

## Research Article

# Is the current network system of protected areas in the Atlantic Forest effective in conserving key species of bryophytes?

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### Abstract

We combined distribution data of bryophyte species with protected areas in the Brazilian Atlantic Forest, using models of potential distribution of species, in order to assess the effectiveness and representativeness of Conservation Units for bryophyte species. We performed potential distribution models for ten bryophyte species classified as bio-indicators for environmental quality and/or endemic to the Atlantic Forest, or endemic to Brazil (key species). Data from online herbarium collections, literature, and sampling were used to estimate the potential distribution of the species, based on the MAXENT method. We performed an intersection between the maps with > 50% of environmental suitability for the occurrence of the studied species and the maps of the Brazilian protected areas. Areas with the greatest potential presence of bryophyte species not superimposed on protected areas were considered areas of gaps in protection. The habitat suitability of the models for nine species was explained by the Mean Diurnal Temperature Range. The consensus map of high environmental suitability for all species showed significant gaps in knowledge about their distribution. However, three centers of potential distribution were recognizable: one in the Northeast, one Central and another one in the Southeast. The total potentially suitable area overlapped with 83 Conservation Units (only 27%), less than adequate for efficient conservation of the species. The Central Corridor was the region with the highest environmental suitability but also has only a few Conservation Units in the Atlantic Forest, and is therefore a priority for conducting inventories and creating reserves.

**Keywords:** Conservation Units, environmental suitability, gap analysis, Maximum Entropy algorithm, potential distribution models, Tropical Forest

### Resumo

Objetivou-se combinar dados de distribuição de espécies de briófitas com áreas protegidas na Floresta Atlântica brasileira, utilizando modelos de distribuição potencial das espécies, visando avaliar a eficácia e a representatividade das Unidades de Conservação para as briófitas. Modelos de distribuição potencial foram realizados para dez espécies de briófitas, todas elas classificadas como bioindicadoras de qualidade ambiental e/ou endêmicas da Floresta Atlântica, ou endêmicas do Brasil (espécies-chave). Os dados de coleções *online* de herbários, da literatura e de amostragem foram utilizados para estimar o potencial de distribuição das espécies, com base no algoritmo MAXENT. Foi realizada uma interseção entre os mapas com >50% de adequabilidade ambiental para a ocorrência das espécies estudadas e os mapas das áreas protegidas brasileiras. Áreas com maiores potenciais de presença de espécies de briófitas não sobrepostas a áreas protegidas foram consideradas lacunas de proteção. A adequabilidade ambiental dos modelos para nove espécies foi explicada pela variação da temperatura média diurna. O mapa consenso de alta adequabilidade ambiental para todas as espécies apresentou significativas lacunas de conhecimento da distribuição das espécies. No entanto, três centros de distribuição potencial foram reconhecidos: um no Nordeste, um central e outro no Sudeste. A área total potencialmente adequada foi sobreposta a 83 Unidades de Conservação (apenas 27%), menos do que o adequado para uma conservação eficiente das espécies. O Corredor Central foi a região com a maior adequabilidade ambiental, mas com poucas Unidades de Conservação, e é, portanto, prioridade para a realização de inventários e a criação de reservas.

**Palavras-chave:** adequabilidade ambiental, análise de lacunas, algoritmo de Máxima Entropia, Floresta Tropical, modelos de distribuição potencial, Unidades de Conservação

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## Introduction

The protection of areas is a key strategy for nature conservation [1]. Over 150,000 protected areas - created and managed for long-term nature conservation - have been designated up to now. They cover 12.9% of earth's land surface, excluding Antarctica [2].

In general, the selection and definition of areas for conservation and management have been carried out using systematic approaches for efficient allocation of scarce resources to protect biodiversity [3]. The extensive literature on this subject primarily focuses on the optimization of number, size, location and costs of networks of nature reserves, in order to ensure that they include the largest amount of biodiversity possible within the smallest protected area, and finally, to identify priority areas for conservation [4,5].

Potential distribution models of species have enriched this discussion by including environmental suitability, which has shown a correlation with populations' persistence, and which is an important factor in the design of networks of protected areas [6]. Associated with distribution of species modeling, gap analyses are important from a conservation perspective. Our analysis overlaps the extent of protected areas with the distribution of target species in order to provide a management planning approach. Areas with high environmental suitability for the occurrence of a species, but without a nature reserve, are identified as gaps in protection coverage. Studies using gap analyses on a regional [7] and global [4] scale revealed that biodiversity protection provided by the current extent of networks of protected areas is insufficient.

In Brazil, as in many other countries, several Conservation Units (acronym in Portuguese – UCs), aimed at the conservation of not only biotic, but also abiotic and cultural elements of these same natural spaces, are being created (Law 9.985 of July 18th 2000, establishing the National System of Nature Conservation Units - SNUC). These UCs are divided into two groups: those with Full Protection and those for Sustainable Use. The main objective of the first category is to preserve nature, allowing indirect use of its natural resources only for educational, scientific and recreational purposes, whilst the UCs of Sustainable Use combine nature conservation and the sustainability of its natural resources [8].

Currently, there are 478 federal and state UCs under full protection, 37,019,697 ha in total (4.3% of the country's area – [9]), and 436 UCs under sustainable use, covering 74,592,691 ha (8.7%) [10]. Other categories of protected areas in Brazil include Private Natural Heritage Reserves (acronym in portuguese – RPPNs), usually small, but important for the conservation

of endangered species and those with very restricted distribution. In addition, indigenous reserves are increasingly recognized as vital for the conservation of biodiversity due to their great expanse. Although a large number of protected areas have been created in Brazil in the last two decades, major challenges remain, not only in their administration and management, but also in protecting the reserves themselves, since Brazil still continues its ambitious development programs for energy, infrastructure, industry and agriculture [11].

Approximately 650 (65%) Brazilian UCs (excluding RPPNs and indigenous reserves) are located in the Atlantic Forest Domain, which represents only 9% of the total extent of the Atlantic Forest [10]. This forest is one of the global priorities for the conservation of biological diversity: a hotspot of biodiversity - an area that shelters at least 1,500 endemic species, but has also lost at least 70% of their original area [12]. The Atlantic Forest shelters about 8,599 endemic species, amongst which are plants, amphibians, reptiles, birds and mammals [12]. Despite its exuberant diversity, this domain is extremely endangered and most of the remaining forest fragments are small (<100 ha), highly disturbed, isolated, under anthropogenic threat, and located in land areas which are densely populated and cultivated [13,14,15].

The Atlantic Forest domain has the greatest bryophyte diversity in Brazil, with 1,341 species (88%) [16,17,18]. However, knowledge of the bryophytes in the country is still incomplete and only concentrated in some specific regions (Silva & Pôrto, unpublished results). This situation is serious because bryophytes, plants which are important conservation indicators due to a number of anatomical and ecophysiological factors [19], are often overlooked in conservation planning and in the selection of priority areas [20].

For some bryophyte species of the genus *Metzgeria* (liverwort) in the Atlantic Forest, Barros et al. [21] recently carried out a gap analysis and highlighted areas with significant gaps of knowledge and protection. Supplementing the study of Barros et al. [21], we combined distribution data from different genera of key species of bryophytes with protected areas in the Atlantic Forest of Brazil, using potential distribution of species modeling. We used a gap analysis to assess the effectiveness of protected areas in representing bryophyte diversity.

## Methods

### *Selection of species and data collection*

We built a comprehensive database on the bryophytes of the Brazilian Atlantic Forest, based on literature revision, search of the Herbaria database, and sampling. From the initial list we selected ten species of bryophytes, five Bryophyta (mosses) and five Marchantiophyta (liverworts), for the study (Table 1; Fig. 1). The criteria used to select the species were: 1) all species have a well studied and established taxonomy, to avoid problems of erroneous identification; 2) all are key species classified as bio-indicators of environmental quality, i.e. shade-tolerant species, or are endemic to the Atlantic Forest or to Brazil [16,22-29]; and 3) all have at least ten points of occurrence in the Atlantic Forest (at locality level, e.g. UCs).

The points of occurrence of the species were compiled from three sources:

1. A literature search in catalogs of bryophyte distribution in Brazil [30-36] and articles from 1985 to 2010;
2. A search of the database of the national Herbaria network available at the speciesLink website (available online: <http://www.splink.org.br/>);
3. Sampling from 2009 to 2010.

Locations without geographic coordinates were geo-referenced using the online tools GEOLOC from the speciesLink website and GEOnet Names Server (<http://earth-info.nga.mil/gns/html>). Specimens with missing localities information were omitted from the analysis. We compiled 205 records of occurrence of all bryophyte species studied.

**Table 1.** Distribution and number of occurrences used in the modeling of potential distribution of the bryophytes studied. Species are sorted alphabetically. M = Marchantiophyta (liverworts), B = Bryophyta (mosses).

