NESTING DISTRIBUTION OF MASKED BOOBY *SULA DACTYLATRA* AT TRINDADE ISLAND, WESTERN SOUTH ATLANTIC OCEAN

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ABSTRACT

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The Masked Booby *Sula dactylatra* is a surface-nesting seabird that breeds on offshore islands across the tropical and subtropical oceans. On inaccessible rocky areas on Trindade Island, located about 1 200 km from Espírito Santo, Brazil, the nesting of this species has been poorly studied. To model the species' nesting habitat suitability at Trindade Island, we mapped active nests during the breeding seasons of 2017 and 2019, from October to November, using a hand-held Global Positioning System receiver and an Unmanned Aerial Vehicle. In order to identify key areas, we created nesting habitat suitability maps using seven different algorithms (Random Forest, Gradient Boosting Machine, Artificial Neural Network, Maximum Entropy, Generalized Additive Model, Generalized Linear Model, and Multiple Adaptive Regression Splines) in response to five topographical variables and one vegetation-related variable. Our sample included 87 active nests. Models generated by all four best algorithms were considered satisfactory. Results indicate that elevation and terrain aspect are the main variables influencing booby selection of nesting sites. We found areas of very high nesting habitat suitability along the southwest and northwest faces of the island, mostly in elevations varying from 150 m to 450 m.

Key words: Sulidae, seabirds, spatial ecology, species distribution modelling

INTRODUCTION

Modelling suitable habitats for biodiversity maintenance under changing environments may serve as an important tool for designing conservation programs (Angelstam *et al*. 2004, Rodríguez *et al*. 2007, Lauria *et al*. 2015). Habitat suitability modelling has been applied in this endeavor over the past 15 years. This technique predicts the probability of a species occupying a given area by statistically relating known occurrence records to landscape features in order to characterize non-surveyed areas (Guisan & Zimmermann 2000, Rushton *et al*. 2004). The assumption is that predictions can indicate priority conservation areas for a species or even for whole communities (Olsson & Rogers 2009, Cook *et al*. 2010).

Trindade and Martim Vaz (20°30′S, 029°20′W) is an oceanic archipelago located about 1 200 km from Espírito Santo, Brazil, and it is the only emerged portion of the Vitória-Trindade seamount chain (Fig. 1A). The archipelago arose from volcanic activity that produced nephelinitic to phonolitic effusive-pyroclastic deposits, dykes, and necks (Almeida 1962). The relief is mountainous, with an altimetry amplitude of 600 m, in which 34% is at 0–100 m, 21.2% at 100–200 m, and 2% at > 500 m. Slope gradients vary from strongly undulated (20%–25%) to hilly (45%–75%), comprising straight slopes, spurs (slightly convex slopes in plan and profile), and hollows (Nogueira *et al*. 2022).

As at several other oceanic islands (e.g., Coblentz 1978, Angel *et al*. 2009), Trindade ecosystems have been substantially modified by human disturbance. The introduction of invasive species such as feral goats *Capra hircus* in the mid-18th century devastated the islands' original arboreal vegetation (i.e., Glandular Nakedwood *Colubrina glandulosa*), which used to cover ~85% of its total surface (Alves *et al*. 2011, Mancini *et al*. 2016). As a result of overgrazing, Trindade Island has suffered intense erosion and severe changes in plant composition. Nowadays, vegetation is predominantly herbaceous, recently undergoing ecological succession after goat eradication in the mid-2000s (Silva & Alves 2011). Given the drastic degradation of Trindade's ecosystems over the past three centuries, the native terrestrial fauna has also been undergoing changes in composition, abundance, and distribution. This is especially true for surface-nesting species—such as several seabirds—that depend on exposed soil for nest sites (Mulder & Ellis 2010).

The Masked Booby *Sula dactylatra* is a colonial seabird inhabiting tropical and subtropical waters ocean wide (Birdlife International 2020). The species breeds mainly on offshore islands, foraging in waters that are deeper than any other booby species (Del Hoyo *et al*. 1992). Despite its wide distribution, the Masked Booby is highly philopatric. Molecular studies identified barriers preventing gene flow among populations on separate islands (Steeves *et al*. 2005). In the Atlantic Ocean, the species breeds only in the western portion, i.e., along the coast and adjacent pelagic waters of South and Central America (Birdlife International 2020), feeding mainly on flying fish and large squids (Schreiber & Hensley 1976, Harrison *et al*. 1983, Spear *et al*. 2007).

