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VICTÓRIA RENATA FONTOURA BENEMANN

**ECOLOGIA ESPACIAL DO ATOBÁ-MASCARADO *Sula dactylatra* (Lesson,
1831) NA ILHA DA TRINDADE, OCEANO ATLÂNTICO SUL**

São Leopoldo

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Orientadora: Profa. Dra. Maria Virginia Petry

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Poesia sobre pardelas

O albatroz - por ora dito errante
é mais que certo:
impávido
pois na Água do Céu é Pássaro
sobrevoa a névoa griséu
que emerge
da dança
das ondas
e ao contemplar a cerúlea
- que é cor como azul do céu, como verde do mar
transcende a fronteira dos homens
da água, do ar
bicho que dorme em mar grosso
não há de temer a tormenta
mas teme a bicha -dito o cabo, marinheiro
que na valuma da vela mestra
orquestra
os ventos do mar
corredora alada
incerta
no gelo, confusa
vê a água ficar cinerea
onde tem peixe, há pardela!
Besta marinha, pelágica
que tem corpo de ave
Alma de Mestre
e faz de lar
a procela.

RESUMO

A modelagem de habitats adequados para a manutenção da biodiversidade em ambientes modificados pode servir como uma ferramenta importante para fins de conservação biológica. Trindade e Martim Vaz é um arquipélago oceânico localizado a 1.200 km da costa do Brasil, e encontra-se em sucessão ecológica desde a erradicação de caprinos introduzidos na ilha, os quais devastaram sua vegetação original. Modelamos a adequabilidade de habitat de nidificação do atobá-mascarado *Sula dactylatra* na Ilha da Trindade, estimando sua potencial distribuição reprodutiva atual, e propusemos a potencial distribuição futura em resposta a quatro cenários de cobertura vegetal na ilha. Foram mapeados 87 ninhos ativos durante as estações reprodutivas de 2017 e 2019 na Ilha da Trindade. Modelamos pontos de ocorrência em resposta a cinco variáveis topográficas (Elevação, Inclinação, Insolação, Aspecto e Comprimento do Fluxo) e duas variáveis de vegetação (Sucessão e Remanescente), usando *Ensemble Species Distribution Models* (ESDM) de sete algoritmos diferentes: *Boosted Regression Trees* – GBM, *Random Forests* – RF, *Generalized Linear Models* – GLM, *Generalized Additive Model* – GAM, *Artificial Neural Network* – ANN, *Multiple Adaptive Regression Spline* – MARS, e *Maximum Entropy* - Maxent. Avaliamos a precisão do modelo com base em duas métricas: AUC e TSS. As análises foram realizadas usando o pacote "biomod2" no software R 3.6.1. Nossos modelos mostraram precisão acima de 0.8 nas duas métricas usadas (AUC e TSS). Os resultados indicam áreas com alta adequabilidade ao longo das faces Sudoeste e Noroeste da ilha, principalmente em elevações variando entre 150 - 450 m. Elevação e Aspecto foram as variáveis que melhor explicaram a seleção de *S. dactylatra* por habitats de nidificação. Com base em nossas previsões de distribuição futuras, concluímos que a sucessão ecológica não afetará substancialmente a distribuição das áreas reprodutivas de *S. dactylatra* na ilha. Uma vez que *S. dactylatra* seleciona áreas de altas elevações, próximas às margens de penhascos, é deduzível que o aumento previsto na cobertura vegetal não irá afetar tais áreas, provavelmente devido a características geomorfológicas como elevação, composição do solo e profundidade. Recomendamos que estudos futuros incluam variáveis topográficas de alta resolução espacial, assim como variáveis bióticas, a fim de modelar a distribuição presente e futura das espécies.

Palavras-chave: Aves Marinhas, Habitat, Adequação, Ecologia Espacial, Modelagem

ABSTRACT

Modeling suitable habitats for biodiversity maintenance under changing environments may serve as an important tool for biological conservation purposes. Trindade and Martim Vaz is an oceanic archipelago located ~1.200km from the coast of Brazil, and has been under ecological succession since feral goat eradication, which have devastated its original vegetation. We modeled nesting habitat suitability of a surface-nesting seabird - the Masked Booby *Sula dactylatra* - at Trindade Is., predicted its current nesting distribution, and proposed the future potential distribution under four possible vegetation scenarios on the island. We mapped 87 active nests of *S. dactylatra* during the breeding seasons of 2017 and 2019, from October to November at Trindade Is. We fitted nest occurrence points in response to five topographical (Elevation, Slope, Insulation, Aspect and Flow Length) and two vegetation (Succession and Remnant) variables, using an Ensemble Species Distribution Model (ESDM) of seven different algorithms: Boosted Regression Trees – GBM, Random Forests – RF, Generalized Linear Models – GLM, Generalized Additive Model – GAM, Artificial Neural Network – ANN, Multiple Adaptive Regression Spline – MARS, and Maximum Entropy - Maxent. We evaluated model accuracy based on two metrics: ROC and AUC, and tested for multicollinearity between variables using VIF test. Analyses were performed using the “biomod2” package in software R 3.6.1. Our models showed accuracy above 0.8 in both used metrics (ROC and TSS). Our results indicate areas of very high nesting habitat suitability along the Southwest and Northwest faces of Trindade Is., mostly in elevations varying from 150-450 m. Elevation and Aspect were the variables that better explained *S. dactylatra* selection for nesting habitats. Based on our predictions of distribution in response to possible vegetation scenarios, we found that the ecological succession will not affect the nesting distribution of *S. dactylatra* on the island substantially. Since *S. dactylatra* select areas of high elevations near cliff edges to nest, it is deducible that the predicted increase in the vegetation coverage does not reach these high areas because of geomorphological characteristics, such as elevation, soil composition and depth. We encourage further studies to address topographical variables of the finest spatial resolution spatial resolution as possible, as well biotic variables in order to model present and future species' distribution.

Key-words: Seabirds, Habitat, Suitability, Spatial Ecology, Modeling

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1 APRESENTAÇÃO

Este documento apresenta informações referentes à dissertação de mestrado, como pré-requisito para obtenção do título de Mestre em Biologia pela Universidade do Vale do Rio dos Sinos. Neste estudo, foi analisada a distribuição espacial e uso de habitat de nidificação do atobá-mascarado (*Sula dactylatra*), ave marinha da família Sulidae, em uma ilha remota que representa o extremo Leste do território brasileiro: a Ilha da Trindade. Uma vez que a Ilha da Trindade se encontra em processo de sucessão ecológica após a erradicação de espécies invasoras que modificaram substancialmente a paisagem da ilha, em decorrência de uma extensa supressão vegetal ocasionada pela herbivoria por cabras-domésticas (*Capra hircus*) introduzidas pelo homem no século XVIII, torna-se imprescindível a compreensão das respostas ecológicas da fauna terrestre da ilha a estes eventos, sob uma perspectiva de biologia da conservação.

As atividades de campo foram autorizadas conforme projeto cadastrado e aprovado no Sistema de Informação da Biodiversidade (SISBIO, n ° 38053-9) e junto ao Comitê de Ética em Pesquisa sobre o Uso de Animais em Pesquisa (CEUA, n ° PPE-CEUA 05.2016) da Universidade do Vale do Rio dos Sinos. Esta dissertação é composta por uma fundamentação teórica, objetivos e hipóteses, capítulo I e considerações finais. O capítulo I desta dissertação é composto por um manuscrito científico intitulado “Potential nesting distribution of Masked Boobies (*Sula dactylatra*) breeding at the remote Trindade Island, western South Atlantic”, o qual se encontra formatado de acordo com as normas do periódico “Diversity and Distributions” (ISSN 1472-4642), Qualis CAPES (Biodiversidade) A1 e fator de impacto 4.092.

2 FUNDAMENTAÇÃO TEÓRICA

2.1 O atobá-mascarado *Sula dactylatra* (Lesson, 1831)

O atobá-mascarado *Sula dactylatra* (Lesson, 1831) é uma ave marinha da família Sulidae amplamente distribuída nos oceanos Atlântico, Pacífico e Índico, ao longo das regiões tropical e subtropical (BIRDLIFE INTERNATIONAL, 2020). É considerada a espécie mais pelágica dentre os atobás, e também a que apresenta maior tamanho corporal médio (DUNNING, 2007; SICK, 1997). Seu status de conservação a nível global é Pouco Preocupante, embora se acredite que a população esteja declinando principalmente em consequência da ação humana, sendo os principais impactos a introdução de espécies invasoras e atividades de turismo em áreas de reprodução, e a caça predatória, especialmente de ovos (BIRDLIFE INTERNATIONAL, 2020).

No Brasil, reproduz-se nas ilhas oceânicas do Arquipélago de Abrolhos, Fernando de Noronha, Atol das Rocas e Trindade e Martim Vaz. A população reprodutiva do Atol das Rocas é a mais abundante, enquanto que a da Ilha da Trindade e Martim Vaz é a menos abundante dentre estas, na qual foram contabilizados 600 indivíduos adultos (FONSECA-NETO, 2004) e 72 ninhos ativos (MANCINI *et al.* 2016). Quanto à sua biologia reprodutiva, o atobá-mascarado realiza a postura de um a dois ovos diretamente sobre o solo exposto, os quais são incubados por cerca de 45 dias (NELSON, 1968; PRIDDEL *et al.* 2016). A espécie realiza o comportamento de fratricídio obrigatório, no qual o ninhego mais desenvolvido assassina o outro por competição pelo cuidado parental, resultando na sobrevivência de apenas um dos filhotes (EDWARDS; COLLOPY, 1983). A longevidade média da espécie é de 16,3 anos (BIRDLIFE INTERNATIONAL 2020).

Quanto à seleção de hábitat para nidificação, o atobá-mascarado utiliza em geral platôs e escarpas rochosas próximas às costas de ilhas oceânicas (Figura 1), uma vez

que parecem ter dificuldade em alçar voo em outros locais, necessitando do apoio do suporte aerodinâmico resultante das correntes de vento nestes locais (DUFY, 1984; PRIDDEL *et al.* 2005). Em geral constroem seus ninhos diretamente sobre o solo rochoso exposto com utilização de seixos, muitas vezes permeado por áreas com ocorrência de vegetação de gramíneas, como por exemplo, comunidades vegetais dominadas por *Enneapogon cenchroides* e *Cyperus atlanticus* (FONSECA NETO, 2004; HUGHES *et al.* 2011).

Na Ilha da Trindade, o atobá-mascarado inicia o período reprodutivo em agosto, realiza a postura dos ovos entre setembro e novembro, e finaliza o período em meados de fevereiro, quando indivíduos adultos e os ninhegos, já na fase juvenil, abandonam as colônias reprodutivas na ilha (FONSECA NETO, 2004). Utiliza fragmentos de rocha dispostos em forma circular para a construção dos ninhos, apresentando comportamento extremamente territorialista, e cuidado parental compartilhado entre macho e fêmea durante a incubação e criação dos ninhegos (NELSON, 1968; FONSECA NETO, 2004; PRIDDEL *et al.* 2005) (Figura 2).