Phylum	Taxonomic family	Species	Distribution	Total records
M	Lepidoziaceae	<i>Bazzania heterostipa</i> (Steph.) Fulford.	Endemic to Brazil	18
M	Lejeuneaceae	<i>Bryopteris filicina</i> (Sw.) Nees	Neotropical	31
B	Fissidentaceae	<i>Fissidens flabellatus</i> Hornsch.	Endemic to the Atlantic Forest	13
B	Hypopterygiaceae	<i>Hypopterygium tamarisci</i> (Hedw.) Brid.	Pantropical	19
B	Meteoriaceae	<i>Meteorium deppei</i> (Hornsch. ex Müll. Hal.) Mitt.	Neotropical	23
M	Metzgeriaceae	<i>Metzgeria brasiliensis</i> Schiffn.	Endemic to the Atlantic Forest	16
B	Neckeraceae	<i>Neckeropsis undulata</i> (Hedw.) Reichardt.	Neotropical	25
B	Phyllogoniaceae	<i>Phyllogonium viride</i> Brid.	Neotropical	40
M	Aneuraceae	<i>Riccardia regnellii</i> (Ångstr) Hell	Endemic to the Atlantic Forest	10
M	Lejeuneaceae	<i>Vitalianthus bischlerianus</i> (K. C. Pôrto & Grolle) R.M. Schust. & Giacotti	Endemic to the Atlantic Forest	10

### *Study area and environmental variables*

To model the distribution of species, we defined the study area as the Neotropics (with a spatial resolution of about 20 km<sup>2</sup>) and then we focused on the Brazilian Atlantic Rain Forest Domain.

We compiled bioclimatic (source: Worldclim <http://www.worldclim.org/>) and topographic variables (source: Consultative Group on International Agricultural Research - CGIAR - <http://www.cgiar-csi.org/data/> and Hidro1K - Elevation Derivative Database <http://eros.usgs.gov/>) and potential evapotranspiration and aridity indices (source: Global Potential Evapo-Transpiration – Global-PET – Geospatial Dataset), which came to 24 environmental parameters in total.

To reduce the number of predictor variables, we used an approach based on the Pearson correlation coefficient ( $r_s$ ) in ENMTools 1.3 software. The result is a matrix of pair-to-pair variable comparisons, where the variables were considered correlated when  $|r_s| > 0.7$  [37]. After the elimination of redundancy between the environmental layers, nine variables were selected for modeling: 1) Mean diurnal temperature range [mean of monthly (max temperature - min temperature)]; 2) Isothermality (oscillation of the day-night temperature compared to summer-winter temperature); 3) Precipitation seasonality (coefficient of

variation); 4) Precipitation of warmest quarter; 5) Precipitation of coldest quarter; 6) Altitude (SRTM); 7) Aridity index (mean annual precipitation / mean annual potential evapotranspiration); 8) Slope; and 9) Aspect of the terrain.

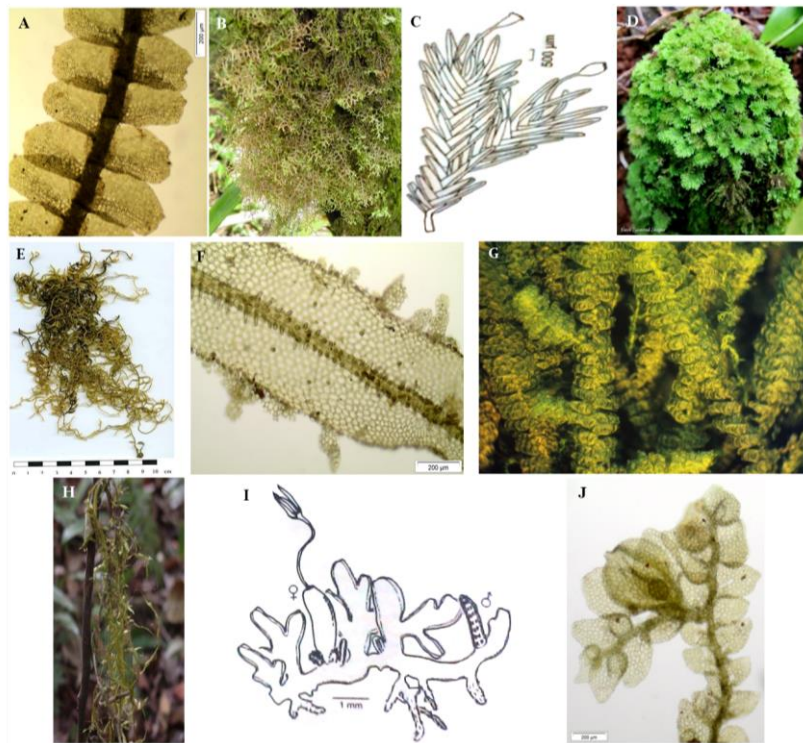


Fig. 1. The ten bryophytes species selected for the study. A. *Bazzania heterostipa* (Steph.) Fulford. (by the authors), B. *Bryopteris filicina* (Sw.) Nees (by G.J. Silva), C. *Fissidens flabellatus* Hornsch. (illustration in [58]), D. *Hypopterygium tamarisci* (Hedw.) Brid. (by Black Diamond Images, available at <http://www.flickr.com/photos/blackdiamondimages/9387167889/>), E. *Meteorium deppei* (Hornsch. ex Müll. Hal.) Mitt. (by J.R.P.M. de Oliveira), F. *Metzgeria brasiliensis* Schiffn. (by the authors), G. *Neckeropsis undulata* (Hedw.) Reichardt. (by Jan-Peter Frahm), H. *Phyllogonium viride* Brid. (by G.J. Silva), I. *Riccardia regnellii* (Ångstr) Hell (illustration in [59]) and *Vitalianthus bischlerianus* (K.C. Pôrto & Grolle) R.M. Schust. & Giacottti (by the authors).

The selected variables were resampled by calculating the values of the pixels of the layers, using the pixels 'nearest neighbor', which is the most suitable method for continuous data [21,38]. This technique allowed us to adapt the original pixel size for the accuracy of biotic data used, which was geo-referenced for each location, establishing a spatial resolution of 20 km<sup>2</sup>.

#### *Model of species potential distribution*

Maxent – Maximum entropy modeling [39,40] – was the algorithm used to model the distribution of the species, since it is well established in literature, in particular for small sampling [41,42]. Maxent is one of the most commonly used methods for inferring distributions of species and environmental tolerances from occurrence data [40]. It uses presence-only data to estimate a set of functions that relate environmental variables and environmental suitability in order to approximate the niche and potential geographic distribution of species [40]. The models were created on Maxent 3.3.3a software.

The models were validated using the bootstrap method, inspecting the AUC value (area under curve), and the statistical significance was tested by binomial proportion.

The threshold applied for environmental suitability was '10 percentile training presence' [43], which discards those 10% of the records that have the lowest values in this index. This threshold was adopted as an extra precaution due to possible inaccuracies in geo-referenced data from different sources [21].

After the models were run and validated, we performed an intersection between the maps with high environmental suitability for the occurrence of the studied species (> 50% of environmental suitability) and the maps of the Brazilian UCs (MMA 2010). Areas with the greatest potential presence of bryophyte species not superimposed on UCs were considered areas of gaps in protection.

## Results

The accuracy of the models for all species was high, with AUC ranging between 0.955-0.992, and all statistically significant (Table 2). The environmental suitability of the models for nine of the 10 studied species was explained by the mean diurnal temperature range; contributions ranged from 20 - 60% of variance explained (Fig. 2).

**Table 2.** Statistical modeling of potential distribution and a more explanatory variable for the distribution of bryophytes in the Atlantic forest. Species are sorted alphabetically. M = Marchantiophyta (liverworts), B = Bryophyta (mosses). <sup>a</sup>Binomial proportion [57].

Phylum	Species	Threshold	p <sup>a</sup>	AUC	Contribution (%)
M	<i>Bazzania heterostipa</i> (Steph.) Fulford	0.3014	< 0.0001	0.956	Mean Diurnal Temperature Range (38)
M	<i>Bryopteris filicina</i> (Sw.) Nees	0.3857	< 0.0001	0.987	Mean Diurnal Temperature Range (21)
B	<i>Fissidens flabellatus</i> Hornsch.	0.1461	< 0.0001	0.98	Mean Diurnal Temperature Range (38)
B	<i>Hypopterygium tamarisci</i> (Hedw.) Brid.	0.3716	< 0.0001	0.992	Mean Diurnal Temperature Range (31)
B	<i>Meteorium deppei</i> (Hornsch. ex Müll. Hal.) Mitt.	0.2909	< 0.0001	0.989	Isothermality (20)
M	<i>Metzgeria brasiliensis</i> Schiffn.	0.528	< 0.0001	0.987	Mean Diurnal Temperature Range (46)
B	<i>Neckeropsis undulata</i> (Hedw.) Reichardt.	0.1675	< 0.0001	0.971	Mean Diurnal Temperature Range (37)
B	<i>Phyllogonium viride</i> Brid.	0.1498	< 0.0001	0.986	Mean Diurnal Temperature Range (20) and Isothermality (20)
M	<i>Riccardia regnellii</i> (Ångstr.) Hell	0.3165	< 0.0001	0.969	Mean Diurnal Temperature Range (42)
M	<i>Vitalianthus bischlerianus</i> (K.C. Pôrto & Grolle) R.M. Schust. & Giancotti	0.2759	0.0002	0.955	Mean Diurnal Temperature Range (60)

The distribution of sites suitable for most species was greater than their actual distribution, with many areas, predicted as environmentally suitable, not currently known to harbor the species (see Appendix A1 – A10 in Electronic Supplementary Material). Two species occurred in rare sites: *Hypopterygium tamarisci* (Hedw.) Brid. (moss) and *Metzgeria brasiliensis* Schiffn. (liverwort), while four showed a wider geographic range within the study area but with few sparse populations: *Bryopteris filicina* (Sw.) Nees (liverwort), *Meteorium deppei* (Hornsch. ex Müll. Hal.) Mitt., *Neckeropsis undulate* (Hedw.) Reichardt and *Phyllogonium viride* Brid (mosses).

