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# The recently discovered Principe Scops-owl is highly threatened: distribution, habitat associations, and population estimates

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## Summary

Species baseline information is required for effective biodiversity conservation. Here we provide sound ecological data to support effective conservation of the Principe Scops-owl, *Otus bikegila* Melo, Freitas, Verbelen, Costa, Pereira, Fuchs, Sangster, Correia, de Lima & Crottini 2022, discovered in 2016. We mapped the observed and potential distribution, inferred habitat associations, estimated population size, and assessed the International Union for Conservation of Nature (IUCN) Red List category for this species. Surveys were carried out across Príncipe Island during the long and short dry seasons, recording owl presence in sampling points along transects. These data were used to model distribution, revealing that the Principe Scops-owl is restricted to 34.4 $km^2$ in the south of the island, inside the Príncipe Obô Natural Park. Most records were in lower altitude native forest. Remoteness was the most important variable to explain presence at island level, followed by land use, which showed that the species is restricted to forest, clearly depending on native forest. Distance sampling using different models suggested a population density ranging between 33.4 individuals/$km^2$ (95% CI: 23.6–47.2) and 46.4 individuals/$km^2$ (95% CI: 29.3–73.6), which extrapolates to an estimated population size ranging from 1,149 individuals (95% CI: 813–1,623) to 1,597 individuals (95% CI: 1,007–2,533). We propose that the species is classified as "Critically Endangered" due to the small extent of occurrence, coupled with occurrence in a single location and inferred continuing declines in the extent of occurrence, area of occupancy, number of mature individuals and area, extent, and quality of habitat. Effective conservation of the Principe Scops-owl requires regular monitoring and further studies focusing on reproduction and potential nest predation by introduced mammals. Widespread support for the conservation of the Natural Park is vital to ensure the protection of this species and the endemic-rich native forests of Príncipe on which it depends.

## Resumo

O sucesso de medidas de conservação está dependente da qualidade da informação de base disponível para as espécies alvo. Neste estudo, recolhemos dados sólidos sobre a ecologia de *Otus bikegila* Melo, Freitas, Verbelen, Costa, Pereira, Fuchs, Sangster, Correia, de Lima & Crottini 2022, descoberto em 2016. Mapeamos a distribuição observada e potencial, inferimos associações de habitat, estimamos o tamanho da população e propomos a categoria da Lista Vermelha da União Internacional para a Conservação da Natureza (IUCN) para esta espécie. Foi feito um levantamento na Ilha do Príncipe durante as estações secas, longa e curta, registando a presença do mocho em pontos de amostragem ao longo de transetos. Estes dados foram usados para modelar a sua distribuição, revelando que *Otus bikegila* está restrito a 34,4 $km^2$ no sul da ilha, dentro do Parque Natural do Obô do Príncipe. A maioria dos registos foram feitos em floresta nativa de baixa altitude. A acessibilidade foi a variável mais importante para explicar a presença do mocho ao nível da ilha, seguida pelo uso do solo, o que demonstrou que esta espécie está restrita a áreas de floresta, preferindo a floresta nativa. Através da análise de distâncias usando diferentes modelos, obteve-se uma estimativa da densidade populacional variando entre 33,4 indivíduos/km$^2$ (IC 95%: 23,6–47,2) e 46,4 indivíduos/km$^2$ (IC 95%: 29,3–73,6), que resulta num tamanho populacional estimado variando de 1.149 (IC 95%: 813–1.623) a 1.597 indivíduos (IC 95%: 1.007–2.533). Propomos que a espécie seja classificada como Criticamente Ameaçada devido à pequena extensão de ocorrência, juntamente com a sua ocorrência num único local e um declínio contínuo inferido na extensão de ocorrência, área de ocupação, número de indivíduos maturos e área, extensão e qualidade do habitat. Para que a conservação de *Otus bikegila* seja eficaz, é necessário que a sua monitorização seja regular e que novos estudos se foquem na sua reprodução e potencial predação no ninho por mamíferos introduzidos. É essencial que haja um apoio generalizado para a conservação do Parque Natural, para garantir a proteção da floresta nativa de que dependem a maior parte das espécies endémicas da ilha, incluindo *Otus bikegila*.

## Introduction

Anthropogenic habitat loss is causing species extinction to occur much faster than natural background rates (Crooks *et al.* 2017, IPBES 2019). Many species go extinct before being described or even discovered (Mora *et al.* 2011). Biodiversity loss could be slowed down by implementing effective conservation strategies, able to prioritise correctly key species and areas. However, this depends on the availability of systematic data on species distribution, population trends, community composition, and ecosystem structure (Collen *et al.* 2013). The International Union for Conservation of Nature (IUCN) Red List of Threatened Species, for example, requires detailed information on distribution, population size, and trends to assess properly the status of species (IUCN 2012).