Masked Boobies establish nests on rocky islands, mostly on cliff ledges and plateaus adjacent to the ocean (Del Hoyo *et al*. 1992).

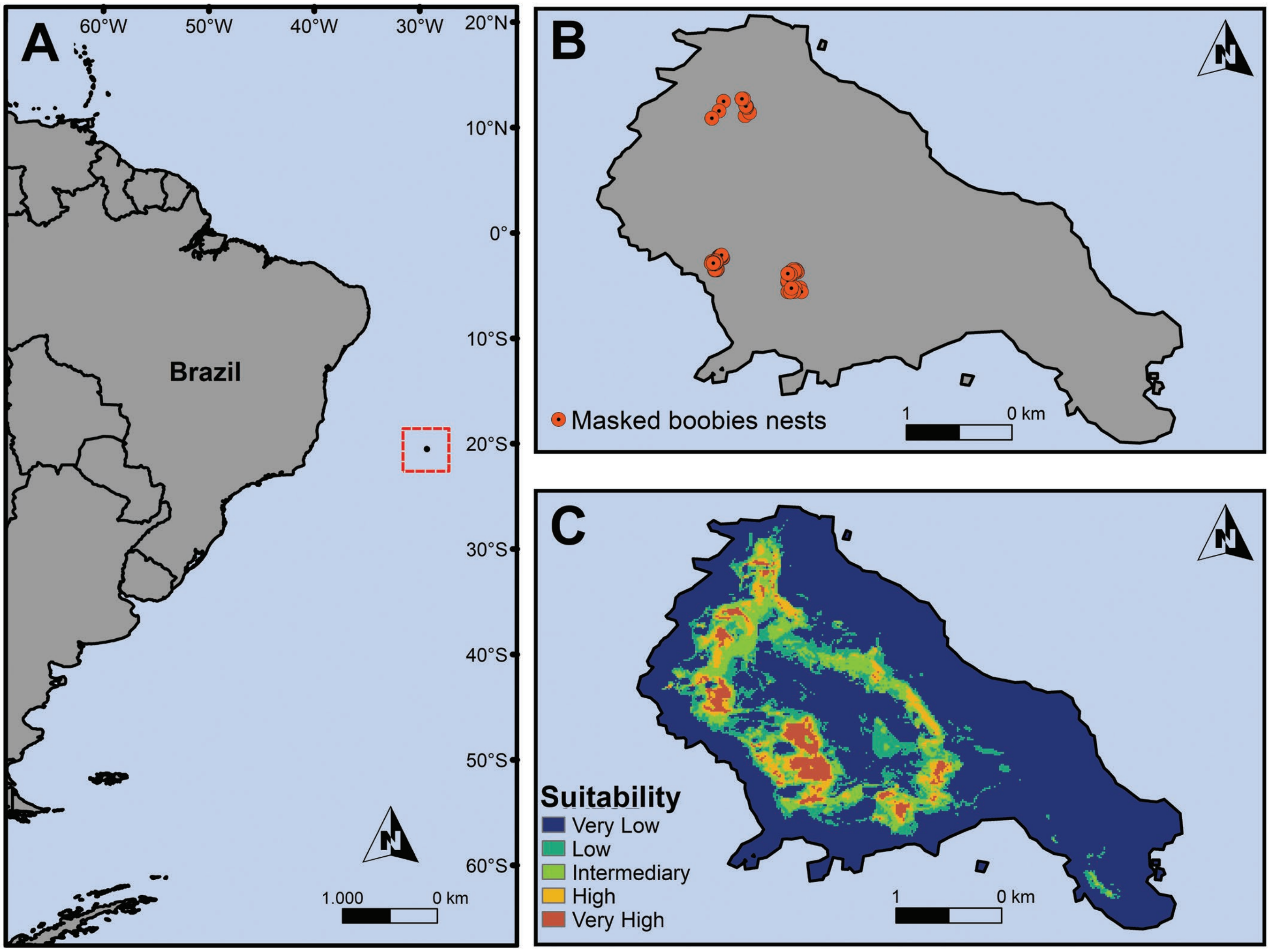

Fig. 1. (A) Study area showing Trindade Island in relation to Brazil territories; (B) Masked Booby *Sula dactylatra* nests (dots) mapped during the breeding seasons of 2017 and 2019; and (C) the areas of high nesting suitability predicted by the Ensemble Species Distribution Model using topographical and vegetation variables as predictors.