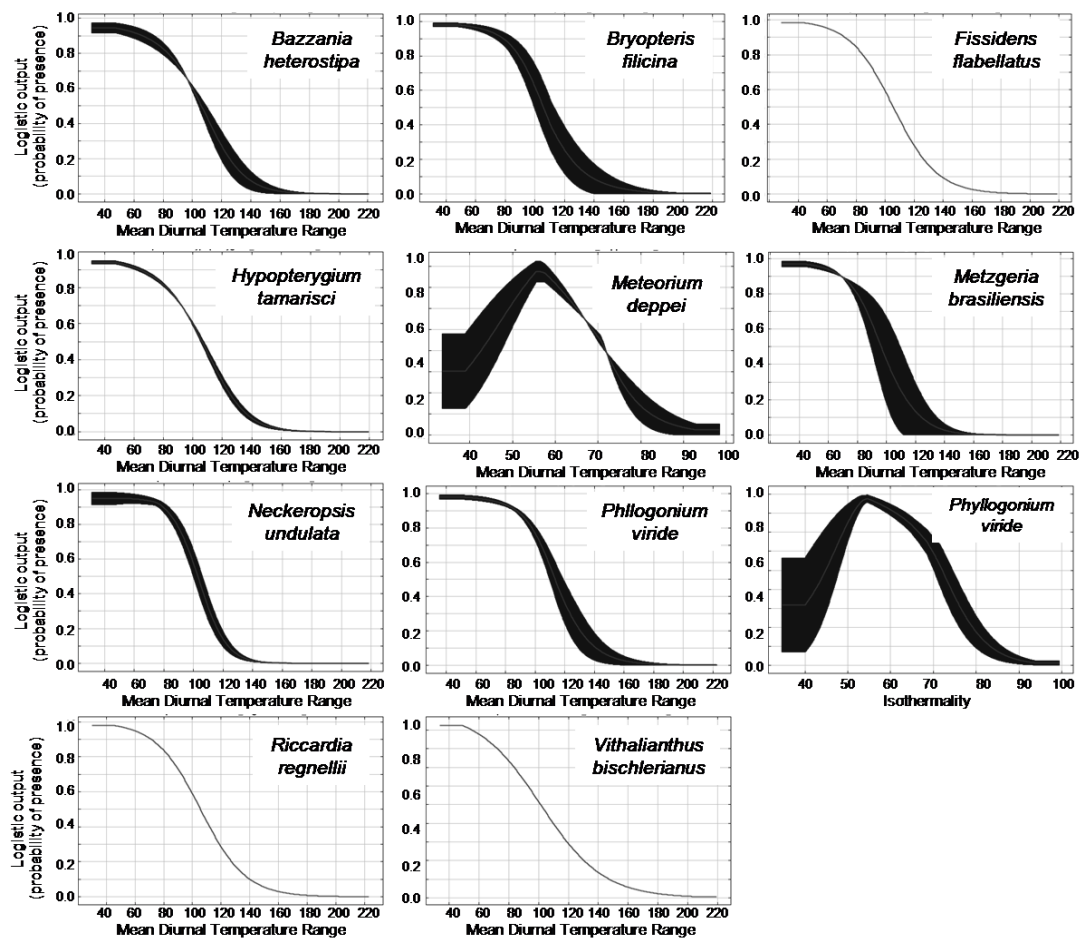


Fig. 2. Average of all partitions in the regression of environmental variables in relation to the environmental suitability of the ten bryophytes species selected for the study.

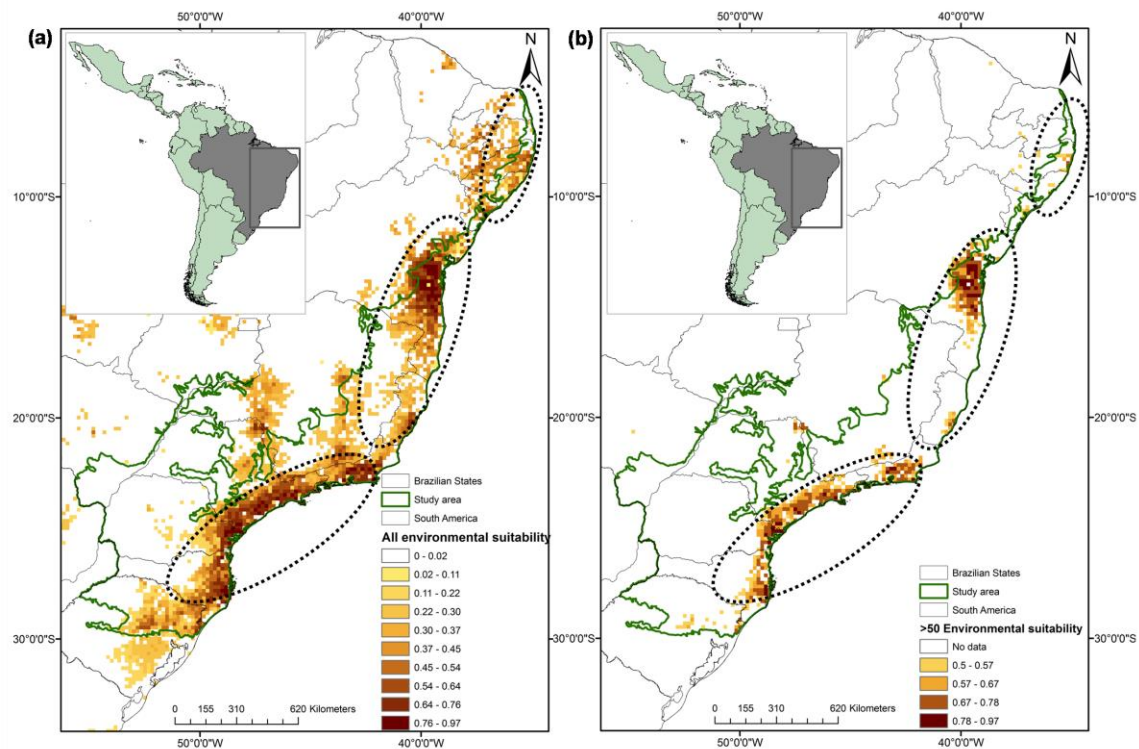
The resulting map from the overlay of the environmental suitability of the species showed that ca. 120,000 km<sup>2</sup> (9%) of the Atlantic Forest Domain was favorable for establishment and development of the studied species. This extension was reduced to ca. 57,000 km<sup>2</sup> when sites with >50% of environmental suitability were analyzed. Three potential distribution centers were distinguished: Northeast, Southeast and Central region (Fig. 3).

Eighty-three UCs overlapped in areas with high environmental suitability (> 50%) for bryophytes, totaling 15,300 km<sup>2</sup> (27%) (Fig. 4). Of all the UCs, 57 were under Full Protection and 26 for Sustainable Use. Four UCs under Full Protection overlapped in areas with high environmental suitability in the Northeast (totaling 185.94 km<sup>2</sup>), six in the Central (271.48 km<sup>2</sup>) and 46 in the Southeast (13,294.35 km<sup>2</sup>) distributions centers. The Central distribution center had high environmental suitability but few protected areas.

## Discussion

The potential distribution of bryophyte species modeling showed a difference between real and potential distribution in the Atlantic Forest, with more sites suitable for most species than their actual distribution. This result might have significant gaps in sampling effort and

knowledge of bryophyte distribution in sites without records of the studied species, which should be critically explored for the registration of new populations of the species in question.