O relevo da ilha é muito acentuado e existem poucas trilhas de acesso às áreas onde há nidificação de *Sula dactylatra* na Ilha da Trindade (Figura 3), uma vez que utilizam costões rochosos de altas elevações, o que pode ter levado a subestimativas do tamanho populacional dessa espécie na ilha (RYAN, 2005; CUTHBERT e SOMMER, 2004; MANCINI *et al.* 2016).



Figura 1: Grupo reprodutivo de atobá-mascarado (*Sula dactylatra*) sobre platô rochoso na Ilha da Trindade, Brasil. Fonte: Autora.



Figura 2: Ninho de atobá-mascarado (*Sula dactylatra*) construído com seixos rochosos na trilha para a praia do Eme, Ilha da Trindade, Brasil. Fonte: Autora.

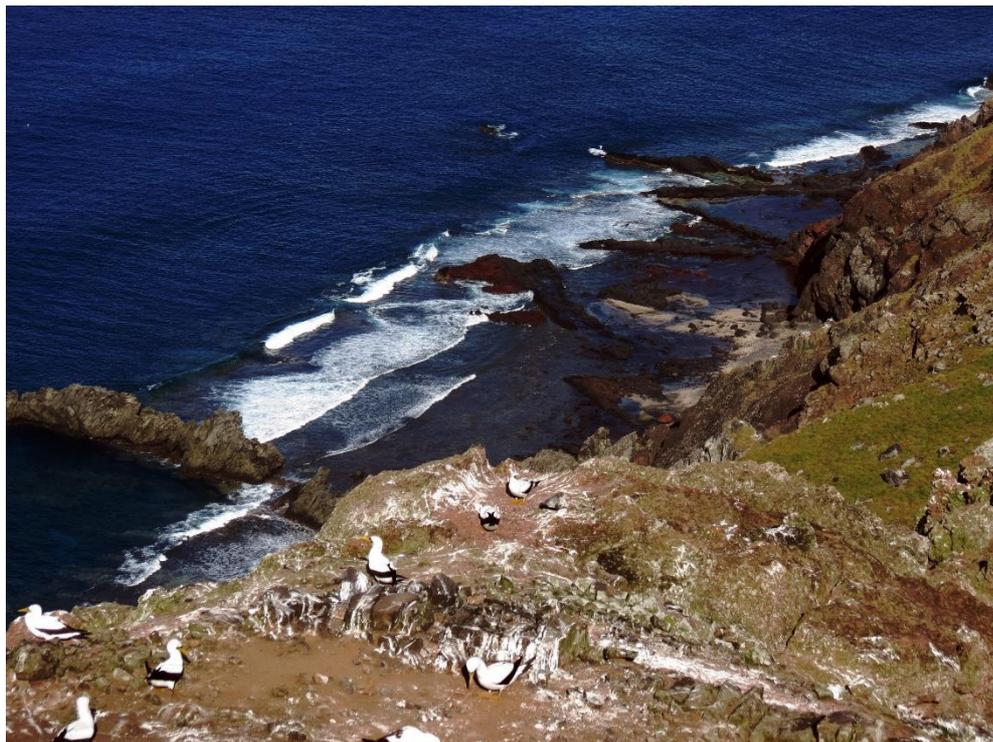


Figura 3: Grupo reprodutivo de atobá-mascarado localizado sobre escarpas rochosas na trilha de acesso para a praia do Eme, localizada na Face Sudoeste da Ilha da Trindade. Fonte: Douglas Ribeiro da Silva.

2.2 A ilha da Trindade

Ambientes insulares possuem alta importância biológica por apresentarem características peculiares, altas taxas de endemismo e, apesar de representarem apenas 5% da área total terrestre, abrigam aproximadamente 20% da biodiversidade global (KIER *et al.* 2009). A Ilha da Trindade dista cerca de 1200km da costa do Espírito Santo, Brasil, sendo considerada uma ilha oceânica brasileira (Figura 2). A ilha situa-se ao extremo Leste do território brasileiro, e constitui, juntamente com Martim Vaz, a única porção emersa da cadeia montanhosa submarina Vitória-Trindade (MOHR *et al.* 2009). A ilha possui superfície emersa de 9,28 km² e o relevo é extremamente acentuado devido à formação geológica da ilha, originada a partir de uma fratura transversal de montes vul-

cânicos (VELTHEIM, 1950; WEAVER, 1990; ALMEIDA *et al.* 2011; ALVES, 1998). O clima é do tipo oceânico tropical, com temperatura média anual de 25°C.

A cadeia montanhosa Vitória-Trindade (CVT) funciona como um trampolim ecológico para diversas espécies da fauna e flora marinha, sendo considerada um *hotspot* para a biodiversidade, em especial a biodiversidade recifal (LAVRADO; IGNACIO, 2017, PINHEIRO *et al.* 2017). Apresenta a maior riqueza de peixes recifais e espécies endêmicas entre todas as ilhas brasileiras (PINHEIRO *et al.* 2015) e uma das maiores taxas de biomassa de peixes recifais do Atlântico Sul (PINHEIRO *et al.* 2011; MORAES *et al.* 2017). Na Ilha da Trindade ocorrem 12 espécies de cetáceos (WEDEKIN *et al.* 2014) e 3 espécies de tartarugas marinhas ameaçadas, representando o maior sítio reprodutivo da tartaruga-verde (*Chelonia mydas*) no Brasil (ALMEIDA *et al.* 2011).

A Ilha da Trindade abriga uma avifauna diversa, e é sítio reprodutivo para pelo menos cinco espécies de aves marinhas: o petrel-da-trindade (*Pterodroma arminjoniana*), a viuvinha (*Anous stolidus*), o trinta-réis-das-rocas (*Onychoprion fuscatus*), a noi-vinha (*Gygis alba*) e o atobá-mascarado (*Sula dactylatra*). O principal predador de ovos e filhotes de aves e tartarugas marinhas na Ilha da Trindade é o caranguejo-amarelo (*Johngarthia lagostoma*), que ocorre em exuberante densidade na ilha e desempenha um papel chave na cadeia trófica local, pois ocupa as posições de consumidor primário, secundário e predador de topo na ilha (FONSECA NETO, 2004; LUIGI *et al.* 2008).

Embora a Ilha da Trindade abrigue hoje uma diversidade florística de cerca de 200 espécies, sendo 15 espécies endêmicas, sabe-se que a vegetação original da ilha, que compunha uma floresta nebulosa, foi devastada em cerca de 80% devido à pressão de pastejo exercida por cabras-domésticas (*Capra hircus*) introduzidas pelo homem no século XVIII. (ALVES, 1998). Atualmente, as principais pressões antrópicas exercidas sobre a biota da Ilha da Trindade são a pesca recreacional (PINHEIRO *et al.* 2011; PI-

NHEIRO e JOVEUX, 2015), e as atividades decorrentes da habitação humana no POIT (Posto Oceanográfico da Ilha da Trindade).

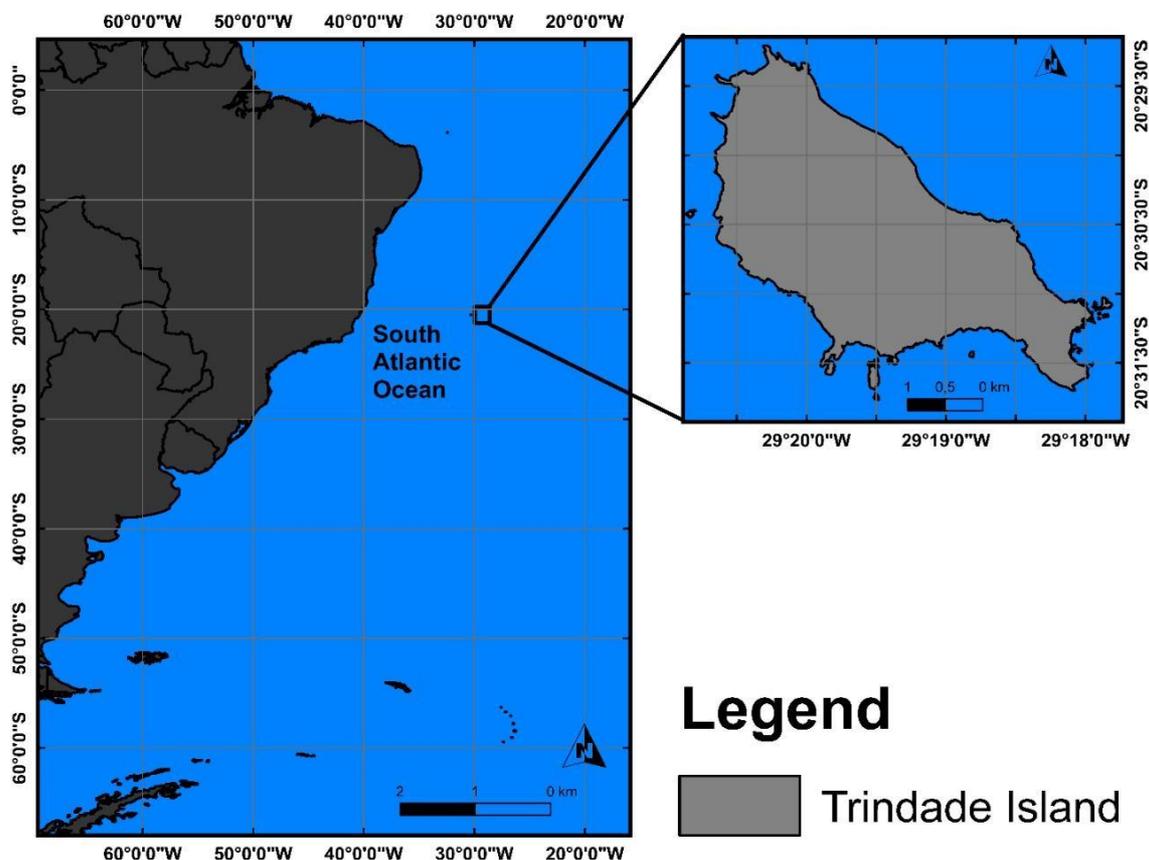


Figura 3: Mapa de localização da Ilha da Trindade em relação à costa Atlântica brasileira. Elaborado por Leonardo Dorneles, modificado de Douglas Ribeiro da Silva.

2.3 Modelagem preditiva de distribuição como ferramenta na ecologia

A modelagem preditiva de hábitat tem se mostrado uma técnica inovadora na área da ecologia e da conservação biológica (ANGELSTAM, 2004; RODRIGUEZ *et al.* 2007; LAURIA *et al.* 2015). Esta técnica vem sendo utilizada ao longo dos últimos 15 anos com o principal objetivo de prever áreas de distribuição de espécies baseando-se na adequabilidade ambiental para a ocorrência das mesmas (GUISAN e THULLER, 2005; NUR *et al.* 2011; CATRY *et al.* 2013; WATSON *et al.* 2013). Os modelos de

predição de distribuição de espécies relacionam características ambientais, como variáveis climáticas, topográficas e de vegetação, com os pontos de ocorrência conhecidos da espécie a fim de identificar áreas de adequabilidade para sua ocorrência em função de suas preferências ambientais e uso de hábitat conhecidos, gerando uma extrapolação da área conhecida para áreas potenciais que compartilham as mesmas características (HIRZEL e LE LAY, 2008).

