for endemic avifauna in the Atlantic Forest.

Materials and methods

Study region

The study region for this research was the Serra do Mar Biodiversity Corridor (SMBC) which comprised an area of 148,006 km^2 in the states of Minas Gerais, Rio de Janeiro, São Paulo, and Paraná (Aguiar, Chiarello, Mendes, & De Matos, 2003) (Fig. 1). Our analysis focused on the SMBC because it has high levels of endemism (Brown & Freitas, 2000; Costa, Leite, da Fonseca, & da Fonseca, 2000; Da Silva, de Sousa, & Castelletti, 2004; Manne, Brooks, & Pimm, 1999) and a high number of threatened birds (Collar, Wege, & Long, 1997; Manne et al., 1999).

Species data

Birds are one of the best-studied vertebrate groups in the Atlantic Forest with numerous, updated, and reliable records (Elith & Leathwick, 2009; Loiselle et al. 2003; Rondinini et al. 2006;). We selected 23 endemic birds that are forest dependent according to Stotz et al. (1996), and have a ranking from medium to high sensitivity to disturbance (Hernandez, Graham, Master, & Albert, 2006; Stotz et al. 1996) (Table 1). Occurrence data for the 23 bird species were obtained from peer-reviewed articles, field ornithologists, as well as point localities gathered by the authors from 1997 to 2009 (Appendix A). All point location data are available from the first author upon request.

Models of Avian habitat in the SMBC

Species distribution modeling, also referred to as ecological niche or habitat suitability modeling, has increasingly been used to address a wide range of conservation issues (Gillespie, Foody, Rocchini, Giorgi, & Saatchi, 2008; Guisan & Thuiller, 2005; Rovzar et al. 2013). We constructed habitat suitability models for 23 birds at a 1 km pixel resolution in the SMBC using the modeling algorithm, Maxent (Phillips, 2008; Phillips, Anderson, & Schapire, 2006). Maxent is a machine-learning program that applies maximum-entropy techniques to predict a species' potential distribution based on a species' point locations and environmental predictors (Phillips et al. 2006). This method for species distribution modeling was chosen because it is particularly effective when only presence information is known and when sample sizes are small, two criteria present in our dataset (Elith et al. 2006; Phillips, 2008). Additionally, Maxent has better computer efficiency than other ecological niche models, which enables the use of large-scale high-resolution data layers and has a continuous output from least to most suitable conditions for species occurrence, making it easier and clearer to interpret the results (Phillips et al. 2006).

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We used a total of 31 environmental predictors, which consisted of 19 climatic metrics and 12 remote sensing metrics that measure vegetation extent, primary productivity, and structure obtained from spaceborne satellites and sensors (i.e. MODIS, SRTM, QSCAT) (Hansen et al. 2002; Long, Drinkwater, Holt, Saatchi, & Bertoia, 2001; Platnick et al. 2003). We used 19 bioclimatic variables from the WorldClim dataset version 1.4 (Hijmans, Cameron, Parra, Jones, & Jarvis, 2005). These metrics are derived from monthly temperature and rainfall and represent biologically meaningful variables for characterizing species ranges (Hijmans et al. 2005; Nix, 1986). The bioclimatic variables were downloaded and clipped to the Atlantic forest domain at the latitudes 4°1′58.91″ S and 35°0′26.48″ S and longitudes 56°29′40.37″ and 31°82′20.45″.