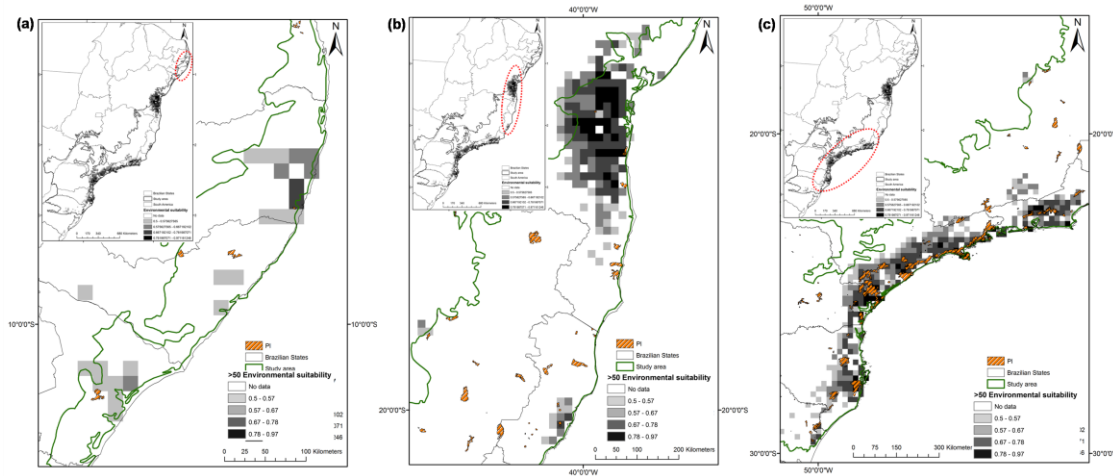
**Fig. 3. Maxent cumulative potential distribution of ten bryophyte species in the Atlantic Forest, Brazil (a) and the optimal niche occupied by this species (environmental suitability area  $\geq 50\%$ ) (b). Projection: WGS84.**

Among the bryophytes studied, six showed interesting distribution patterns along the Atlantic Forest and therefore deserve more attention with respect to their conservation. Two species have restricted distribution, occurring in rare sites: *Hypopterygium tamarisci* (Hedw.) Brid. and *Metzgeria brasiliensis* Schiffn., while four showed a sparse populations pattern: *Bryopteris filicina* (Sw.) Nees, *Meteorium deppei* (Hornsch. ex Müll. Hal.) Mitt., *Neckeropsis undulata* (Hedw.) Reichardt. and *Phyllogonium viride* Brid. These species are all evaluated as indicators of forests with high humidity and shaded environments [18,44,45] and should be considered in management plans and in effective conservation strategies in the Atlantic Forest.

The models for all species had high accuracy and all were statistically significant. The mean diurnal temperature range was the variable that best explained the environmental suitability of the models for nine of the 10 studied species, which like most bryophytes are restricted to limited temperature conditions, mainly due to a lack of protective cell cuticles, enabling solutions and gases to enter freely into the tissue [46]. Our results also provide important insights into the efficiency of the group for monitoring global climate change. The bryophytes represent a largely untapped and extremely viable resource for monitoring the effects of global warming on the environment, having been compared to "canaries in a coal mine" [47]. In a pioneering experimental study in the tropics, Jácome et al. [48] investigated the impact of simulated climate change on epiphytic bryophytes, using a translocation approach, showing that exposure to a temperature increase of 1.5 °C had a measurable effect on community



structure over a period of two years. Thus, bryophytes might help answer questions about how fast climate change affects species and ecosystems, which must be taken into account in further studies [49].



**Fig. 4. Overlay of the optimal niche occupied (environmental suitability area  $\geq 50\%$ ) by ten bryophyte species with the network of Full Protection Conservation Units of the Brazilian Atlantic Forest, for Northeast (a), Central (b) and Serra do Mar (c) centers of diversity. Projection: WGS84.**

The resulting map from the overlay of the environmental suitability of the species showed that ca. 120,000 km<sup>2</sup> (9%) of the Atlantic Forest Domain was favorable for their establishment and development. However, considering sites with  $>50\%$  of environmental suitability reduced the area by more than half (ca. 57,000 km<sup>2</sup>). Nevertheless, it was possible to observe three potential distribution centers: in the Northeast, in the Southeast and in one portion of a central region between them. These regions correspond to those described by Prance [50,51] as endemism centers: the Pernambuco Endemism Center, the Rio de Janeiro - São Paulo Endemism Center and the Bahia - Espírito Santo Endemism Center, respectively. These regions are of fundamental importance to many biological groups due to their endemic species, most of them threatened [52]. These areas were therefore designated as biodiversity corridors (large regional planning units which comprise a mosaic of land uses and key areas for conservation, to enable biological exchange between them) in the Atlantic Forest hotspot: the Northeast biodiversity Corridor, the Serra do Mar Corridor (Southeast), and the Central Corridor (Bahia - Espírito Santo).

With regard to bryophytes, these Endemism Centers were confirmed as highly relevant to the group. However, the map with the greatest levels of environmental suitability for all species showed areas of the Southeast and the Central Corridor as more favorable to the establishment and development of the group, while only a few sites were found in the Northeast Corridor. This result is explained by the large area of forest remnants in the Southeast and in the Central Corridor of Atlantic Forest [52]. While the Northeast is highly fragmented, with only 2% of the original forest cover [53], the Serra do Mar Corridor, for example, covers one of the few areas of continuous Atlantic Forest [52].

Ribeiro et al. [54] quantified how much Atlantic Forest remains in Brazil and determined the spatial distribution of the remnants, finding that the largest fragment of this domain is located in the Serra do Mar, mainly along the coastal mountains of the state of São Paulo. This isolated

remnant has 1,109,546 ha of continuous forest, which represents 7% of the total remains. The second and third largest fragments are also located in the Serra do Mar Corridor with 508,571 ha and 382,422 ha, respectively. Altogether, the three fragments total over 2 million hectares, i.e. more than 13% of the remaining forest. Moreover, the same authors showed that the Serra do Mar Corridor was the best preserved bio-geographic region studied, with 36.5% of its original vegetation cover, followed by the Central Corridor, with 17.7%. On the other hand, the Northeast Corridor had only 4.7% of forest cover. In fact, a recent study of bryophyte distribution in Brazil showed a great diversity of indices for the Southeast Atlantic Forest, which was attributed to the great altitudinal variation and habitat suitability in the region, and consequent greater variety of ecological niches for species (Silva and Pôrto, unpublished results).

Furthermore, bryophyte species distribution might be compromised by habitat loss. The Atlantic Forest is one of the most threatened domains in the world [55], 7% - 16% of its original area having been reduced [54,55], depending on the author in question. According to the Fundação SOS Mata Atlântica [56], the amount of deforestation in the period from 2002 to 2010 was 21,380 ha. This inexorable loss of habitat reflects the current landscape of this forest, with small fragments of irregular shape, isolated and inserted into an inhospitable matrix [13,14]. For example, estimates for an area of 4,000 km<sup>2</sup> in the Northeast region, in the period from 1989 to 2000, showed that there was a loss of 10% in coverage, while 5% of the remnants disappeared [53].

Paradoxically, the Atlantic Forest remains relatively unprotected. Although a significant number of UCs have been established in this domain, most of these are small and for Sustainable Use (74%), without control or a rigid management plan for natural resources [11]. In our study, 83 UCs overlapped in areas with high environmental suitability (> 50%) for bryophytes (totaling 15 300 km<sup>2</sup> - 27%), with 57 under Full Protection and 26 for Sustainable Use. The Northeast and Central Corridors were the areas with the fewest protected areas. The overall extent of the UCs was unrepresentative, and although there has been a predominance of Full Protection UCs in the Atlantic Forest, these constitute, on average, smaller areas compared to those for Sustainable Use [56].

Therefore, new protected areas need to be created in the Northeast and the Central Corridor, particularly in areas bigger than 300 ha, which is regarded as a minimum habitat for a functioning bryophyte population [24]. In the Serra do Mar Corridor, it will be necessary to strengthen the system of protected areas and restore and maintain connectivity through biological corridors.

Moreover, UCs designed for full protection of biodiversity should transform unmanaged areas into well-managed entities that conserve biodiversity effectively. On the other hand, it is up to the UCs of Sustainable Use to face the biggest challenge of defining what can be used, who can use it, and how much use is sustainable. The UC system still faces the challenge of working with government institutions that compete politically [11]. Indeed, human and financial resources should be expanded to increase the efficiency of protected areas.

### **Implications for conservation**

With this work, we draw a conclusion similar to Barros et al. [21]: an efficient recovery of databases for use in modeling potential distribution of species, followed by further analysis of species distribution, provide important information for the implementation of conservation

procedures. Our results support the fostering of conservation for the bryophytes studied, considering that most of them displayed restricted or sparse distribution and sensitivity to temperature variation, which may indicate susceptibility to climate change. Furthermore, significant gaps in knowledge distribution and in protection were identified in the Atlantic Forest, mainly in the Central and the Northeast Corridor, suggesting these areas as priorities for conducting inventories and, after detailed studies to confirm the potential distribution, the creation of new reserves. The number and effectiveness of protected areas suitable for bryophytes were still less than adequate for the efficient conservation of the species.