Nesting habitats are grass-free, generally in high areas, and on the top of islands (Lerma *et al*. 2020). Nests are robustly constructed by boobies by cleaning the ground to remove surface debris and expose the soil, forming circles of about 2 m in diameter, generally with a few rocks circling the area (Nelson 1978, Hughes 2011). The species may form small to medium-sized colonies of 7–100 pairs/km^2 (Nelson 1968). Although classified as Least Concern under IUCN criteria, the species' global population is decreasing as a consequence of hunting, invasive species predation, and human disturbance in breeding areas (Birdlife International 2020).

At Trindade Island, little is known about the species' biology, spatial distribution, and population size. The few studies that are available have been focused on the whole seabird community, thus not detailing Masked Booby breeding biology, spatial distribution, and population size at Trindade Island in particular (Olson 1982, Fonseca-Neto 2004, Luigi *et al*. 2009, Mancini *et al*. 2016). Available information indicates that the Masked Booby breeds along the West face of the island, from Ponta do Noroeste up to Farilhões, encompassing the rocky plateaus near the Eme beach. The population is estimated to be ~600 individuals (Fonseca-Neto 2004).

Here we used the Ensemble Species Distribution Model (ESDM) approach to estimate the potential breeding distribution of Masked Boobies nesting at Trindade Island based on occurrence points of active nests and topographic and vegetation variables. Our aim was to predict areas of potential nesting suitability. We hypothesized that Masked Boobies select elevated areas of exposed rocky soil over escarpments, facilitating take-off for foraging trips.

METHODS

Field sampling

Nest counting and mapping was done during October to November in the breeding seasons of 2017 and 2019 (Fig. 1B). In the first survey, we used the hand-held GPS receiver GARMIN GPSMAP® 60CSX (average precision ± 4 m) to mark nests in two localities of Masked Booby nesting activity that were accessible by land (Northwest Plateau, and trail to Eme beach; Fonseca-Neto 2004). The island's relief is highly accentuated and there are few sites accessible by trails, which were established by the Brazilian navy. The two sampled colonies differed in density and nesting substrate. The colony at the Northwest plateau is located in areas of exposed soil and isolated rocky outcrops within a matrix of Trindade Sedge *Cyperus atlanticus* herbaceous fields (Martins & Alves 2007); it is composed of equidistant nests (about 15 m apart). The colony located along the trail to the Eme beach is arranged on two rocky plateaus; it is far more dense (nests ~5 m apart) and more isolated from vegetation than the other colony. During the 2019 survey, we used an Unmanned Aerial Vehicle (UAV) from DJI (Mavic Pro®) to capture georeferenced aerial pictures of a breeding group located at an inaccessible plateau on the western part of the island. We used the software Agisoft Photoscan Pro® to create an orthomosaic from the overlapped pictures, and then we imported it to Google Earth Pro® as a .kmz file to manually extract geographic coordinates of each nest. Breeding adults were performing both incubation and chick rearing duties during sampling in 2017 and 2019.

Predictive variables

We modelled the current nesting distribution of the species in response to five topographical-related variables: Insulation (KW•m^{-2}), Elevation (m), Slope (°), Flow Length and Aspect (°), as well as one vegetation-related variable: Remnant Vegetation. We used ESDMs within the "biomod2" package (Thuiller 2003, Thuiller *et al*. 2009, Thuiller *et al*. 2014), through the software R 3.6.1 (R Core Team 2016). Insulation represents the year-round incidence of sunlight, mediated by geography and topography. Elevation represents the altitude in meters. Slope represents inclination of the terrain in degrees. Flow length represents the distance that water from precipitation travels downstream to move from one grid cell to another. Aspect represents the direction, in degrees, of the terrain slope. Remnant represents the areas in which it is still possible to find remnant vegetation. Variables were obtained from Krüger (2018) and then standardized and sampled into grids with a spatial resolution of 17 × 17 m using ArcGIS 10.5 software (ESRI 2011; Appendix 1, Fig. S1, available on the website).