We also used 12 remote sensing metrics from spectral and radar sensors collected over the study region (Fig. 2a). We used the MODIS 8-day LAI (Leaf Area Index) product derived from atmospherically corrected MODIS surface reflectance over the 5-year period 2000–2004 to quantify spatial and temporal vegetation patterns. We created monthly composites by averaging the 8-day LAI product for each year. Even though the MODIS algorithm is equipped with improved cloud masking (Platnick et al. 2003), there were effects from subpixel cloudiness on LAI estimates over areas with persistent cloud cover, such as the highlands of the Serra do Mar coastal forests. To reduce these effects, along with any natural inter-annual variability present in the data, monthly climatologies were created by averaging five years of data (2000–2004). Five LAI metrics were generated through these monthly composites: annual maximum, minimum, mean, standard deviation, and range (difference of maximum and minimum). These LAI metrics provide information on primary productivity and vegetation seasonality (Fig. 2a). MODIS-derived vegetation continuous field (VCF) product is a measure of percentage of tree canopy within a 500 m-pixel (Hansen et al. 2002). This dataset was produced from time-series composites of MODIS data of the year of 2001. Groundwork validation results over the United States (Hansen et al. 2002) suggest that VCF product can reliably separate more open areas (e.g. shrubs and savanna-like areas), deforested areas, and, to some extent, fragmented areas from those of closed forest areas (Fig. 2b). The 500 m tree cover data were aggregated and resampled to 1 km so that it was consistent with the climatic variables.

We also included remote sensing radar datasets that has been proved useful for studying tropical forest. Microwave QSCAT data in the Ku band was available in 3-day composites at 2.25 km resolution and were included as environmental variables (Long et al. 2001). The 3-day data from 2001 with complete data coverage were used to create average monthly composites at 1 km resolution and then further processed to produce four metrics that included annual mean and standard deviation of radar backscatter in the horizontal (h) or vertical (v) polarizations. The QSCAT data are sensitive to large-scale variations in canopy structure and moisture; hence its measurements may improve the identification of the Atlantic Forest heterogeneity (Fig. 2c). Finally, two metrics were created from the Shuttle Radar Topography Mission (SRTM) elevational dataset. Digital elevation data at 90 m resolution were aggregated to 1 km resolution to quantify mean elevation (Fig. 2d) and the standard deviation based on 90 m data were included as an indicator of surface ruggedness.

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We used the Maxent default settings for regularization (regularization multiplier 1.0) and in selecting feature classes (functions of environmental variables) for all runs. These include linear/quadratic/product, categorical and hinge features, depending on the number of point localities (Phillips et al. 2006). To validate Maxent output for each species, we divided the data so that 70% of the occurrences of the determined species were used to train the model and the other 30% of point localities were used as test data. Habitat distribution models were validated by calculating the omission rate and the area under the receiver operating curve (AUC) on the withheld occurrences. The AUC is the probability that a randomly selected site will be correctly classified as suitable or unsuitable habitat (Phillips et al. 2006).

Prioritization of conservation areas

We used an algorithm based on rarity and complementarity implemented in the ResNet software package (Sarkar, Fuller, Aggarwal, Moffett, & Kelley, 2009) to design two sets of conservation areas for endemic birds in the SMBC. The algorithm required setting a target for each species, which is the percentage of the species' habitat that will be protected in the proposed conservation areas. We used a target of 10% as suggested by the Convention on Biological Diversity (CBD., 2009), which has argued for a minimum of 10% of all habitat types to be represented in conservation area networks and the signatories of the Convention of Biodiversity, including Brazil, agreed to implement a 10% target. In each iteration, the algorithm selects the site that contains the bird species with the smallest predicted habitat area and has their cells selected first. Ties were broken by complementarity, meaning that the algorithm selects the site that contains the most species that do not yet have 10% of their habitat included in previously selected sites. Site selection terminates when all species have 10% of their habitat included in the selected sites. We utilized this algorithm because it is transparent to decision-makers and finds near-optimal solutions rapidly (Sarkar et al. 2006). The first set of conservation areas, hereafter the “protected areas solution”, was designed by selecting all sites in existing protected areas, which occupy 24% of the SMBC, then adding sites until each species had 10% of its habitat included in the selected sites. The second set was designed by selecting sites based on rarity and complementarity without incorporating existing protected areas (hereafter the “rarity solution”).