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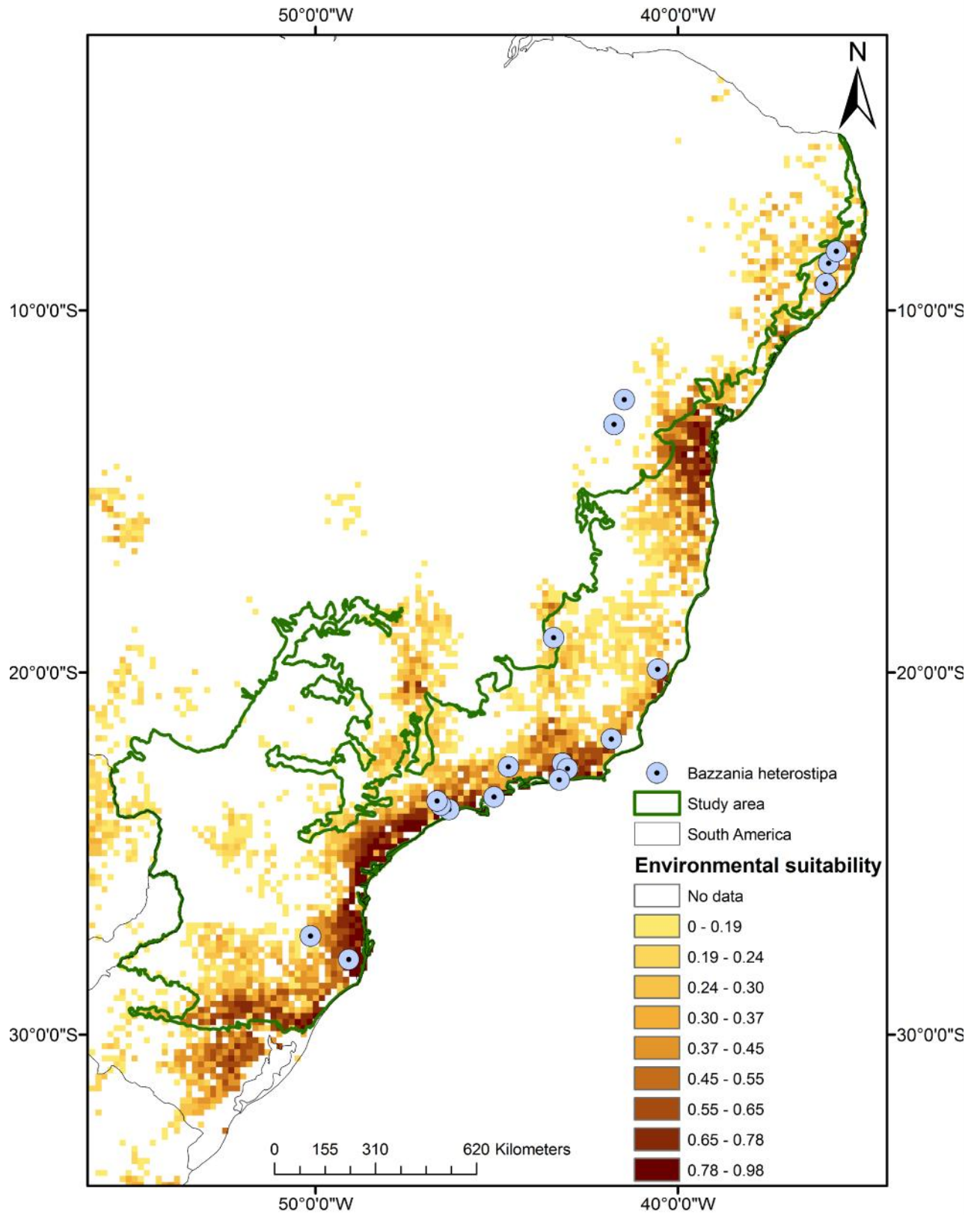
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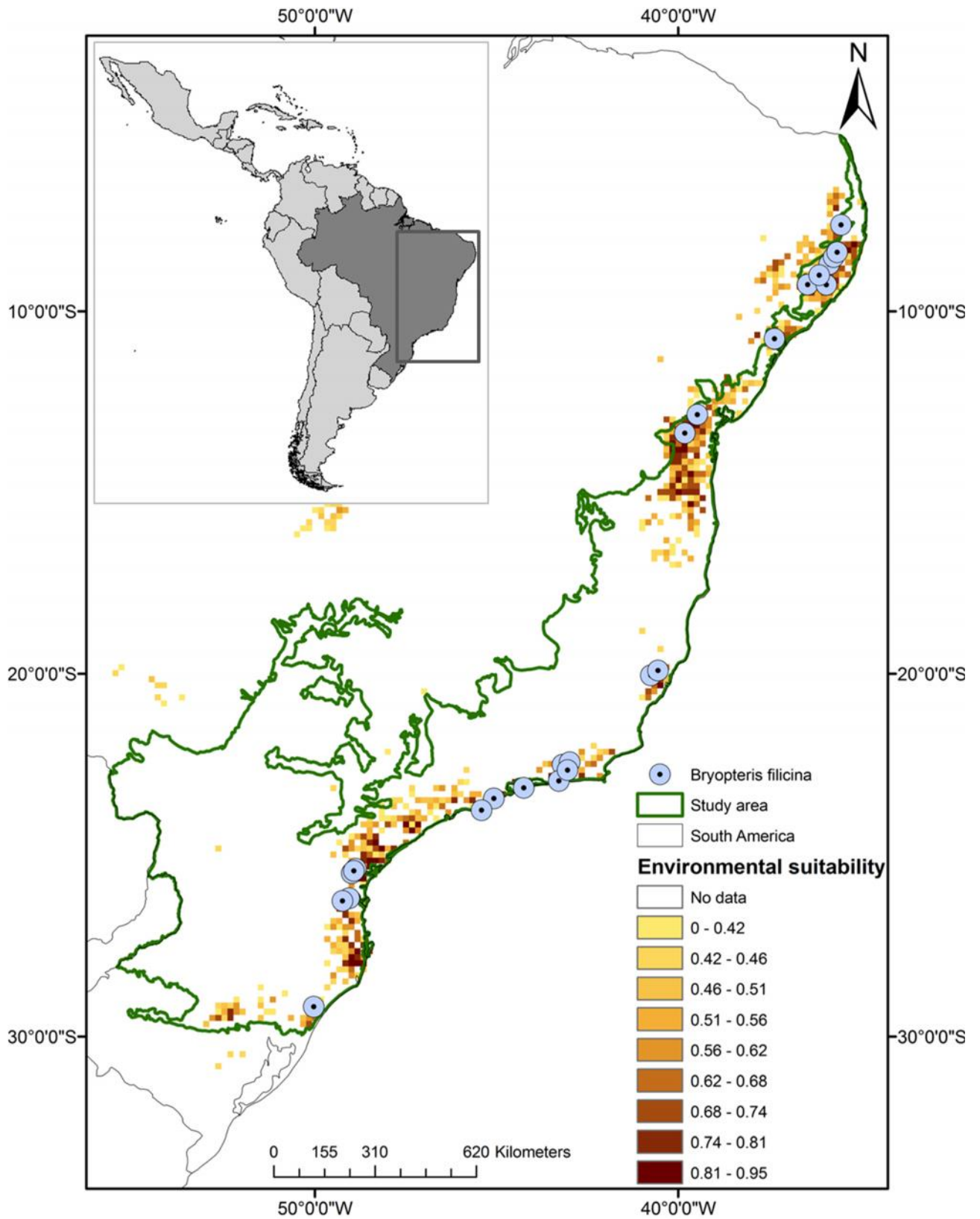
**ELECTRONIC SUPPLEMENTARY MATERIAL**

**Appendix A1.** Maxent potential distribution model for the *Bazzania heterostipa* (Steph.)  
Fulford species in the Brazilian Atlantic Forest.