Diversos termos são utilizados para se referir à modelagem preditiva de distribuição de espécies (*Predictive Species Distribution Modeling*), como: modelagem de hábitat, modelagem de nicho, modelagem ecológica, etc (HIRZEL e LE LAY, 2008; GUI-NAN *et al.* 2009; SILLERO, 2011). Entretanto, deve-se ter cuidado em relação a nomenclatura utilizada tendo em vista a limitação das variáveis utilizadas em cada estudo, uma vez que o conceito de nicho ecológico (LEIBOLD, 1995) inclui tanto variáveis abióticas e ambientais, ou seja, aquelas que compõem o eixo cenopoético no denominado nicho de uma espécie, quanto variáveis bióticas, *e.g.* interações intra e interespecíficas (eixo bionômico), as quais não são consideradas na maioria dos trabalhos que buscam prever a distribuições geográficas através de análises de modelagem (SILLERO, 2011; MCINERNY e ETIENNE, 2012).

Ainda, até muito recentemente, era comum se utilizar apenas um algoritmo para estimar a distribuição das espécies, especialmente o *Maximum Entropy* (Maxent) (PHILLIPS *et al.* 2006), um método baseado em *machine-learning* que permite utilizar apenas pontos de presença para estimar áreas de adequabilidade ambiental para ocorrência de espécies (*e.g.* KUMAR e STOHLGREN, 2009; TONG *et al.* 2015; LATHROP *et al.* 2018; CORRÊA *et al.* 2019). Entretanto, a utilização de uma combinação de diferentes algoritmos (*Ensemble Species Distribution Modelling*) para gerar

tais estimativas vem sendo extensivamente recomendada, uma vez que diminui os vieses decorrentes da utilização de um único algoritmo, e assim produzindo estimativas de distribuição mais robustas através de um consenso, ou modelo ajustado (*fitted model*), entre os diferentes métodos estatísticos utilizados para predizer áreas de adequabilidade ambiental (THUILLER *et al.* 2005; THUILLER *et al.* 2006; GRENOUILLET *et al.* 2011; PARKER, 2013).

A modelagem preditiva também pode ser uma poderosa ferramenta quando aplicada a biologia da conservação, pois pode indicar potenciais áreas prioritárias para a conservação de espécies ameaçadas e comunidades (OLSSON e ROGERS, 2009; COOK *et al.* 2010; RAYNER *et al.* 2007; KRÜGER *et al.* 2017), e ainda gerar estimativas de distribuição e tendência populacional futuras, por exemplo, em resposta a mudanças climáticas ou outros impactos decorrentes da ação antrópica sobre a biodiversidade (IVERSON *et al.* 1999; BEUMONT *et al.* 2008; MAINALI *et al.* 2015; KRÜGER *et al.* 2017). Contudo, tais predições devem ser assumidas com prudência, uma vez que a projeção de cenários climáticos e ambientais futuros enfrentam uma série de incertezas e limitações (BEAUMONT *et al.* 2008).

3 OBJETIVOS E HIPÓTESES

3.1 Objetivos geral e específicos

O objetivo geral dessa dissertação de mestrado é estimar a ocupação reprodutiva do atobá-mascarado (*Sula dactylatra*) na Ilha da Trindade. Os objetivos específicos são:

- 1) Identificar áreas de alta adequabilidade ambiental para seleção de áreas de nidificação pelo atobá-mascarado;
- 2) Investigar a relação entre as variáveis ambientais do relevo da Ilha da Trindade e a seleção de áreas reprodutivas pelo atobá-mascarado;
- 3) Predizer cenários futuros da distribuição da espécie na ilha em resposta ao processo de sucessão ecológica da vegetação.

3.2 Hipóteses

Uma vez que o atobá-mascarado necessita de platôs e escarpas rochosas para levantar voo (DUFY, 1984), a primeira hipótese dessa dissertação é de que a elevação é a variável ambiental mais importante na escolha de locais para nidificação para a espécie, que optaria por construir seus ninhos obre as escarpas, em áreas com mudanças abruptas no relevo para facilitar os deslocamentos de forrageio.

Considerando que a população de *S. dactylatra* na Ilha da Trindade dependa de solos expostos para estabelecer suas colônias reprodutivas (FONSECA NETO, 2004), e que a ilha encontra-se em processo de sucessão ecológica da vegetação, potencialmente reduzindo as áreas de adequabilidade para a nidificação dessa espécie (SILVA e ALVES 2011; ALVES *et al.* 2011), a segunda hipótese desse projeto é de que, em cenários futuros de vegetação, a população reprodutiva de *S. dactylatra* na Ilha da Trindade irá declinar em decorrência da escassez de recursos de nidificação.

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4. CAPÍTULO I

Potential nesting distribution of Masked Boobies (*Sula dactylatra*) breeding at the remote Trindade Island, western South Atlantic

(Manuscrito nas normas da revista Diversity and Distributions)

4. CAPÍTULO I

Potential nesting distribution of Masked Boobies (*Sula dactylatra*) breeding at the remote Trindade Island, western South Atlantic

Benemann V. R. F.^{1*}

¹Laboratório de Ornitologia e Animais Marinhos, Universidade do Vale do Rio dos Sinos, São Leopoldo, Brasil

*corresponding author: victoriabenemann@gmail.com

INTRODUCTION

Modelling suitable habitats for biodiversity maintenance under changing environments may serve as an important tool for biological conservation purposes (Angelstam et al. 2004; Rodriguez et al 2007; Lauria et al. 2015). Habitat suitability modelling is a powerful technique that has been applied in the ecology field over the past 15 years, in order to predict the probability of a species to occupy a given area by statistically relating known occurrence records to landscape features, which are mathematically selected by the model itself as the most important variables compounding the scenopoetic axis of the species niche (Guisan & Zimmermann, 2000; Rushton, et al. 2004). Such predictions could potentially indicate priority conservation areas for a species or even for whole communities, helping to address action plans for ecological restoration of human-degraded ecosystems (Olsson & Rogers, 2009; Cook et al. 2010; Rayner et al. 2007).

Trindade and Martim Vaz (20°30'S, 29°20'W) is an oceanic archipelago located ~1.200km from the coast of Espírito Santo, Brazil, and represents the only emerged portion of the Vitória-Trindade seamount chain. As in several other oceanic islands (for instance, see Coblenz 1978 and Angel et al. 2009), Trindade genuine ecosystems were substantially modified as a result of human disturbance, especially due to the introduc-

tion of invasive species such as the feral goats *Capra hircus* that devastated the original arboreal vegetation (i.e. *Colubrina glandulosa*) of the island, which used to cover about 85% of its total surface before human occupation in the mid-18th century (Mancini et al. 2016; Alves et al. 2011). As a result of overgrazing by feral goats, Trindade Island has suffered intense erosion and severe changes in plant composition, nowadays predominantly herbaceous, and has been under ecological succession after goat eradication in the mid-2000s (Silva and Alves, 2011). Given the drastically degradation of Trindade's ecosystems over the past three centuries, the native terrestrial fauna has also been undergoing changes in composition, abundance and distribution, especially regarding surface-nesting species – such as most seabirds - that depends on exposed soil for colonies' establishment (Mulder and Ellis, 2010).

The Masked Booby is a colonial seabird that inhabits tropical and subtropical waters (Birdlife International, 2019). The species breeds mainly on offshore islands, preferring deeper waters than any other booby species (del Hoyo et al. 1992). It occurs in tropical zones of all Atlantic, Pacific and Indian oceans, although there are molecular evidences of gene flow barriers isolating these populations, since it is a philopatric and thus low dispersive species (Steeves et al. 2005). In the Atlantic Ocean, it breeds only at the western portion, occurring along the coast and adjacent pelagic waters of South and Central America (IUCN, 2019). As a large tropical pelagic seabird species, it feeds mainly on flying fish and large squids (Schreiber and Hensley, 1976). It breeds on rocky islands, and mostly depends on cliff ledges and plateaus near the shoreline of pelagic water to nest (del Hoyo et al. 1992). It may form small to medium-sized colonies of densities generally varying from 7-100 pairs/km² (Nelson, 1968). The global population, although considered as Least Concern under the IUCN criteria, it is believed to be de-

creasing as a consequence of hunting, invasive species and human disturbance in breeding areas (IUCN 2019).

At Trindade Island, little is known about the species biology, spatial distribution and population size. The few studies mentioning data on the species biology on the island were focused on the whole seabird community and present only primary data on the species breeding biology, spatial distribution and population size (Olson et al. 1982, Luigi et al. 2009, Fonseca-Neto 2004, Mancini et al. 2016), whilst no study have focused exclusively on *S. dactylatra* ecology on the island. The available information indicates that *S. dactylatra* breeds along the West face of the island, from the Ponta do Noroeste to the proximity of Farilhões, encompassing the rocky plateaus near the Eme beach, and the population is estimated at ~600 individuals (Fonseca-Neto, 2004). Here we used the Predictive Nest Habitat Modeling approach to estimate the breeding occupancy of *Sula dactylatra* nesting at Trindade Island, based on occurrence points of active nests and both topographic in order to predict areas of nesting suitability for the species on the island nowadays, and predictive vegetation variables in order to investigate possible responses of the species' distribution in the future, resulting from four different possible vegetation scenarios which may be driven by ecological succession. We hypothesize that an expansion of the successional vegetation would decrease nesting habitat availability for Masked Boobies at Trindade Island, thus reducing the occurrence area in future scenarios of vegetal coverage.

METHODS

We mapped 87 active nests of *Sula dactylatra* during the breeding seasons of 2017 and 2019, from October to November. In the first survey (2017), we used a handheld GPS receiver GARMIN GPSMAP® 60CSX (average precision ± 4 m) to mark

nests from breeding groups in the only two localities of Masked Boobies nesting activities that are currently accessible by land (Northwest Plateau and trail to Eme beach, Fonseca-Neto 2004), since the island's relief is highly accentuated and there are few accessible sites through trails, which were established by the Brazilian navy. The two sampled colonies differed from each other in density and nesting substrate, where the colony at the Northwest plateau was composed by more equidistant nests (~15m from each other) in areas of exposed soil and isolated rocky outcrops within a matrix of *Cyperus atlanticus* herbaceous fields (Martins and Alves, 2007), whereas the colony located in the trail to the Eme beach is arranged on two rocky plateaus and is far more dense (nests distant ~5m from each other) than the above-mentioned, and more isolated from vegetation. During the 2019 survey, we used an Unmanned Aerial Vehicle (UAV) DJI Mavic Pro® to capture georeferenced aerial pictures of a breeding group located at an inaccessible plateau in the West of the island (Figure 1). We used the software Agisoft Photoscan Pro® to create an orthomosaic from the overlapped pictures, and then we imported it as a .kmz file to manually extract geographic coordinates of each nest using Google Earth Pro®. Breeding adults were performing both incubation and chick rearing during sampling in 2017 (Figure 2).