Results

Models of Avian habitat in the SMBC

For all the species, the AUC values were highly statistically significant ($p < 0.001$, one-tailed Wilcoxon rank sum test of AUC), meaning that the habitat distribution models performed better than random predications (0.5) (Table 1, Appendix B). The high AUC values suggest that the models had high performance and are thus, useful for identifying suitable habitat. The most important environmental determinant of species' distributions were precipitation metrics (Table 2). The precipitation of the driest month was the most important climatic metric for predicting habitat suitability followed by precipitation of warmest quarter and precipitation seasonality. Temperature metrics, such as temperature seasonality, was important for five species but temperature metrics in generally were not as important as precipitation metrics for modeling species distribution in Brazil. QSCAT radar backscatter appears to be an important remote sensing metric ranking in the three most important variables for 11 out of the 23 target species. Topography metrics were important for four species. The addition of MODIS metrics such as LAI and percent tree canopy cover did not perform as well as QSCAT radar.

Prioritization of conservation areas

The total protected area in the study region cover 36,026 km^2. The existing protected areas do not include 50% of the habitat of each of the 23 endemic species. Indeed, existing protected areas fail to cover even 10% of the habitat for each endemic bird species (Fig. 3a). We found high concordance between the set of protected areas designed from scratch based on rarity and complementarity solution of endemic birds. ResNet designed a reserve system that contained 10% of the habitat for all 23 endemic bird species that covered an area 9586 km^2 which occupy 6.47% of the SMBC (Table 3). This design was better than the existing protected areas gazetted by IBAMA (Fig 3b). There was also high concordance between the rarity solution and BirdLife's Important Bird Areas (Fig. 3c).

Discussion

Models of Avian habitat in the SMBC

The environmental metric that appeared most often as one of the most important variables in determining the potential distribution of the targeted species distributions was precipitation of the driest month. This metric was especially important for the frugivores. Of the 21 times that precipitation of the driest month appears as the most important variable, seven were frugivore species (Appendix B). The driest quarter in the Atlantic Forest occurs in the winter from June to September. According to Talora and Morellato (2000), this is the fruiting season for the majority of the Atlantic forest fruiting trees. This may support the fact that precipitation is an important factor, which defines the fruiting season of Atlantic Forest tree species (Morellato & Haddad, 2000; San Martin-Gajardo & Morellato 2003).

Another important environmental metric was radar backscatter from QSCAT. Microwave QSCAT contributed in the improvement of the model results due to the high accuracy calibration of its measurements, and long term averages ensuring the reduction of any possible high-frequency noise from compositing the data or from atmospheric disturbances (e.g. rain events) while preserving information on the backscatter variability (Appendix B). In addition, the QSCAT radar measurements, at 2 cm wavelengths, are sensitive to surface canopy roughness, surface canopy moisture, and other seasonal attributes, such as deciduousness of vegetation. Other studies also found that QSCAT contributes to the improvement of ecological niche modeling results (Buermann et al. 2008; Freedman, Buermann, Lebreton, Chirio, & Smith, 2009; Saatchi et al. 2008). The Atlantic Forest is generally composed of three vegetation strata but some forests have lost this strata due to selective logging or disturbance in many places (Dean, 1995). In other cases, the forest was destroyed and regenerated, resulting in some level of structure but lacking plant diversity. The QSCAT Ku band is able to measure the forest canopy and provide information about its structure and moisture (better quality forests retain more moisture), highlighting the importance of this metric in improving species distribution models.

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Implications for conservation planning in the Atlantic Forest

We found little agreement between the SMBC's existing protected areas and an optimal set of protected areas designed from scratch to protect endemic birds. Historically, reserves in old deforestation frontiers were typically established in areas that were still forested and in areas under less pressure from land-use change such as mountainous areas. Our analysis supports previous studies on the extent to which the Atlantic Forest's protected areas conserve other taxa. For example, the Atlantic Forest's protected area system does not protect all of the 20 endemic primate species of the biome (Pinto & Grelle, 2009). According to Pinto and Grelle (2009), using complementarity principles to define a conservation area network could be completely achieved with a reserve network that occupies 7.5% of the existing reserve system.