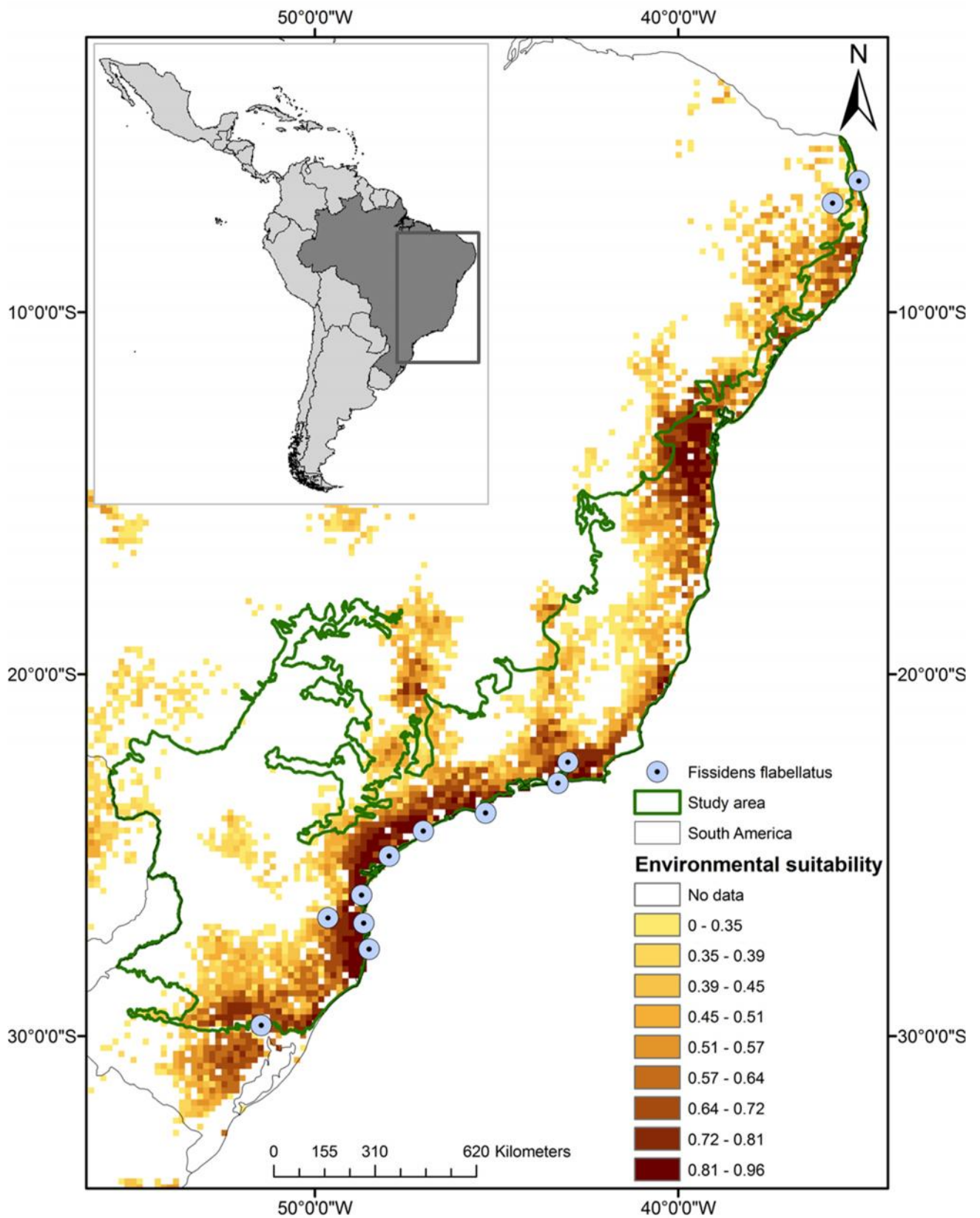




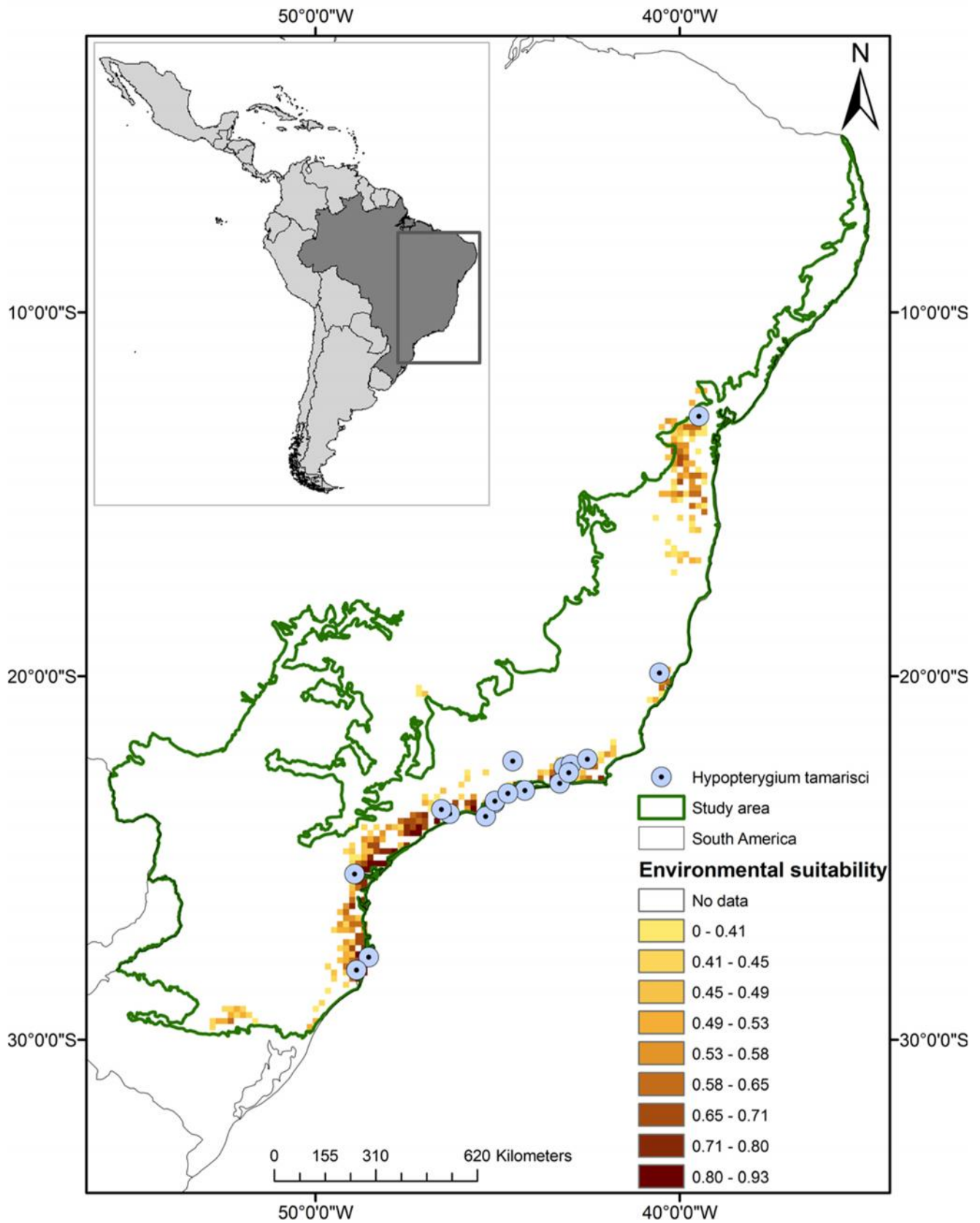
**Appendix A2.** Maxent potential distribution model for the *Bryopteris filicina* (Sw.) Nees species in the Brazilian Atlantic Forest.



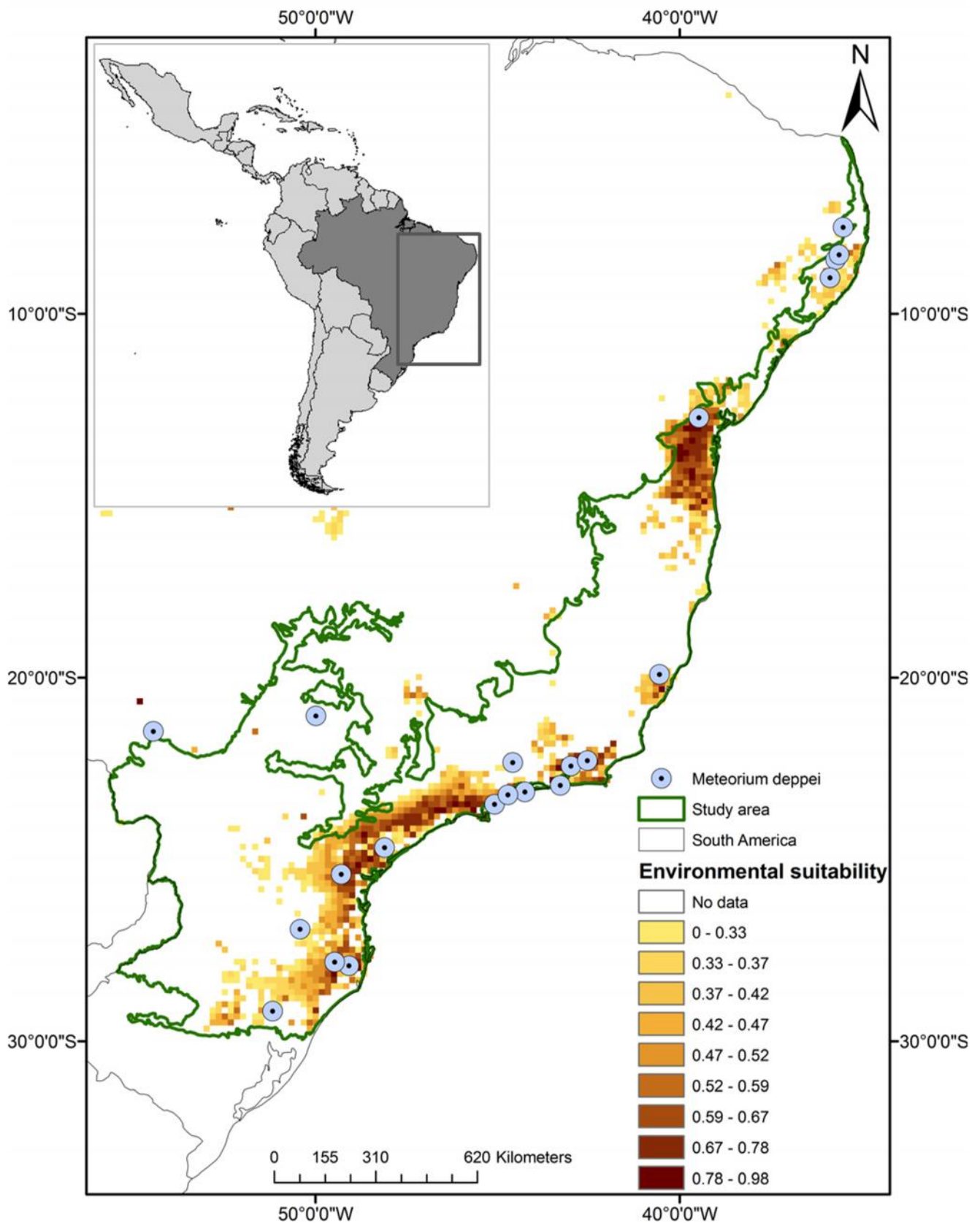
**Appendix A3.** Maxent potential distribution model for the *Fissidens flabellatus* Hornsch species in the Brazilian Atlantic Forest.