Predictive Variables

We modeled the current nest occurrence of the species in response to five topographical-related (Figure 3) and two vegetation-related variables (Figure 4), following Krüger et al. 2018 and Krüger 2018, using Ensemble Species Distribution Models (ESDMs) with the “biomod2” package (Thuiller, 2003, Thuiller et al., 2009, 2014), in software R 3.6.1 (R Core Team, 2016). All variables were standardized and processed using ArcGIS 10.5 software (ESRI, 2011). Insulation represents the year-round inci-

dence of sunlight, mediated by the geographic and topography. Elevation represents the altitude in meters. Slope represents inclination of the terrain in degrees. Flow length represents the distance for water resulting from precipitation to move from one grid cell to another, downstream. Aspect represents the direction, in degrees, of the terrain slope. For estimating future distribution scenarios according to predicted changes in vegetation, since Trindade Island is under ecological succession after goat eradication, we used vegetation variables available at Krüger 2018, where four possible scenarios for vegetation coverage were proposed: increase of 25% (T1) and 50% (T2) of the successional vegetation (herbaceous fields) with no alteration in the forest (remnant) vegetation, increase of 50% of the successional vegetation plus an increase of 25% (T3) and 50% (T4) in the forest vegetation. Succession represents the areas of vegetal coverage mainly composed by grassy and shrubby fields, which are under ecological succession process after human-driven deforestation. Remnant represents the remaining arboreal forests in the island, mostly composed by bryophytes, the so-called “giant ferns” *Cyathea copelandii*. All variables present a spatial resolution of 17x17m grid.

Modelling Procedures

We used seven different algorithms for modelling the potential breeding distribution of Masked Boobies (*S. dactylatra*), using four machine-learning techniques for select the better adjust between environmental variables and occurrence: Random Forest (RF), Generalized Boosted Model (GBM), Artificial Neural Network (ANN), Maximum Entropy (Maxent); and three correlative-based methods: Generalized Additive Models (GAM), Generalized Linear Model (GLM) and Multiple Adaptive Regression Splines (MARS). The search for the best suitability model should consider different modeling methods, since the existence of a single model explaining the distribution of a

species is rarely ecologically justifiable (Reichert and Omlin, 1997; Wintle et al., 2003) and combining different mathematical approaches will always be recommended when facing uncertainty (Araújo and New, 2007; Gallien et al., 2012). For each model was set 10-fold cross-validation, with data split at 80% for model calibration (training) and 20% for testing, the replicates were elaborated with the bootstrapping method, for each algorithm 10 replicates were performed, in which the average of these samples was used as the result of each algorithm. Collinearity between variables causes instability in parameter estimation in regression models (Dormann et al., 2013). To detect and remove highly correlated variables, we performed the VIF (Variation Inflation Factor) test using the “vifstep” and “vifcor” function of the “usdm” package (Naimi and Araújo, 2016) in the R software (R Core Team, 2016). The VIF is a multicollinearity test based on the square of the multiple correlation coefficient (R^2), resulting from the regression of a predictor variable against all other predictor variables. The function calculates the variation inflation factor for a set of variables and excludes highly correlated variables from the set. Here we consider higher VIF values ($th= 10$ and 0.7) as adequate (Dormann et al., 2013; Naimi and Araújo, 2016).

After the models were evaluated using true skill statistics: TSS (Allouche et al., 2006) and the area under the ROC curve: AUC (Fielding & Bell, 1997). The TSS is a threshold dependent accuracy measure and has the advantages of Cohen's Kappa statistics (Cohen, 1968), while AUC is a highly effective measure of the performance of ordinal scoring models and a threshold-independent precision measure (Thuiller et al., 2005). The TSS values ranged from -1 to +1, with -1 being predictions systematically wrong and +1 systematically correct, TSS values > 0.8 are considered excellent. The AUC values ranged from 0 to 1, with 0 for systematically wrong model predictions and 1 for systematically correct model predictions, AUC values > 0.8 are considered signifi-

cant. From the best algorithm, we calculate the relative importance of the different predictor variables based on the training datasets. Subsequently, we estimated the response curve of the suitability of the species in relation to the predictor variables that presented the highest relative importance.

RESULTS

Current predicted nesting distribution

We mapped a total of 87 active nests of *Sula dactylatra* during the breeding seasons of 2017 and 2019. Our results indicate areas of very high nesting habitat suitability for Masked Boobies predominantly along the Southwest and Northwest faces of Trindade Island, in elevations mostly varying from 150-450 meters above sea level, although the model also indicates few areas of high suitability along the Northeast face as well (Figure 5). Based on our model, we estimated an area of ~ 0.14 km² (14.72 ha) of Masked Boobies' spatial breeding occupancy in Trindade island, which corresponds to $\sim 1.3\%$ of the island total area.

The results of VIF's multicollinearity tests indicate no correlation between our all initial variables (Supplementary Material, Table S1), thus, all of them could be included in the final model. We modeled the potential breeding distribution of Masked Boobies using seven different algorithms: Maxent was the one with the lowest performance (Supplementary Material, Figure S1), whereas RF, GBM, GAM and GLM were the four more accurate, respectively (Table 1). The suitability map of the potential distribution of Masked Boobies' nesting areas was constructed based on the average of the best replications of the four algorithms that performed better, all presenting values of TSS and AUC above 0.8. These results, along with our sample size of nesting records ($n = 87$), provide a more than satisfactory prediction for the nesting distribution of *S. dac-*

tylatra at Trindade Island. Among the variables that were inserted in the model, Elevation and Aspect were the ones that better explained Masked Boobies selection for nesting habitats (more than 50%), while Flow Length, Slope and Insulation were of minor importance (Figure 6 and 7). Masked Boobies had a higher probability of nesting in elevations between 150 and 450 meters, in areas with aspect above 200° of inclination, in terrains usually facing Northeast direction, of slope between 10° - 40° of inclination and of intermediate incidence of sunlight (Figure 7).

Predicted distribution for future vegetation scenarios

All the repetitions for modeling the response of Masked Boobies' distribution to the four future vegetation scenarios proposed had AUC>0.9 and TSS>0.8 (Table 2, 3, 4 and 5). By plotting the ensemble map of the best algorithms, using the best repetitions for all four future vegetation scenarios (T1, T2, T3 and T4, see Figure 8), we observed a discrete change in the most suitability areas for Masked Boobies' nesting, specifically, a small decrease in the suitable areas (Figure 8). However, the contribution of vegetation variables to the final models of future scenarios was not substantial for all the repetitions (Figure 9-12). In all four models, Elevation remains the most important variable to shape the selection of nesting areas by Masked Boobies at Trindade Island (Figure 9-12).

DISCUSSION

Current predicted distribution

Elevation was the most important variable to shape the selection of nesting habitats for Masked Boobies breeding at Trindade Island. Our results indicate that these birds are using areas generally varying from 250 to 450m above sea level (Figure 6), which

contrast past studies conducted in that island that suggested nesting areas from 50 – 100m of elevation (Fonseca Neto 2004). However, Fonseca Neto (2004) estimations of the altitudinal ranges used by breeding birds from Trindade Island were based on a nautical chart from 1965 provided by the Brazilian Navy, while ours was based on a contour line shapefile that was produced recently, also provided by the Brazilian Navy, so we believe it has far more accuracy than the first. Insulation showed an intermediate contribution to the model. There are evidences that overheat may be an aspect of concern for many seabird species when choosing nesting habitats, since heat stress may alter physiological processes of egg development that may compromise breeding success of surface-nesting birds (Oswald et al. 2008; Whittow et al. 2002), and because overheat may influence on parasite infestation (Gaston et al. 2002).

Although the Masked Booby is an abundant and well-known species in other Brazilian oceanic islands, for the population from Trindade Island, there is a lack of information about the breeding biology and population trends (Mancini et al. 2016). The most recent population estimates of abundance and nesting areas of the species in this island is that conducted by Mancini et al. 2016, but is important to highlight that it has been more than one decade since the population data reported in that work was sampled.

Furthermore, in the work conducted by Mancini et al. 2016, the number of counted active nests was 76, which may be by far underestimated, given the results found in our study. Since this species nests at high elevations, and often in inaccessible cliffs, and that the relief of Trindade Island is highly accentuated and so has too many blind spots from the current passable paths, it is likeable that surveys based on direct counts of individuals and nests may present underestimates, which is common when surveying seabird species that breeds on inaccessible areas (Williams and Dowdeswell, 1998; Ryan, 2005; Cuthbert and Sommer, 2004).

Predicted distribution for future vegetation scenarios

Our results show that the predicted increase in vegetation coverage does not exert a considerable influence on Masked Boobies' nesting occupation on Trindade Island, since elevation remains the most important variable in all four proposed scenarios. Considering that the first confirmed records of Masked Boobies breeding at Trindade Island date from the early 1990s (Antas 1991; Luig 2009), and that this island has been under ecological succession during the past decades after goat eradication (Martim and Alves, 2007; Alves et al. 2011), it is assumable that the species has benefit from deforestation, since it depends on exposed rocky soils (Nelson, 1968) and the suppression of the vegetation may have provided new nesting substrates for breeders.

In the other hand, the congeneric species, the Red-footed Booby *Sula sula* used to be a common species breeding at Trindade Island, and despite the unavailability of data regarding the population size at that time, there are evidences that the population was already declining in the early 1900s, probably due to the suppression of vegetation caused by goats' overgrazing (Sharpe, 1906; Murphy, 1915; Fonseca Neto, 2004). The Red-footed Booby is a tree-breeder that depends on high trees with exposed branches to nest, such as *Columbrina granusla*, the most conspicuous species of Trindade original forests (Alves et al. 2011). Therefore, the replacement of this species for another Suidae that nests on a completely different habitat suggests that the historical absence of these species' coexistence in the island is not a result of competitive exclusion, but the absence of nesting habitat for one of them, although the two species feed on similar prey (Schreiber and Hensley, 1976; Gouvêa and Mello, 2017).

Our former hypothesis, *i.e.* that the expansion of the successional vegetation would decrease nesting habitat availability for Masked Boobies at Trindade Island, was not corroborated in this study. Since Masked Boobies select areas of high elevations near

cliff edges to nest (Nelson, 1968; Dufy, 1984; Priddel et al. 2005), it is deducible that the predicted increase in the vegetation coverage does not reach these high areas because of geomorphological characteristics, such as elevation, soil composition and depth (Shure et al. 1977, Wisser et al. 1996, Marler and Moral 2018, Eichel 2019). When comparing Trindade Islands' topographical map and satellite image with the proposed future vegetation scenarios, it is possible to observe that the high rocky outcrops –where our models indicate high suitability for Masked Boobies' nesting- does not seem to be affected by the increase in both successional and remnant vegetation (Figure 13 and Figure 5).