These results are compatible with the results of area prioritization analyses from many other regions in the world (Fuller, Munguía, Mayfield, Sánchez-Cordero, & Sarkar, 2006; Pawar et al. 2007; Pressey, 1994; Sarakinos et al. 2001), indicating that in most of the cases, systems of existent protected areas do not conserve biodiversity effectively. The adequacy of protected areas cannot be measured by land area alone. For instance, in the last 40 years more than 600 protected areas were created in the Atlantic Forest (Tabarelli et al. 2005), representing different sizes, and ranging from the coast to the interior region of the biome. However, these large numbers alone are insufficient. The Atlantic Forest protected area covers only 1.6% of the entire biome and represents 14.4% of the remaining forest cover, protecting just 9.3% of this remaining forest (Ribeiro et al. 2009). Our finding that the SMBC protected areas are insufficient raises the question of whether existing protected areas elsewhere in the Atlantic Forest are inefficient and this should be investigated systematically.

We found high agreement between our designed protected areas and BirdLife IBAs. This could be because the BirdLife experts are adept at identifying important areas for rare birds and our algorithm selected sites to include rare bird habitat. The IBAMA protected areas do not include 10% of the habitat for the endemic birds analyzed here, most of which are on the IUCN Red List. This means the existing protected areas are not likely to be effective at protecting birds because conserving Red List species may require protecting much more than 10% of their habitat.

One of the results obtained from the rarity-complementarity solution that is particularly interesting is related to the Mantiqueira mountain range (Serra da Mantiqueira), a large group of protected areas in the western SMBC (Becker, Rodriguez, & Zamudio, 2013). The bird diversity of the Serra da Mantiqueira, with the exception of very few species, is almost identical to the bird diversity of the Serra do Mar, which is the other mountain range in the study area. The Serra do Mar is represented by the long chain of protected areas close to the coast in the eastern part of the study area. However, the Serra do Mar has greater forest cover, is better preserved, and is closer to other forest fragments than the isolated block of the Serra da Mantiqueira. The results show that ResNet, based on complementarity criteria, selected more areas inside the Serra do Mar mountain range, and only a few areas in the Serra da Mantiqueira. By selecting many cells in the Serra do Mar and fewer cells in the Serra da Mantiqueira, ResNet was able to achieve the conservation target of 10% in a more economical way. Although few cells were selected in the Serra da Mantiqueira, those that

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were selected were close to the IBAs, providing further evidence of the concordance between the ResNet rarity solution and IBAs.

The rationale for constructing the protected area solution was to assess the effectiveness of the protected areas by comparing them to an ideal reserve network constructed from scratch. In practice, it would be infeasible for political and financial reasons to degazette the existing protected areas and create a new reserve network from scratch nor is it our intention to be dismissive of the decades of effort by many parties that resulted in the establishment of the Atlantic Forest's existing protected areas. Instead, the goal is to gain insight about how we might refine the Atlantic Forest's system of protected areas in the future by carrying out a hypothetical planning exercise to compare the current protected areas to an ideal network of protected areas designed to protect species' habitat assuming that we have unlimited resources for setting up the network. If the existent protected areas are similar to the ideal network, that would increase stakeholders' confidence in the existent protected area's effectiveness, whereas if significant differences between the ideal and existent protected areas become apparent, that could inform future decision-making to improve the existent protected areas.