Modelling procedures

We used seven different algorithms to model the potential breeding distribution of Masked Boobies using four machine-learning techniques that selected the better adjustment between environmental variables and occurrence: Random Forest (RF), Gradient Boosting Machine (GBM), Artificial Neural Network (ANN), and Maximum Entropy (Maxent). We also used three correlative-based methods: Generalized Additive Model (GAM), Generalized Linear Model (GLM), and Multiple Adaptive Regression Splines (MARS). In each model, 10-fold cross-validation was set and data were split into 80% portions for calibration (training) and 20% for the testing. Bootstrapping was used to elaborate the replicates, 10 of which were performed for each algorithm; the result of each algorithm was based on the average of these samples. Collinearity between variables causes instability in regression models (Dormann *et al*. 2013), and therefore we used variance inflation factors (VIF) that consider higher VIF values (*th* = 10) as adequate (Dormann *et al*. 2013, Naimi & Araújo 2016) in the R software (R Core Team 2016). 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 values ranged from -1 to +1, where -1 represented the predictions that were systematically wrong and +1 represented the predictions that were systematically correct. TSS values > 0.8 were considered excellent. The AUC values ranged from 0 to 1, where 0 represented systematically wrong model predictions and 1 represented systematically correct model predictions. AUC values > 0.7 were considered significant. The relative importance of the predictors from the best algorithm was based on training datasets, and then we estimated the response curves of Masked Boobies' suitability based in the most relative important predictor.

RESULTS

We mapped 87 active Masked Booby nests during the breeding seasons of 2017 and 2019 (Fig. 1B). The results of VIF's multicollinearity tests indicated no correlation between our initial variables (Appendix 1, Table S1); thus, all variables could be included in the final model. Our results indicated areas of very high nesting habitat suitability, predominantly along the southwest and northwest faces of Trindade Island, at 150–450 m elevation. However, the model also indicated a few areas of high suitability along the northeast face (Fig. 1C). Based on our model, we estimated an area of approximately 0.14 km^2 (14.72 ha) for Masked Booby nesting activities at Trindade Island, an estimate that corresponds to around 1.3% of the island's total area.

MaxEnt, MARS, and ANN were the lowest performing algorithms, whereas RF, GBM, GAM, and GLM were the four most accurate performing algorithms (Table 1). The potential distribution of Masked Booby nesting areas was constructed based on the average of the best replications of RF, GBM, GAM, and GLM algorithms (TSS and AUC > 0.8). These results, along with our sample size of nesting records (*n* = 87), provided a more than satisfactory prediction for the potential nesting distribution of the species at Trindade Island. Among the variables used in the models, Elevation, Aspect, and Remnant were considered the most important because they better explained booby selection of nesting habitats; Flow Length, Slope, and Insulation had lower contributions (Fig. 2). Masked Boobies had a higher probability of nesting in the following conditions: at elevations between 150 and 450 m, in areas with slope aspects > 200° of inclination, in coverage areas up to 450 of Remnant Vegetation, in terrains facing northeast, on slopes between 10° and 40°, and at an intermediate incidence of sunlight.

DISCUSSION

Two topographical variables, Elevation (0.50 of contribution) and Aspect (0.35 of contribution), were the most important variables shaping the selection of nesting grounds by Masked Boobies breeding at Trindade Island. Together they explained > 50% of the total importance variable index. Our results indicate that these birds use areas generally varying from 150 to 450 m elevation, having ~250° of inclination (Fig. 3). These findings contrast with

TABLE 1
Area Under the Curve (AUC) and True Skill Statistic (TSS) metrics: average values of the four algorithms used to model the potential nesting distribution of Masked Boobies *Sula dactylatra* at Trindade Island, Brazil

Algorithms	Metrics	
	AUC	TSS
Random Forest (RF)	0.985	0.931
Gradient Boosting Machine (GBM)	0.975	0.919
Generalized Additive Models (GAM)	0.960	0.874
Generalized Linear Model (GLM)	0.946	0.841