CONCLUSION

This study indicates that Masked Boobies nesting areas at Trindade Island are concentrated in the West face of the island, where the wind is weaker and the insulation is intermediate, and that suitable nesting habitat depends mostly on rocky exposed soils above cliffs between 150-450m of elevation, and that the successional vegetation does not seem to cause a direct effect on Masked Boobies' nesting distribution. Overall, our results may be limited by the resolution of variables (17x17m grid) and by the lack biotic variables to fully explain Masked Boobies' choices for nesting sites. Although the use of Ensemble Species Distribution Models (ESDMs) is a highly recommended and reliable tool to predict a species breeding distribution, especially for those that nest in inaccessible areas, we encourage further studies to address topographical variables of the finest spatial resolution as possible, as well other biotic variables.

ACKNOWLEDGES

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Table 3. AUC and TSS metrics. Average values of the four algorithms used to model the nesting distribution of Masked Boobies at Trindade Island in response to the T2 scenario, represented by a 50% increase of the successional vegetation coverage (herbaceous fields), with no alteration in the forest (remnant) vegetation.

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Figure 13. Satellite image of Trindade Island, Brazil. Map prepared by Douglas Ribeiro da Silva. Source: Landsat 8.

SUPPLEMENTARY MATERIAL

Table S1. Result of the VIF (Variation Inflation Factor) collinearity test with the ‘vifstep’ function, with recommended topographical variables to be used in the model.

Table S2. Result of the VIF (Variation Inflation Factor) collinearity test with the ‘vifcor’ function, with recommended topographical variables to be used in the model.

Table S3. Result of the VIF (Variation Inflation Factor) collinearity test with the ‘vifstep’ function, with recommended topographical and vegetation variables to be used in the model.

Table S4. Result of the VIF (Variation Inflation Factor) collinearity test with the ‘vifcor’ function, with recommended topographical and vegetation variables to be used in the model.

Figure S1. Performance of each algorithm used in the Ensemble Nesting Habitat Model for the current distribution of Masked Boobies at Trindade Island

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	AUC	TSS
Random Forest (RF)	0.985	0.931
Generalized Boosted Model (GBM)	0.975	0.919
Generalized Linear Model (GLM)	0.960	0.874
Generalized Additive Model (GAM)	0.946	0.881

Table 2.

	AUC	TSS
Generalized Boosted Model (GBM)	0.992	0.938
Random Forest (RF)	0.991	0.923
Generalized Additive Model (GAM)	0.960	0.918
Generalized Linear Model (GLM)	0.959	0.891

Table 3.

	AUC	TSS
Generalized Boosted Model (GBM)	0.992	0.955
Random Forest (RF)	0.991	0.938
Generalized Linear Model (GLM)	0.961	0.901
Generalized Additive Model (GAM)	0.957	0.921

Table 4.

	AUC	TSS
Generalized Boosted Model (GBM)	0.992	0.949
Random Forest (RF)	0.991	0.943
Generalized Additive Model (GAM)	0.965	0.924
Generalized Linear Model (GLM)	0.953	0.884

Table 5.

	AUC	TSS
Random Forest (RF)	0.991	0.936
Generalized Boosted Model (GBM)	0.989	0.941
Generalized Additive Model (GAM)	0.965	0.928
Generalized Linear Model (GLM)	0.952	0.851

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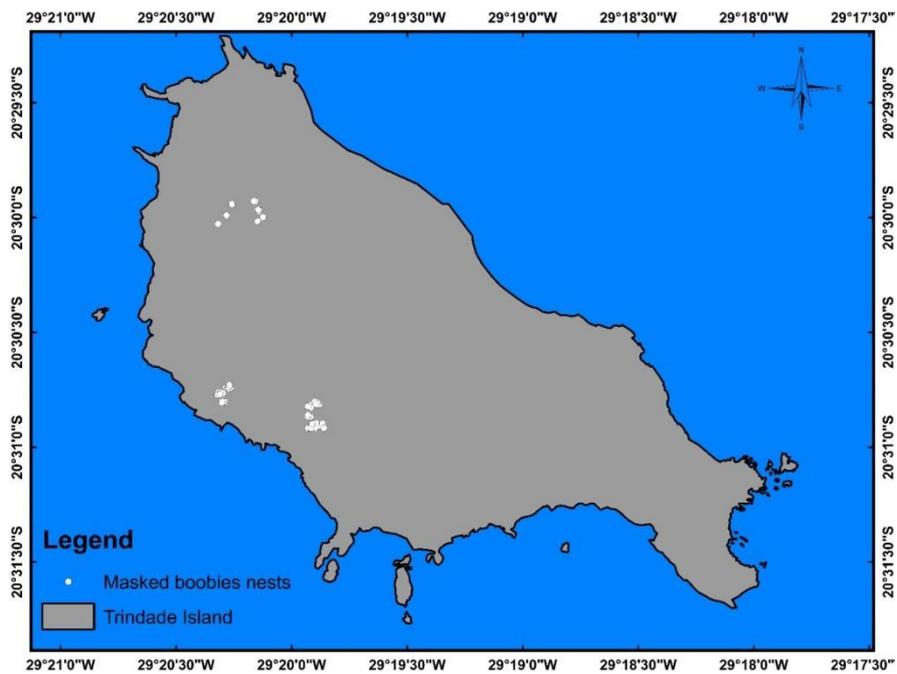


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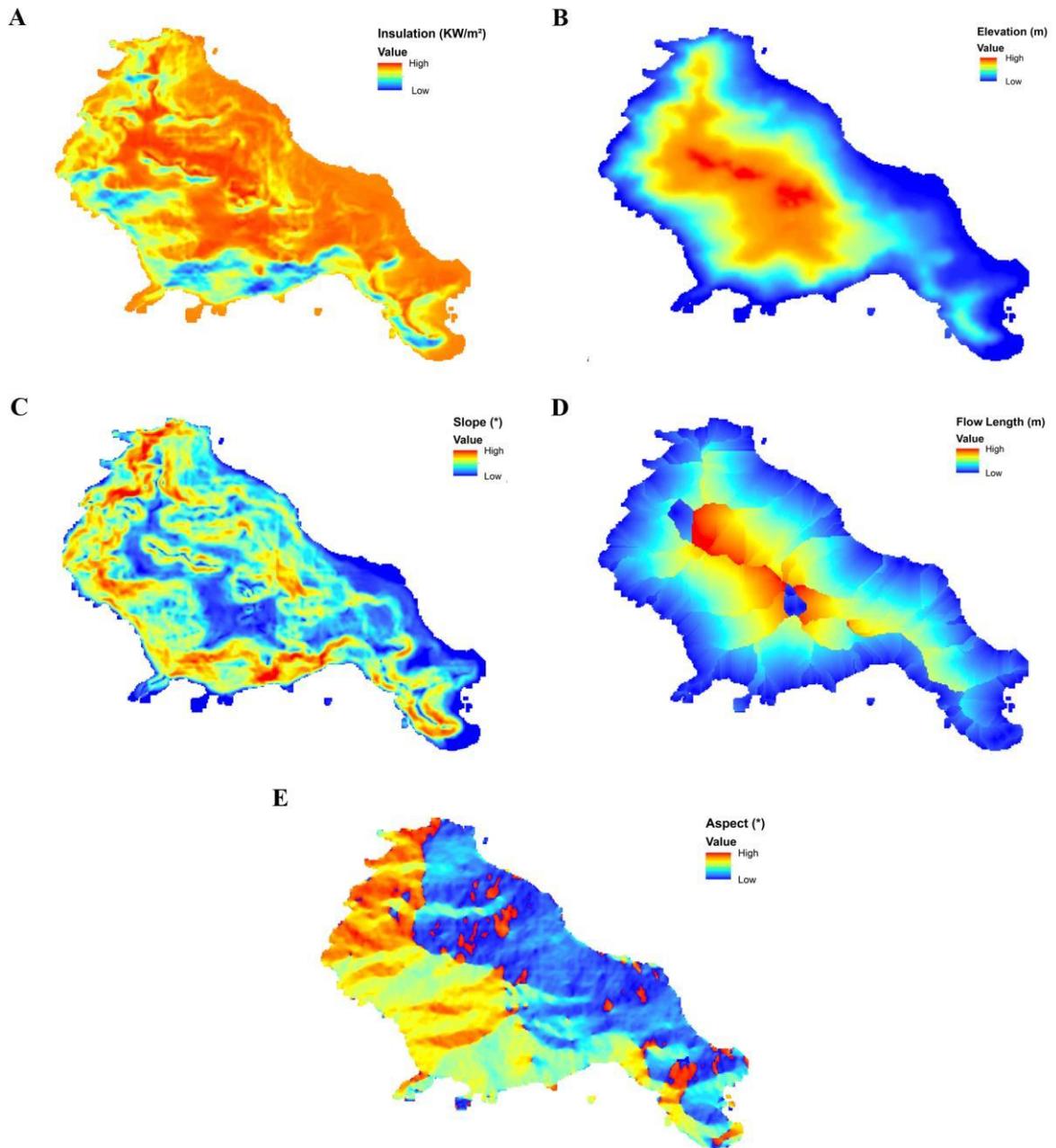


Figure 3: Topographical features of Trindade Island used as predictive variables in this study (Krüger 2018).