Applied conservation Geography

It is clear that is possible to model species distributions and identify areas that deserve a high priority of conservation in the Atlantic Forest of Brazil. However, there appears to be a need to increase the number of species and taxa, update species location data and remote sensing sources, and undertake conservation planning assessments at regular intervals. For birds, there are now a number of public access databases (i.e. www.ornis.net, www.wikiaves.com.br, http://splink.cria.org.br, http://www.biota.org.br) that provide species location to within 1 km pixel resolution, date the species were identified, and the source of the data. Avian databases such as eBird provide location and date data (Appendix C) while others databases like xeno-canto provide recordings an evidence or voucher of species identification. This data can be used to update distribution and conservation models. There is also a need to update spatial conservation analyses with other taxa such as mammals, herpetofauna, and threatened species and updated climatic and remote sensing metrics used in species distribution models. Recent data such as forest cover from TerraSAR-X, Tan-DEM-X or Cosmo-SkyMed can provide radar backscatter up to 1 m pixel resolutions and this may be useful for improving models. Undertaking these steps at regular intervals could provide the best overview of the distribution of biodiversity in the Atlantic Forest and provide natural resource managers with priority areas for biodiversity, select taxonomic groups, and threatened species.

Conclusions

Our results develop a new conservation areas network that may prove to be more effective than the existing one to protect the biodiversity and sustaining natural habitats and their natural processes through larger continuums of forests. This model reserve system may better represent the region's biodiversity by targeting habitat important for biodiversity surrogates and utilizing the principle of complementarity in reserve design. A comparison of

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the model reserve system developed in this study and the actual reserve system shows little overlap between the two. This provides evidence that the current reserve may not adequately represent the biodiversity of the Atlantic Forest. These finding demonstrates the need to critically evaluate reserve systems throughout the world to ensure they are effectively protecting important species and ecological services. While the current Atlantic Forest reserve system may be insufficient, completely redesigning it is impractical. Models of optimal reserve systems like the one developed in this study can be used to inform decisions about how to improve current reserve systems. This study points to the need to better utilize conservation planning techniques to optimize conservation efforts.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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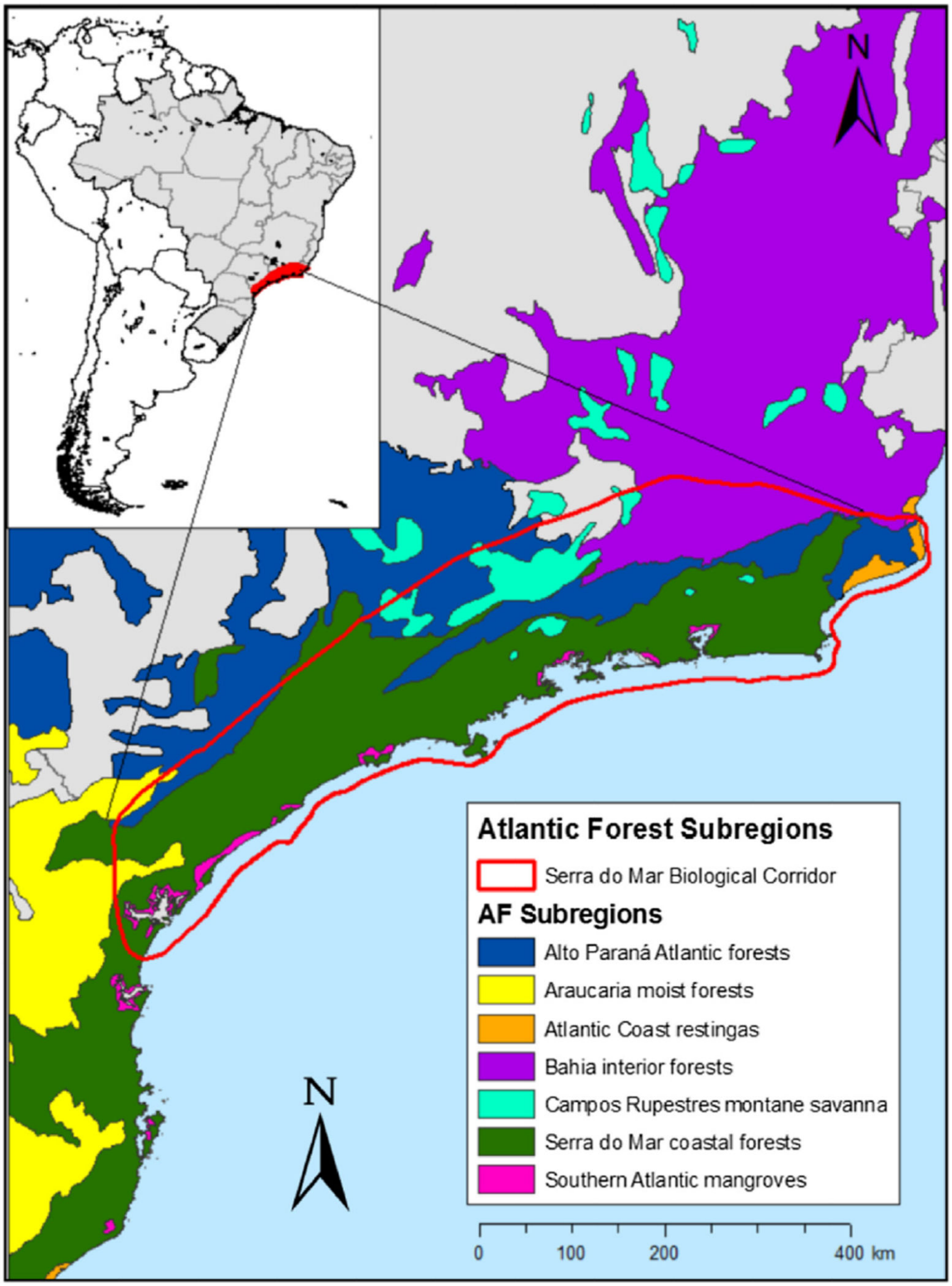