**Appendix A4.** Maxent potential distribution model for the *Hypopterygium tamarisci* (Hedw.) Brid. species in the Brazilian Atlantic Forest.

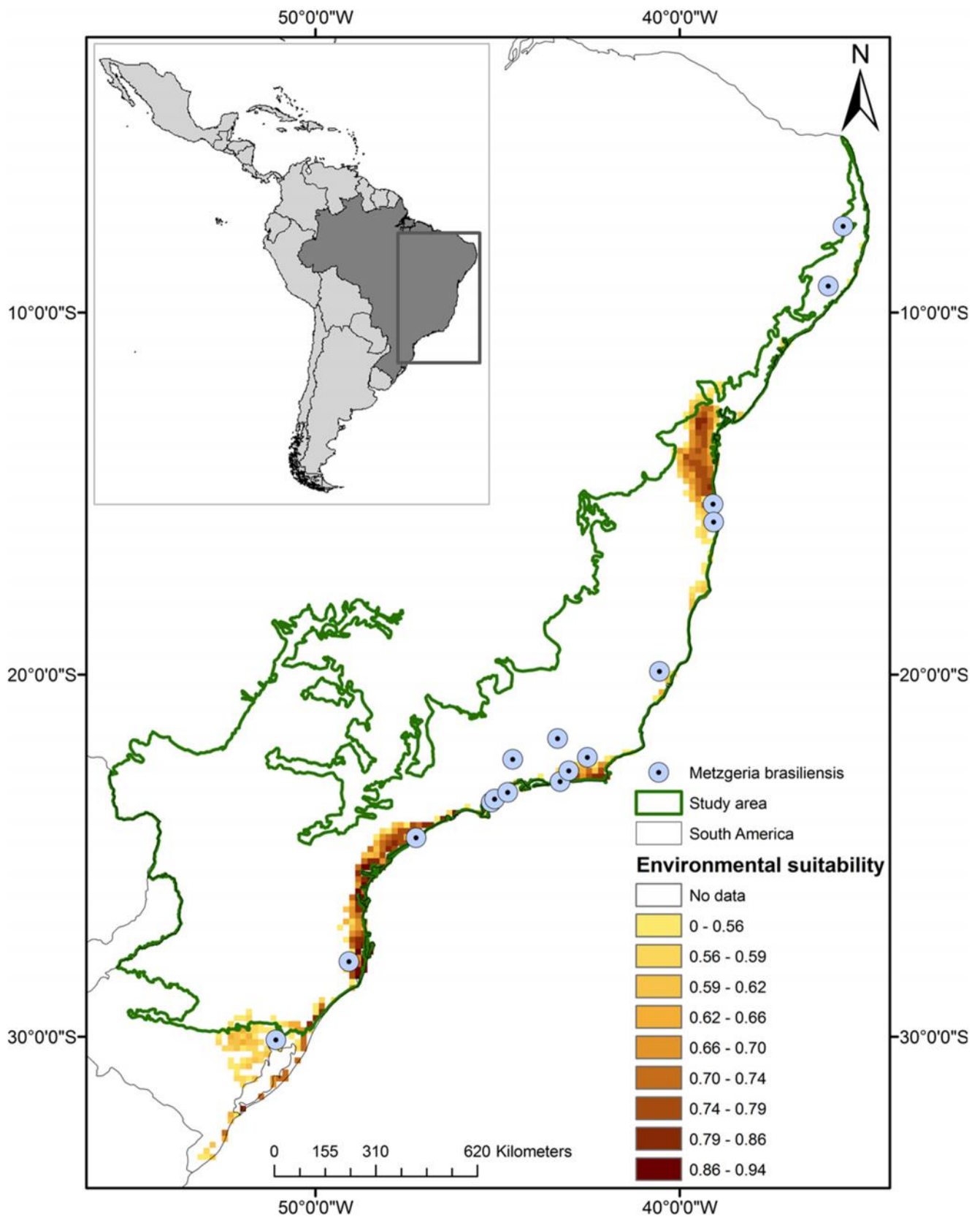


**Appendix A5.** Maxent potential distribution model for the *Meteorium deppei* (ex Hornsch. Müll. Hal.) Mitt. species in the Brazilian Atlantic Forest.



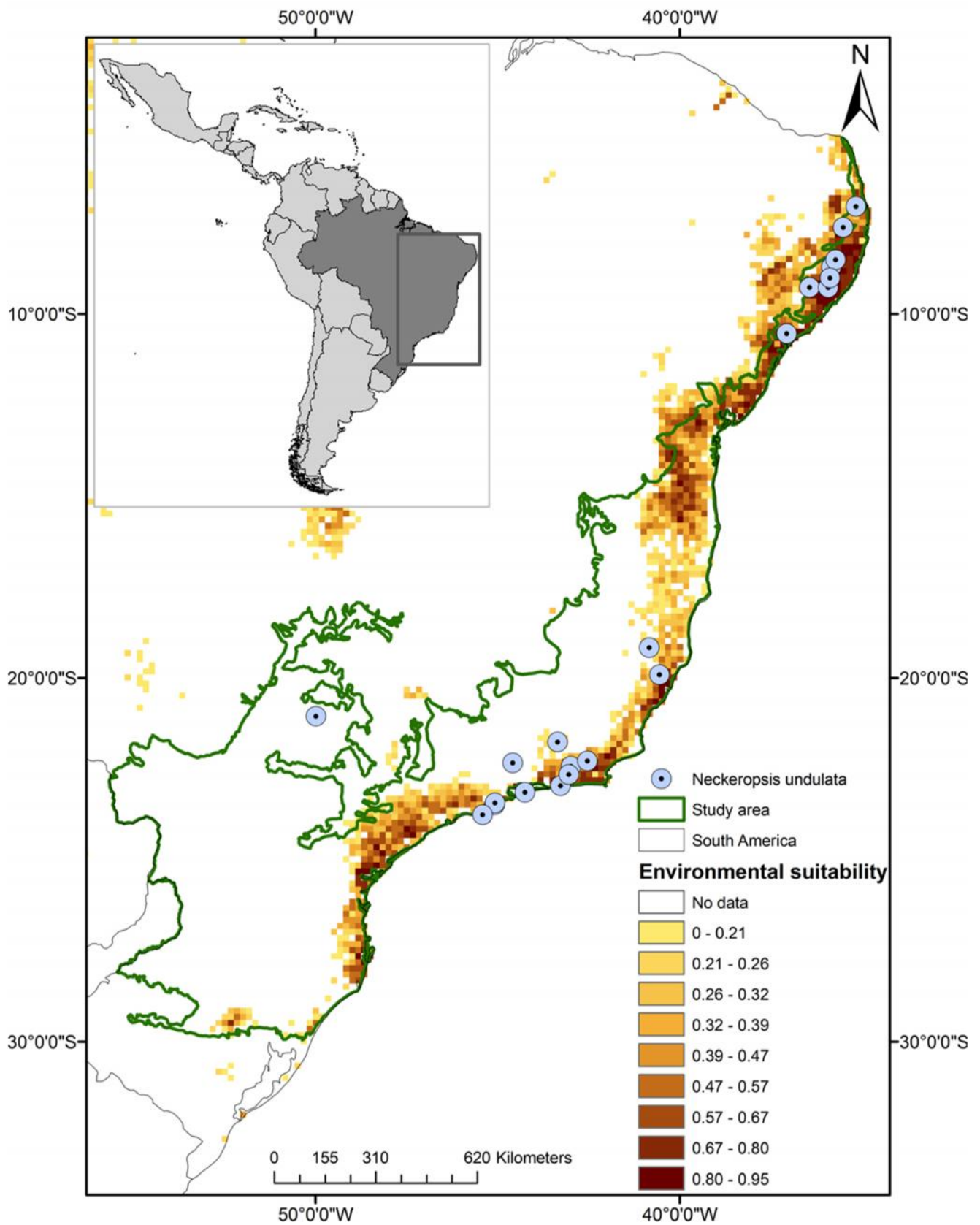
**Appendix A6.** Maxent potential distribution model for the *Metzgeria brasiliensis* Schiffn.

species in the Brazilian Atlantic Forest.