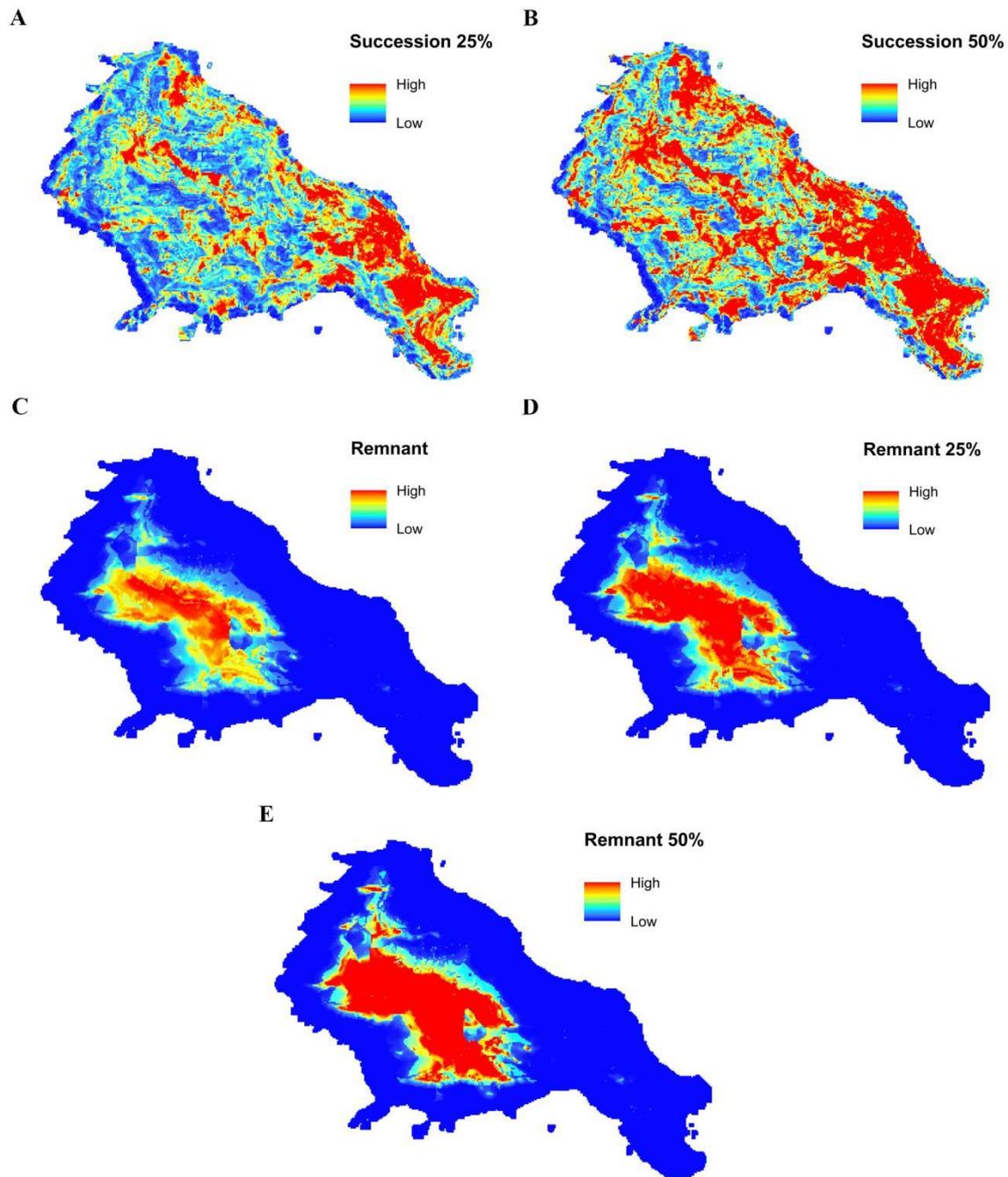


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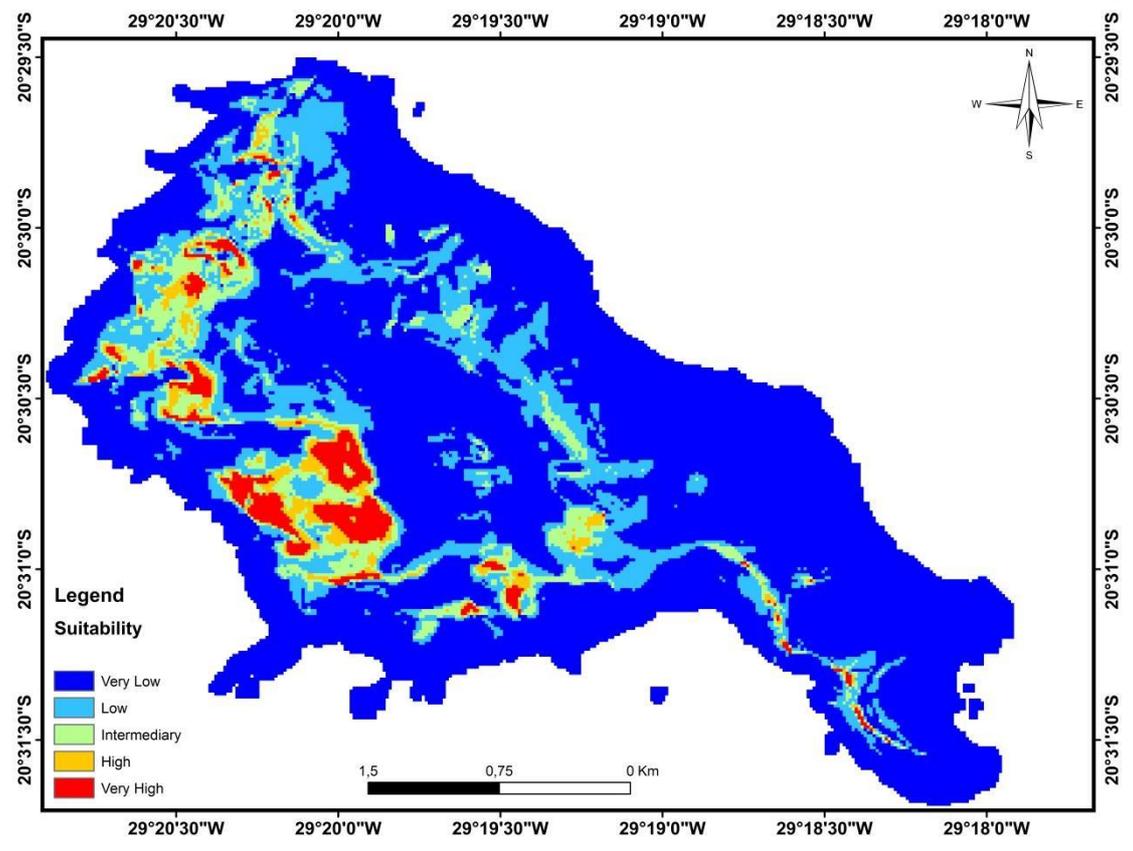


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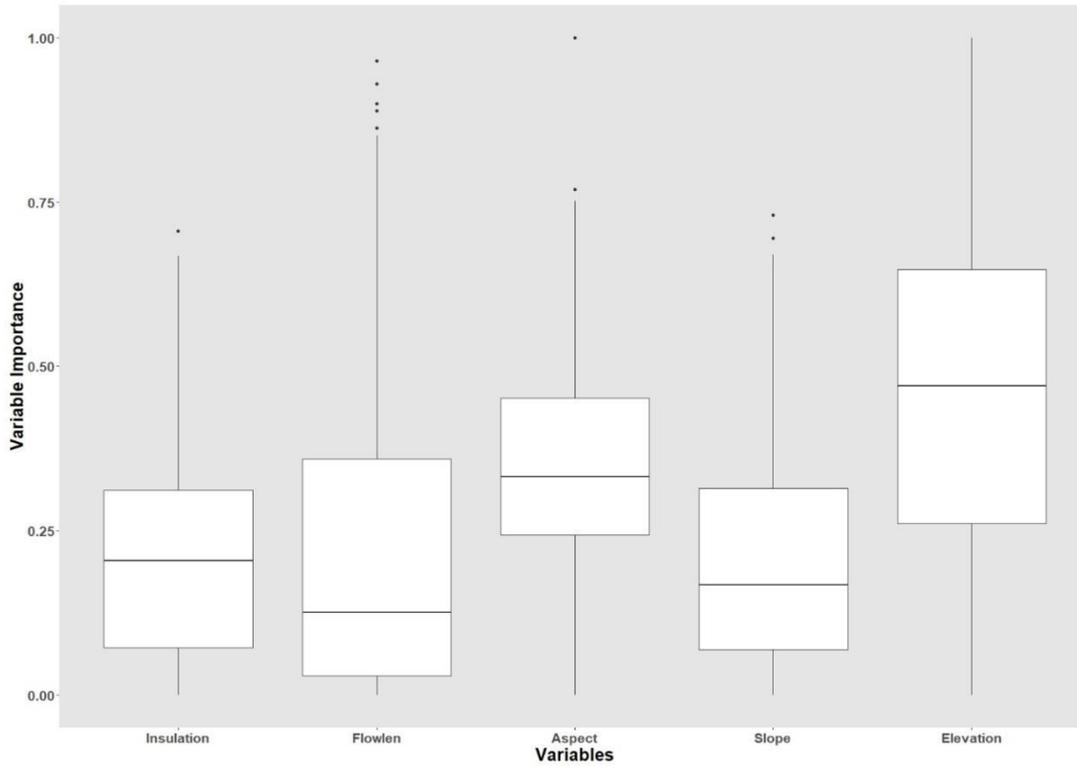


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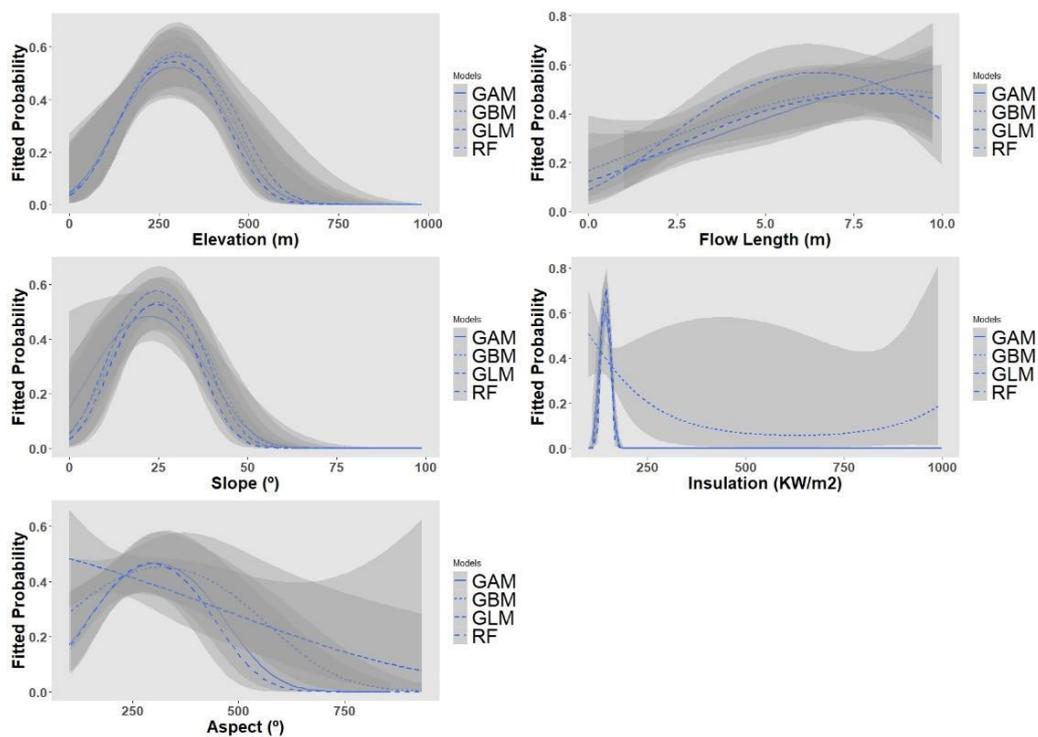