Figure 1.

The Serra do Mar Biological Corridor and Atlantic Forest subregions from the World Wildlife Fund.

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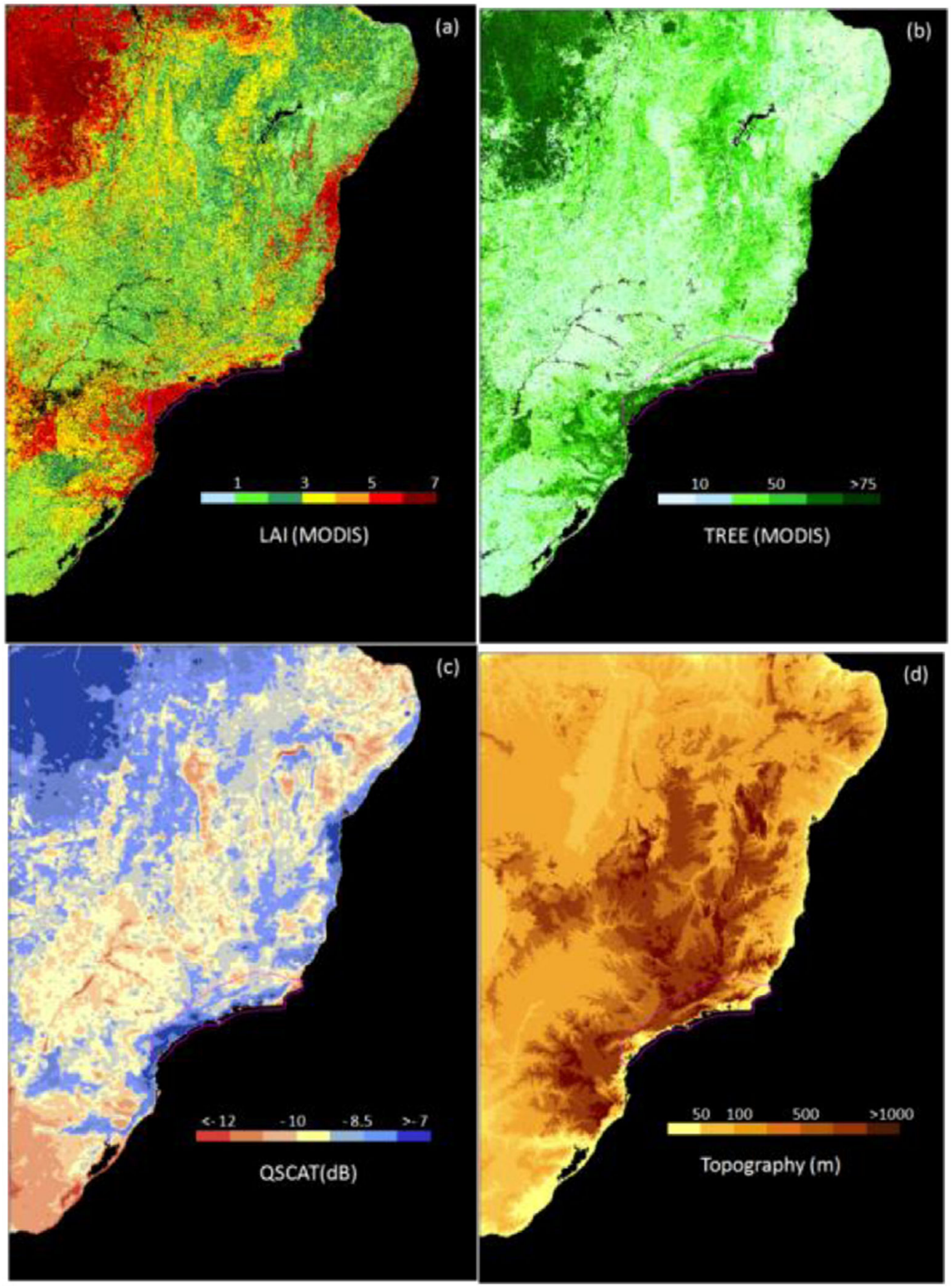