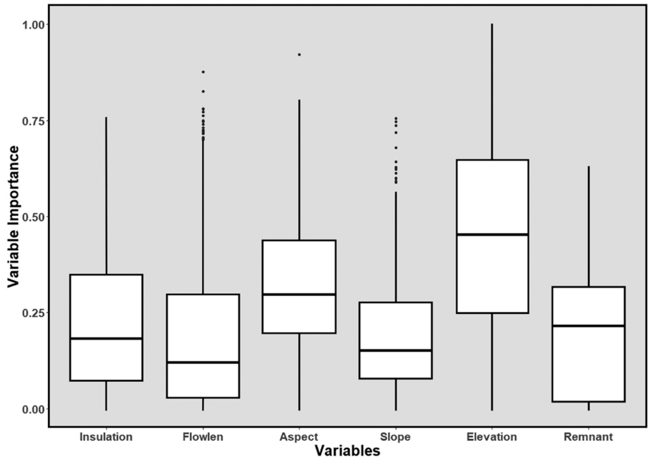

Fig. 2. Boxplot showing the most important variables for predicting areas of high nesting suitability for Masked Booby *Sula dactylatra* through the Ensemble Species Distribution Model, which was based on the average of the best replications of Random Forest, Gradient Boosting Machine, Generalized Additive Model, and Generalized Linear Model methods.

past studies indicating that nesting areas are located from 50 to 100 m elevation (Fonseca-Neto 2004). However, the estimations of Fonseca-Neto (2004) were based on a nautical chart from 1965 provided by the Brazilian navy, while ours are based on a contour line shapefile that was produced recently by the navy using current information. Thus, the map that we used was likely far more accurate.

Remnant was the third most important variable, but this may be indirectly explained by the proximity of remaining arboreal forests. Remnant vegetation is mostly composed of pteridophytes *Cyathea copelandii* growing on areas of high elevation, and vegetation-covered areas clearly represent unsuitable nesting habitat for Masked Boobies. Insulation showed an intermediate contribution to the model. There was evidence that overheating may be an aspect of concern for many surface-nesting seabird species when choosing nesting habitats because heat stress may alter physiological processes involved in egg development (Oswald *et al*. 2008, Whittow *et al*. 2002). Overheating may also influence parasite infestation (Gaston *et al*. 2002).

Although the Masked Booby is an abundant and well-known species at other Brazilian oceanic islands, there is little information on the population from Trindade Island (Mancini *et al*. 2016). The most recent population estimates of abundance and nesting areas