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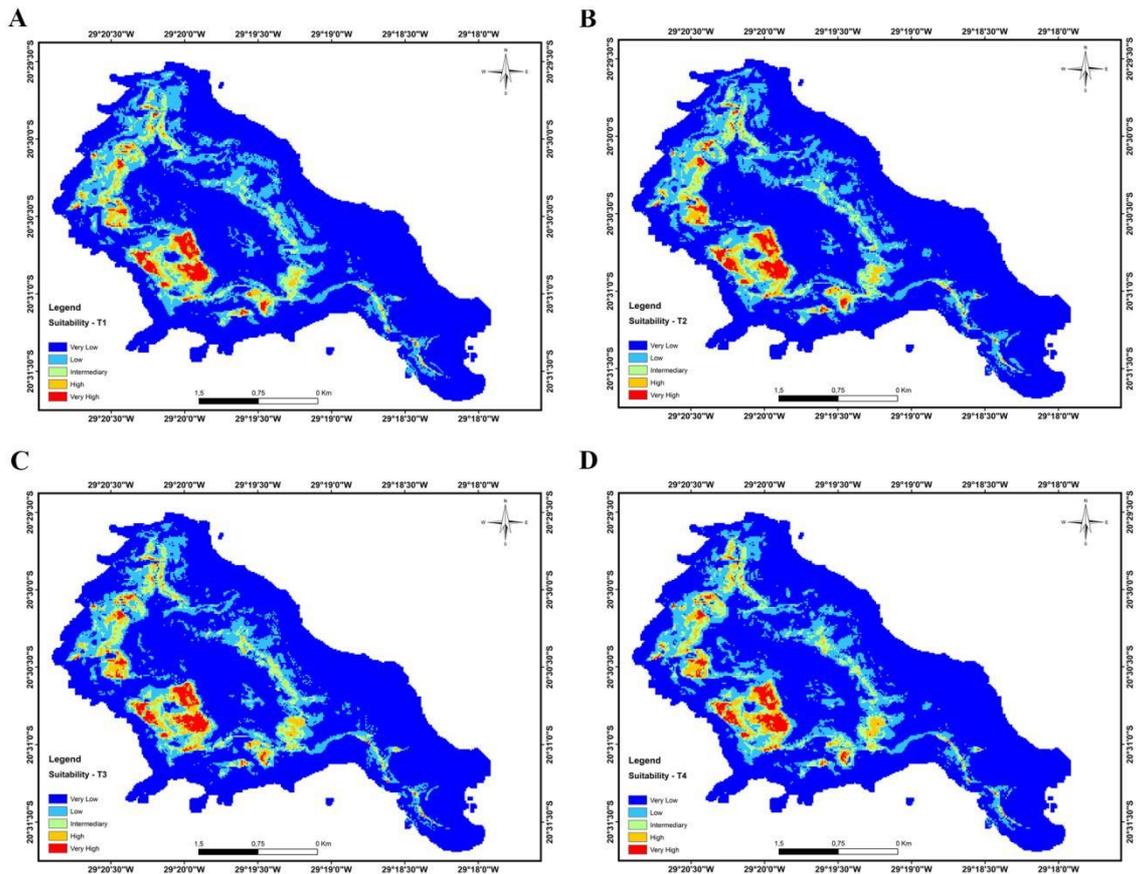


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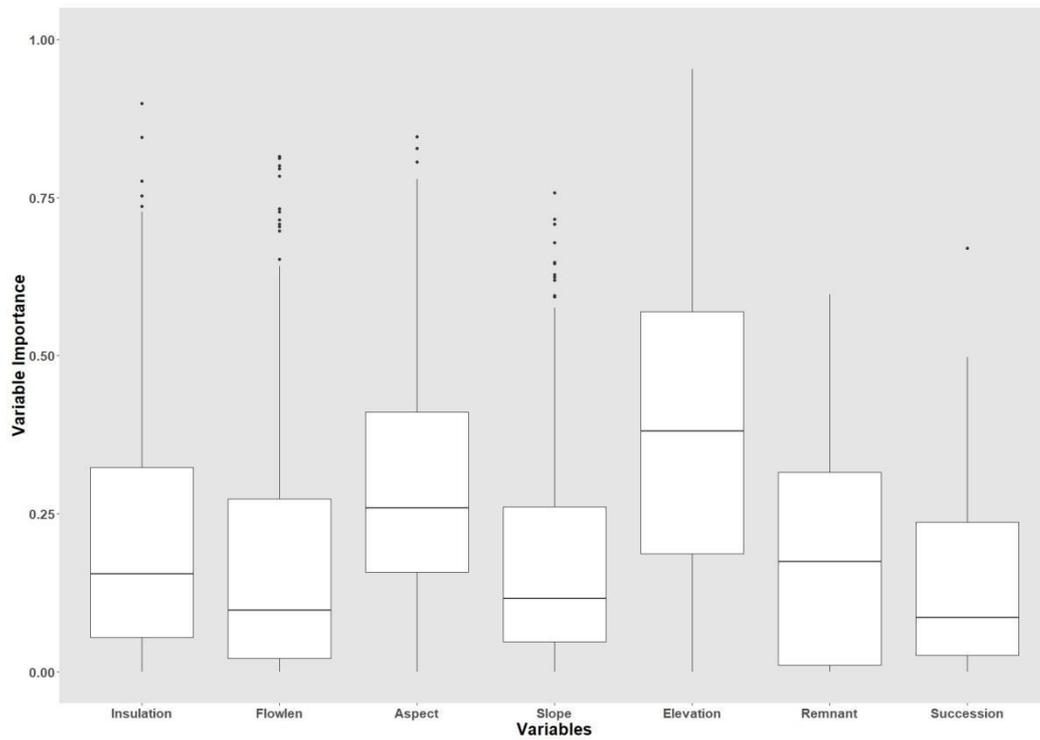


Figure 9. Importance of each variable in the final Ensemble Nesting Habitat Model under T1 vegetation scenario.

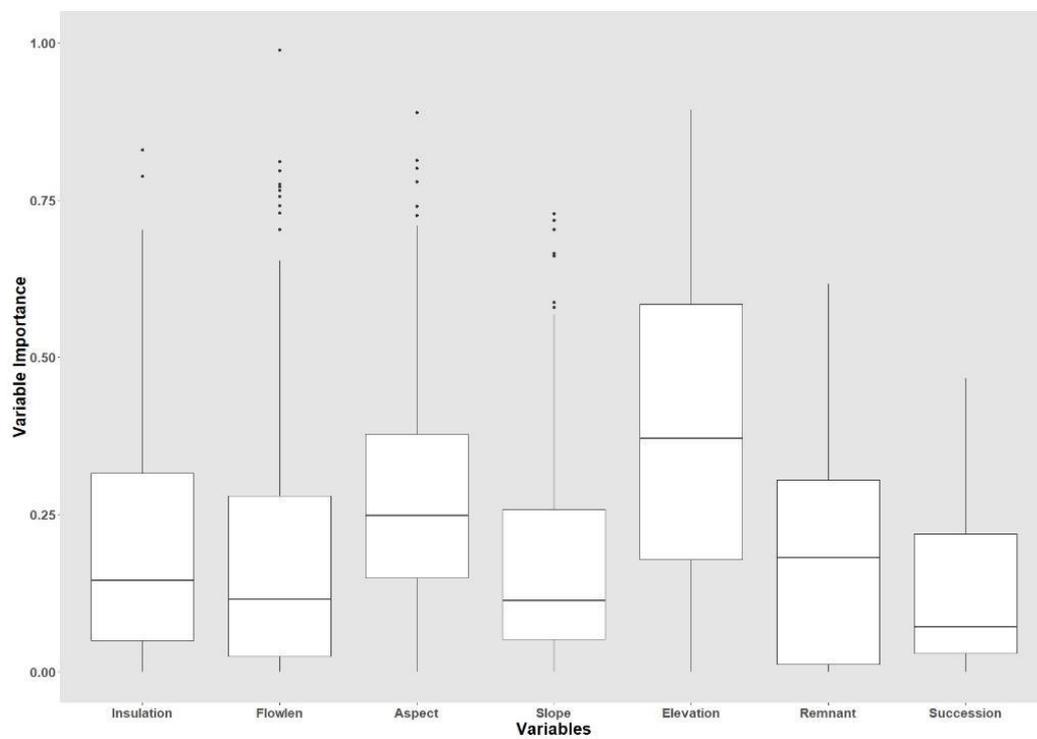


Figure 10. Importance of each variable in the final Ensemble Nesting Habitat Model under T2 vegetation scenario.

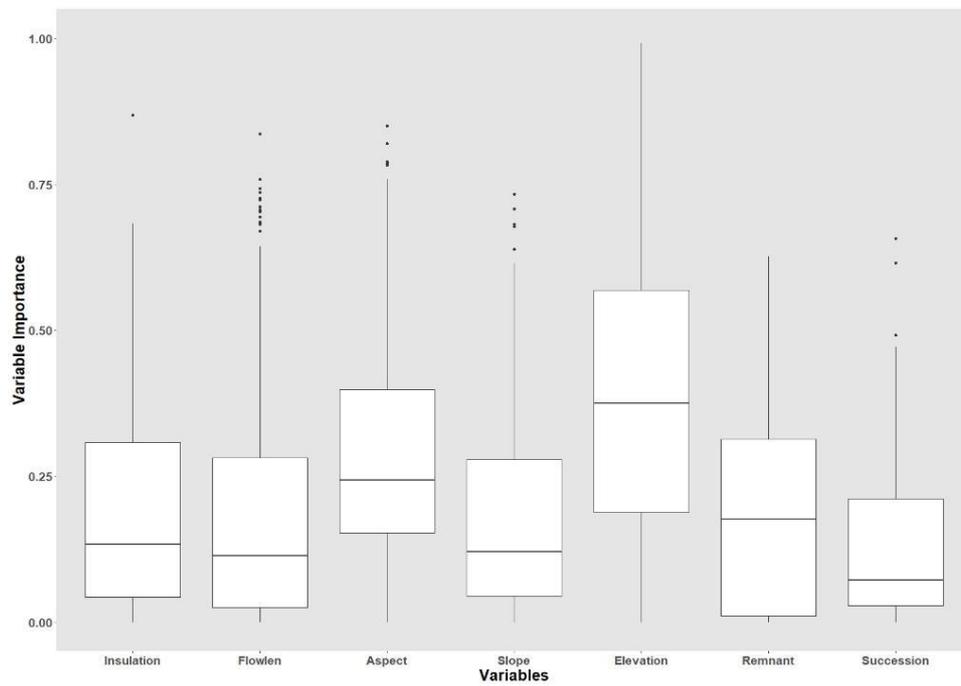


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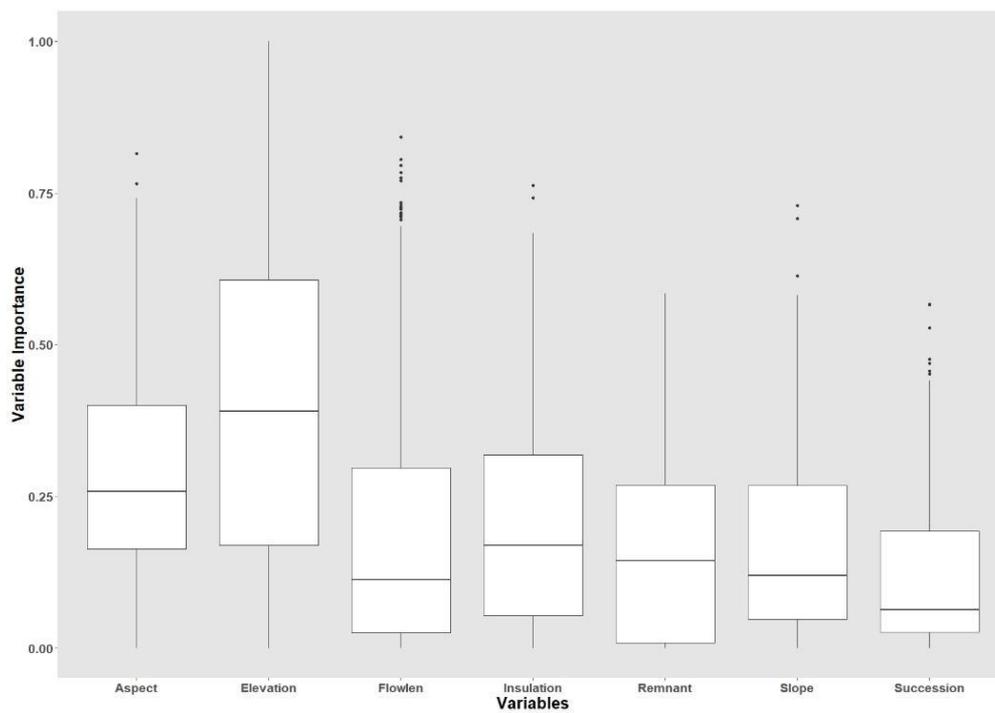