Figure 2.

Remote sensing layers used as environmental predictors. The panels depict (a) MODIS LAI annual maximum, (b) MODIS percentage of tree cover, (c) QSCAT annual mean, and (d) mean elevation derived from SRTM.

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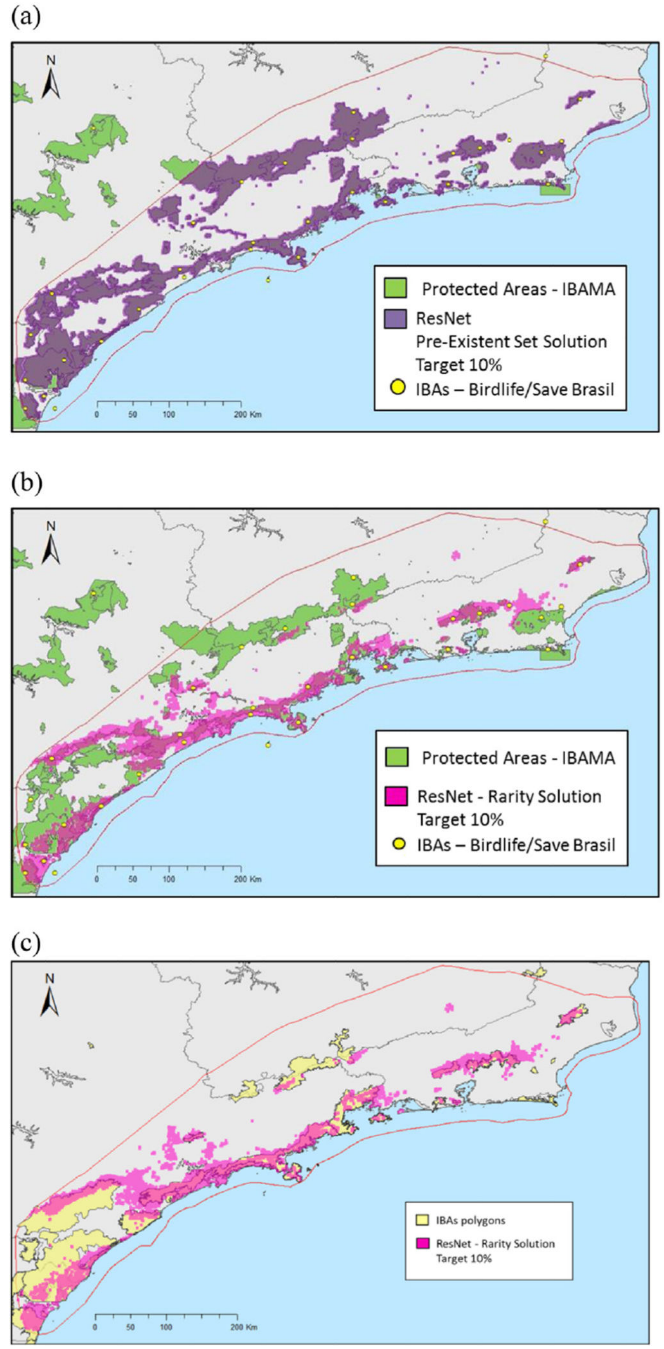