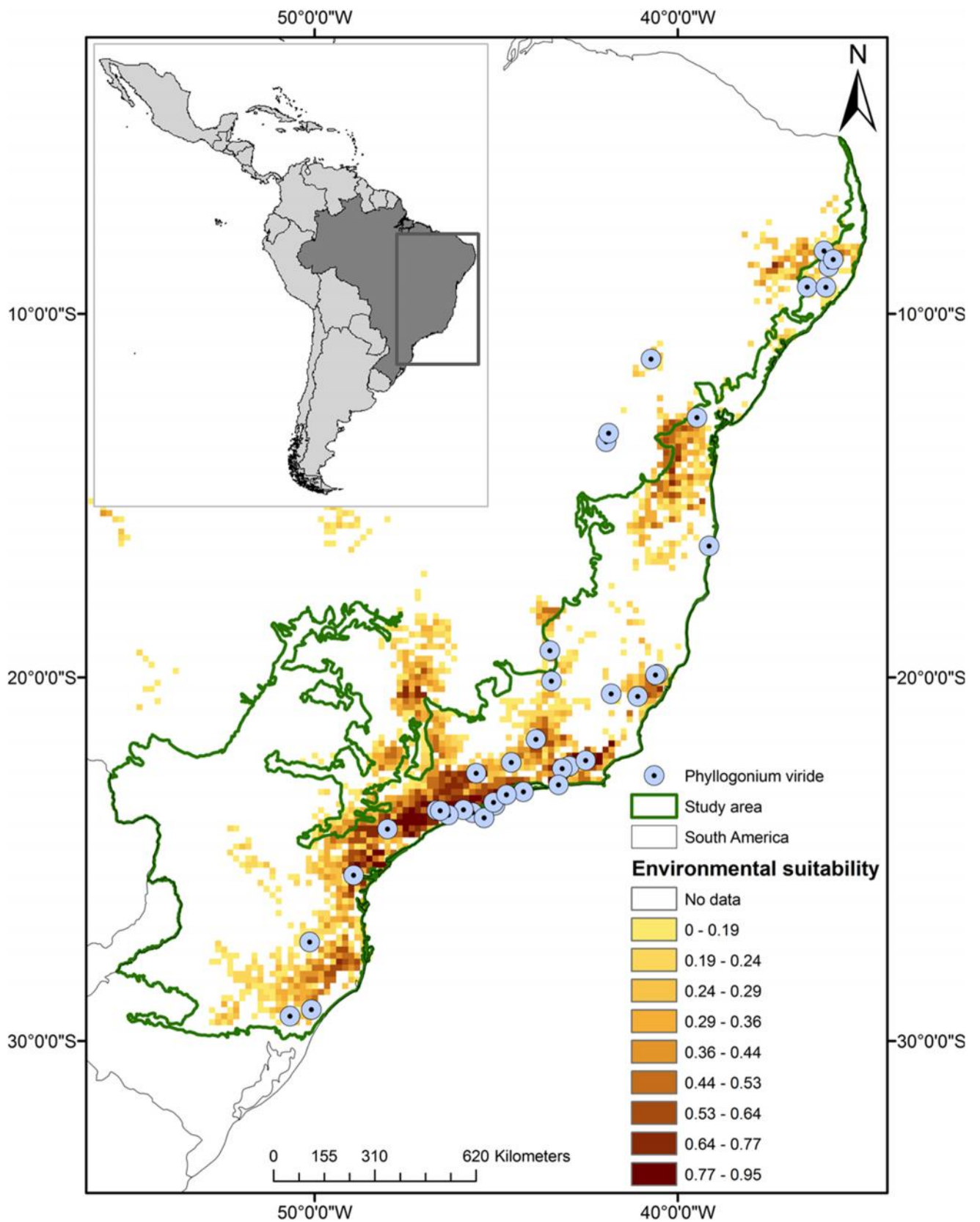


**Appendix A7.** Maxent potential distribution model for the *Neckeropsis undulata* (Hedw.)

Reichardt species in the Brazilian Atlantic Forest.

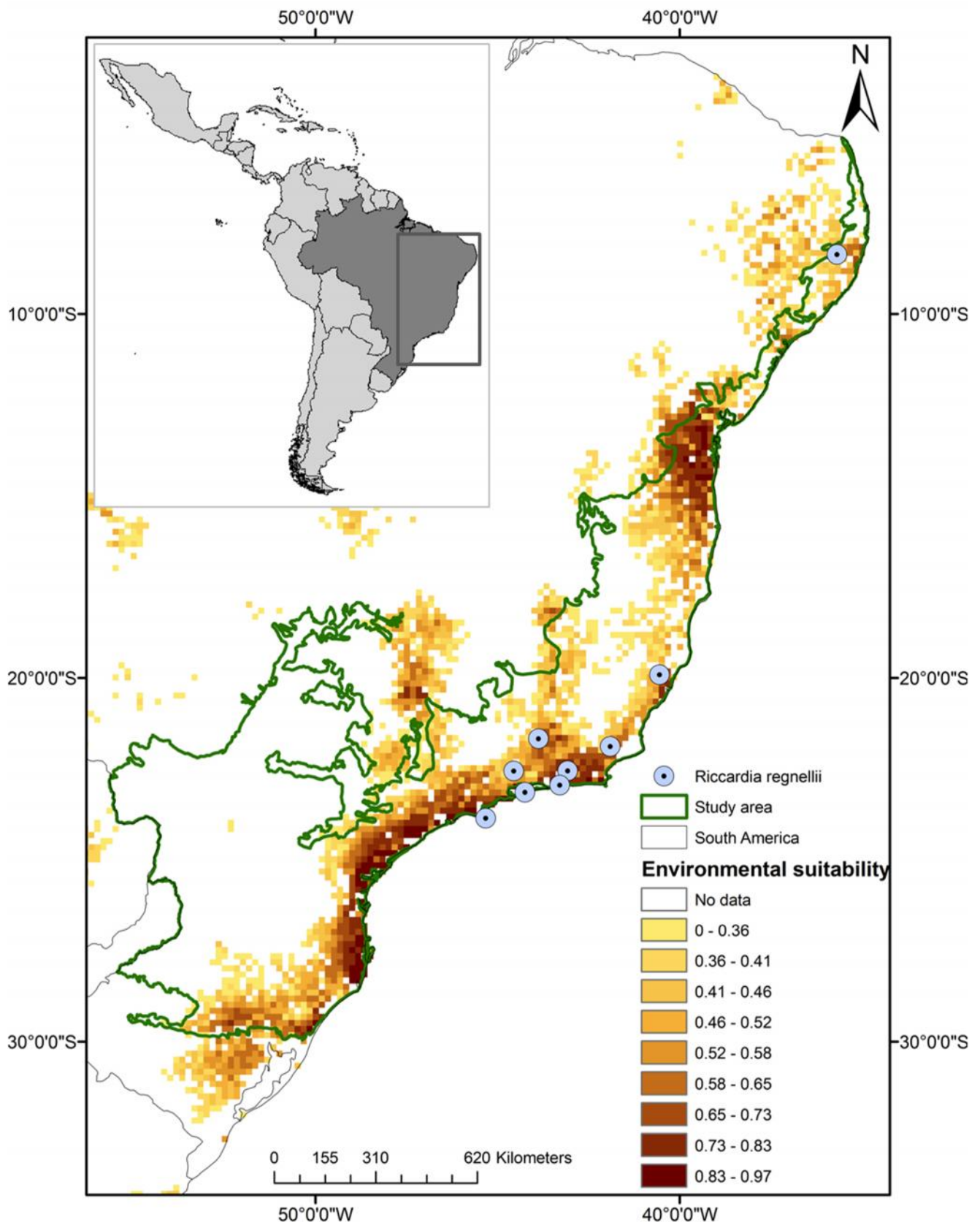


**Appendix A8.** Maxent potential distribution model for the *Phyllogonium viride* Brid. species in the Brazilian Atlantic Forest.



**Appendix A9.** Maxent potential distribution model for the *Riccardia regnellii* (Ångstr.)

Hell species in the Brazilian Atlantic Forest.





**Appendix A10.** Maxent potential distribution model for the *Vitalianthus bischlerianus* (K.C. Pôrto & Grolle) R.M. Schust. & Giacotti. species in the Brazilian Atlantic Forest.