Figure 12. Importance of each variable in the final Ensemble Nesting Habitat Model under T4 vegetation scenario.

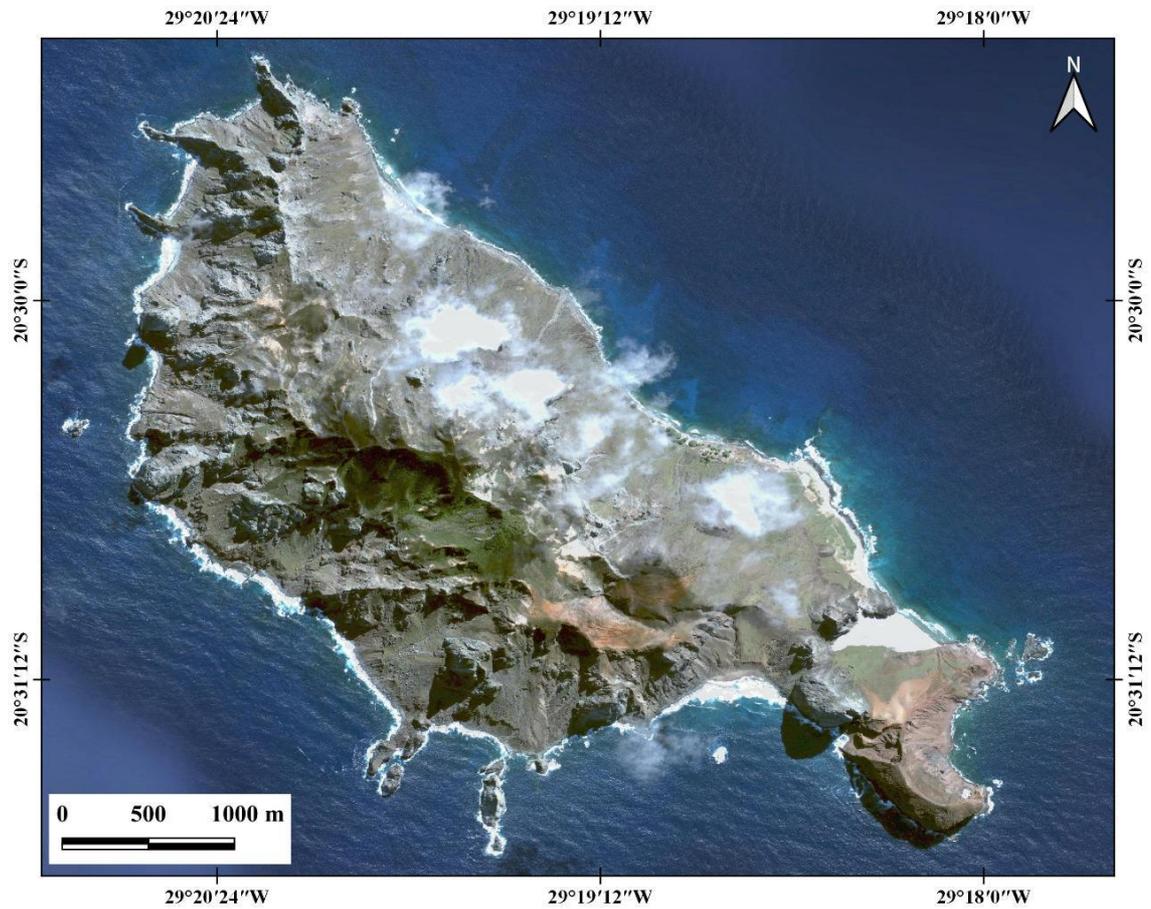


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SUPPLEMENTARY MATERIAL

Table S1. Result of the VIF (Variation Inflation Factor) collinearity test with the ‘vifstep’ function, with recommended topographical variables to be used in the model.

Variables	VIF <i>(th=10)</i>
Elevation	3.149242
Slope	2.221197
Flow Length	3.312469
Insulation	2.462437
Aspect	1.155939

Table S2. Result of the VIF (Variation Inflation Factor) collinearity test with the ‘vifcor’ function, with recommended topographical variables to be used in the model.

Variables	VIF <i>(th=7)</i>
Elevation	3.519516
Slope	2.322273
Flow Length	3.613704
Insulation	2.524116
Aspect	1.230752

Table S3. Result of the VIF (Variation Inflation Factor) collinearity test with the ‘vifstep’ function, with recommended topographical and vegetation variables to be used in the model.

Variables	VIF <i>(th=10)</i>
Elevation	4.591555
Slope	2.795892
Flow Length	3.742423
Remnant	3.143327
Insulation	2.731574
Aspect	1.294272
Succession	1.123886

Table S4. Result of the VIF (Variation Inflation Factor) collinearity test with the ‘vifcor’ function, with recommended topographical and vegetation variables to be used in the model.

Variables	VIF ($th=7$)
Elevation	4.839870
Slope	2.909497
Flow Length	4.053051
Remnant	3.149242
Insulation	2.854693
Aspect	1.316383
Succession	1.174319

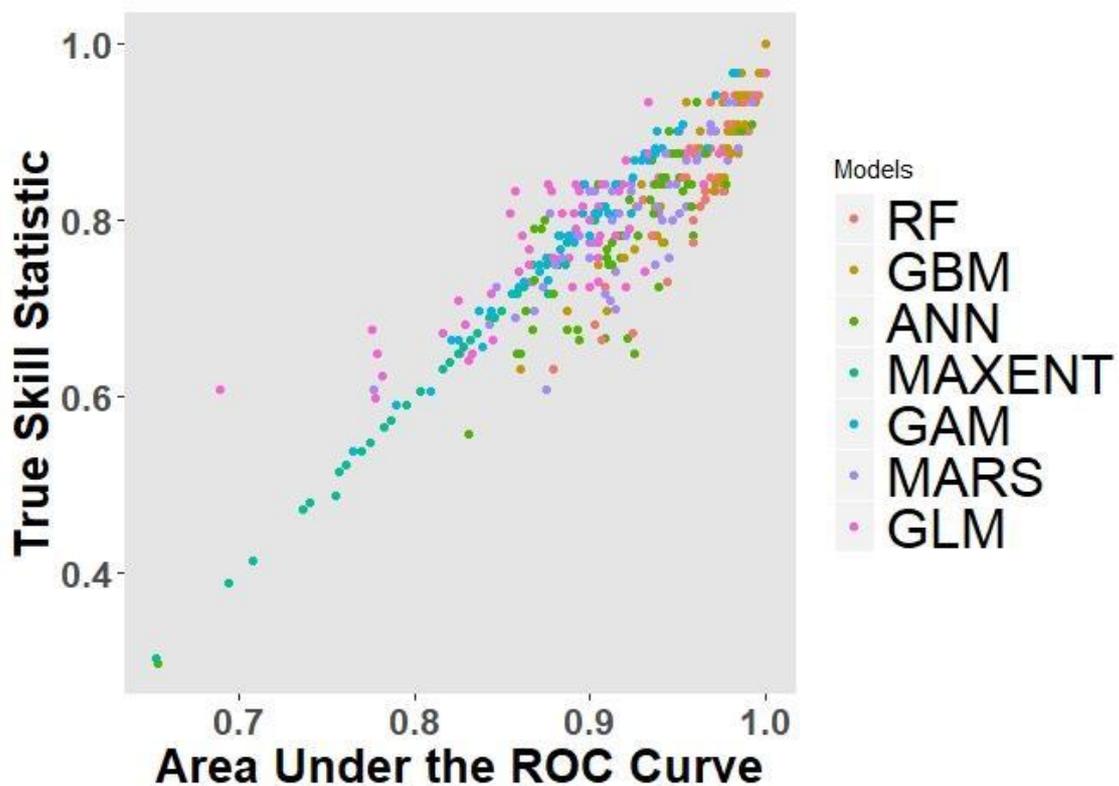


Figure S1. Performance of each algorithm used in the Ensemble Nesting Habitat Model for the current distribution of Masked Boobies at Trindade Island.

5 CONSIDERAÇÕES FINAIS

Este estudo analisou a distribuição reprodutiva de uma espécie predadora de topo, o atobá-mascarado *Sula dactylatra*, na Ilha da Trindade, Brasil. Este é o primeiro estudo a investigar a ecologia espacial da espécie na ilha, e traz informações relevantes quanto à sua distribuição e uso de hábitat nesse local remoto e ainda pouco estudado do território brasileiro. Neste estudo foi utilizada uma técnica inovadora na área da ecologia, a Modelagem Preditiva de Distribuição de Espécies. Os resultados desse estudo sugerem que a população de atobá-mascarado encontra-se subestimada na literatura disponível até o momento, uma vez que as áreas de nidificação em locais inacessíveis tornam os métodos convencionais de censo e mapeamento insuficientes para realizar tais estimativas. Ainda, sugere-se que o processo de sucessão ecológica da vegetação que se encontra em andamento na Ilha da Trindade não irá afetar substancialmente a distribuição espacial das áreas de nidificação da espécie, uma vez que os locais selecionados para o estabelecimento de colônias não serão atingidos pela vegetação sucessional por estarem, principalmente, localizados em altas elevações, sobre escarpas rochosas de declividade acentuada. Estudos visando compreender as respostas ecológicas das espécies a mudanças ambientais ocasionadas pelo homem são essenciais para que se possa elaborar medidas de manejo e conservação eficazes, especialmente em ambientes sensíveis como ilhas oceânicas.