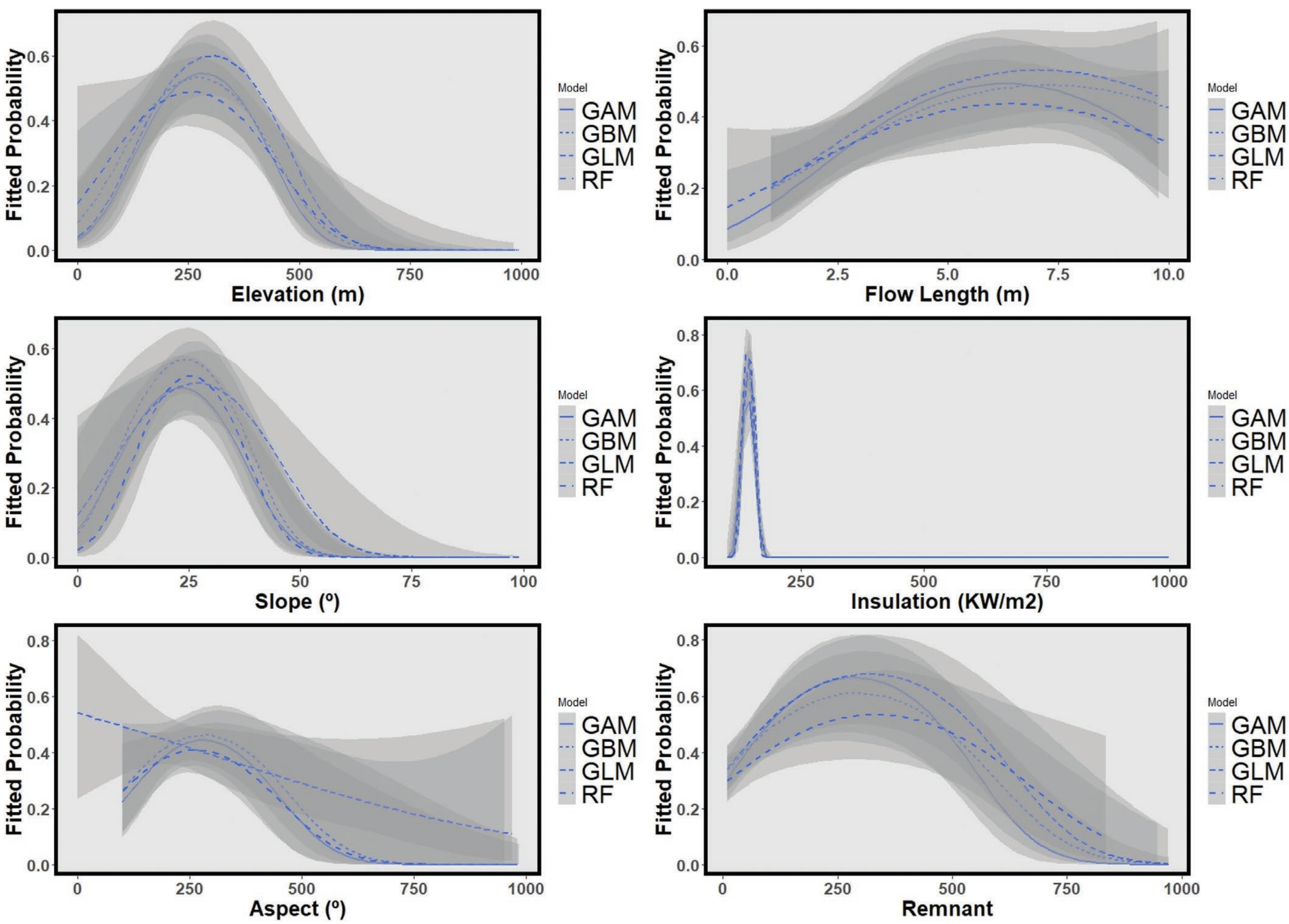

Fig. 3. The variable response curves in the model generated by the average of best replications of Random Forest (RF), Gradient Boosting Machine (GBM), Generalized Additive Models (GAM), and Generalized Linear Model (GLM) methods.

of the species was conducted by Mancini *et al*. (2016), although data were acquired 10 years ago. At that time, 76 active nests were reported, although this figure may underestimate numbers given the results of our study. Surveys based on direct counts of individuals or nests often present underestimates, particularly for seabird species that breed in inaccessible areas with an accentuated relief full of blind spots, and such areas do occur at Trindade Island (see also Williams & Dowdeswell 1998, Cuthbert & Sommer 2004, Ryan 2005).

Considering that the first confirmed records of Masked Booby breeding at Trindade Island date from the early 1990s (Antas 1991; Luigi *et al*. 2009), and that this island has been under ecological succession during the past decades after goat eradication (Martins & Alves 2007, Alves *et al*. 2011), it may well be that the species has benefitted from deforestation, as it depends on exposed rocky soils (Nelson 1968). In fact, the suppression of vegetation on the island may have provided new nesting substrate. On the other hand, because Masked Boobies select areas of high elevation near cliff edges to nest (Nelson 1968, Duffy 1984, Priddel *et al*. 2005)—a behavior that makes use of the wind or lack thereof for takeoff—it is quite possible that the increase in vegetation did not reach these high elevation areas, where geomorphological characteristics may have inhibited plant colonization (Shure and Ragsdale 1977, Wiser *et al*. 1996, Marler & Del Moral 2018, Eichel 2019). Thus, booby population dynamics may not have been affected by the revegetation currently underway.

Our study shows that nesting areas of Masked Boobies are concentrated along the western face of Trindade Island, where the wind is weaker and the insulation is intermediate, and that suitable nesting habitat depends mostly on rocky exposed soils above cliffs. Overall, our results may be limited by the resolution of variables (17 × 17 m grid) and by the lack of bionomic variables (e.g., species interactions, risk of predation) to fully explain Masked Booby choices for nesting sites. Nevertheless, the combined use of UAVs and ESDMs appear to have served as a reliable tool to predict this species' breeding distribution and population size, especially for those nesting in inaccessible areas. We encourage further studies to address topographical variables using the finest spatial resolution possible, as well as to introduce biotic variables into the predictions.

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AUTHORS' CONTRIBUTION

VRFB participated in sample design, field work, data analysis, and writing. LDA participated in data analysis and writing. AZF participated in sample design and field work. RCM and MVP participated in sample design, project coordination, and manuscript revision.

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