Figure 3.
Protected area solution and existing protected areas (a), rarity solution (b), and rarity solution and IBA polygons (c).

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Table 1

Endemic birds of the Atlantic Forest of Brazil, number of point locations, and area under the receiver operating curve (AUC).

Family	Scientific name	Point locations	AUC
Tinamidae	*Tinamus solitaries*	40	0.991
	Crypturellus noctivagus	48	0.986
Cracidae	*Pipile jacutinga*	69	0.988
Ramphastidae	*Selenidera maculirostris*	35	0.993
	Ramphastos dicolorus	56	0.994
	Pteroglossus bailloni	21	0.993
Psitacidae	*Pyrrhura frontalis*	77	0.986
	Pionopsitta pileata	25	0.995
	Amazona brasiliensis	53	0.995
	Triclaria malachitacea	20	0.996
Trochilidae	*Phaethornis eurynome*	121	0.994
	Phaethornis squalidus	40	0.991
Thamnophilidae	*Drymophila squamata*	41	0.993
	Myrmotherula gularis	54	0.995
Furnaridae	*Anabacerthia amaurotis*	29	0.995
	Anabazenops fuscus	68	0.991
	Heliobletus contaminatus	27	0.993
Dendrocolaptidae	*Dendrocincla turdina*	60	0.992
Formicariidae	*Chamaeza meruloides*	31	0.995
Cotingidae	*Carpornis cucullata*	60	0.994
	Carpornis melanocephala	44	0.991
	Procnias nudicollis	78	0.991
Conopophagidae	*Conopophaga melanops*	49	0.994

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Table 2

Important environmental variables based on the top three metrics that explained the most variance for 23 endemic bird species predicted range distributions in the Atlantic Forests of Brazil.

Environmental metrics	Top three most important metrics
Climate	
Precipitation of driest month	21
Precipitation of warmest quarter	8
Precipitation seasonality	7
Mean temperature of the driest quarter	6
Temperature seasonality	5
Max temperature of warmest month	2
Remote sensing	
QSCAT – Radar backscatter	11
SRTM – Topography	4
MODIS - Leaf Area Index	1

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Table 3

Summary of results from the prioritization models of the two different ways to initialize ResNet.

Algorithm Initialization	Total area (km^2)	Area selected (km^2)	Total area prioritized (%)
By pre-existent set (Protected Area Solution)	36,026	40,000[a]	27
By rarity-complementarity (Rarity Solution)	148,006	9586	6.5

[a]After adding approximately 4000 buffer cells to the 36,026 existent Protected Area cells, the existent Protected Area Solution did not protect 10% of the distribution of the 23 bird species analyzed here.