The existence of the Principe Scops-owl, *Otus bikegila*, was confirmed in 2016 (Verbelen *et al.* 2016), and it was subsequently described as endemic for Príncipe Island, São Tomé and Príncipe (Gulf of Guinea) (Melo *et al.* 2022). There had been strong evidence of its existence for almost 20 years, including anecdotal reports of sightings and records of its calls (Melo and Dallimer 2009). It is somewhat surprising that the species eluded scientists for so long, considering it occurs in a small island where birds are the best-known taxa (Jones 1994). However, it is worth noting that only a few ornithologists had explored the island until the end of the 20th century and hardly any had ventured into its southern forests (Jones and Tye 2006). At this time, the uniqueness of Príncipe Island as a centre of bird endemism (Mayr 1965, Stattersfield *et al.* 1998, Melo 2007) triggered a new wave of ornithological exploration.

Príncipe has never been connected to mainland Africa, allowing for the evolution of a fauna and flora rich in endemics, including angiosperms (Figueiredo *et al.* 2011), land snails (Holyoak *et al.* 2020), butterflies (Mendes and Bivar de Sousa 2012), mosquitoes (Loiseau *et al.* 2019), amphibians and reptiles (Ceríaco *et al.* 2018), and birds (de Lima and Melo 2021). Its avifauna includes eight species and six subspecies that are single-island endemics, and three species and two subspecies that are shared only with other oceanic islands in the Gulf of Guinea. This represents a remarkably high concentration of endemic birds for a 139 km$^2$ oceanic island, making Príncipe a global priority for bird conservation (Stattersfield *et al.* 1998, Le Saout *et al.* 2013). In 2006, the Príncipe Obô Natural Park (PONP), covering around one third of the island, was created to protect the remaining old-growth forest (UNEP-WCMC 2021), and in 2012, the entire island and its marine environment was declared a UNESCO Biosphere Reserve (UNESCO 2012).

When a new species is discovered in an area as small as the remote southern forests of Príncipe Island, efforts should be made to promptly collect the data required to get a firm understanding on the species ecology, particularly its distribution, habitat associations, and abundance. The aim of this study was to collect data on the ecology of the Principe Scops-owl to provide baseline information on this little-known endemic species. We mapped observed and potential distribution, inferred habitat associations, and estimated population size. Finally, this information was used to assess conservation status and to identify research and conservation priorities for this species.

## Methods

### Study area

Príncipe Island (1.53°N – 1.72°N, 7.33°E – 7.47°E) is part of the Democratic Republic of São Tomé and Príncipe, 220 km west of the African mainland, in the Gulf of Guinea. Covering 139 km$^2$ (c. 17 km long and 8 km wide), it comprises a relatively flat plateau in the north, and a rugged central and southern region characterised by ridges that rise to 948 m asl at Pico do Príncipe (Jones and Tye 2006). It has an oceanic equatorial climate, in which temperatures fluctuate between 20ºC and 30ºC, annual precipitation can reach 5,000 mm, and humidity is usually above 80% across the island (Jones and Tye 2006). Conspicuous rainfall determines the seasons, occurring throughout most of the year (wet season), and decreasing only from June to August (long dry season), and during a few weeks between December and February (short dry season).

Príncipe can be divided into: i) non-forested areas, which comprise multiple land-use types that have no or little tree cover, including urban areas and horticultural fields; ii) agroforests, mostly corresponding to accessible regions in the north that were cleared and converted to agriculture but still maintain dense tree cover; iii) secondary forests, corresponding to natural regeneration of land that was cleared but later abandoned; iv) native forests, which were never cleared and are almost entirely restricted to rugged portions of the PONP (Jones *et al.* 1991) (Figure 1). Native forest includes lowland forest and the montane forest surrounding Pico do Príncipe (Exell 1944).

### Fieldwork

Príncipe Island was first surveyed for the Principe Scops-owl for 30 field days during the long dry season, between 17 July and 5 September 2018, trying to ensure an adequate coverage of the whole island and its environmental conditions (Figure 2A). A second survey took place for 12 field days during the small dry season, between 15 and 28 January 2019, concentrating efforts in the areas where the presence of the owl had been previously confirmed (Figure 2B).

Considering the rugged terrain and that we were targeting a nocturnal species, sampling took place on points along transects (Buckland *et al.* 2001). Transects were set during the day, reflective tape was used to mark trees along the way and each sampling point,


**Figure 1.** Altitude, land use (see Figure S1) and protected areas on Príncipe Island. Príncipe Obô Natural Park (PONP) is the protected area covering c. one third of the island. The red circle in the inset shows the location of Príncipe Island in Africa.

and both the transects and the sampling points, were saved into a GPS device (Garmin GPS Map 62s). To increase the coverage of the island, sampling points were set 300 m apart during the first survey. In the second survey, focusing on the previously identified area of occurrence of the species, points were set 150 m apart, as both our results and those for similar species (Borges *et al.* 2004, Pilla *et al.* 2018) indicated that double counting can still be avoided at this distance.

The transects were travelled at a slow constant pace of approximately 1 km/h. Points were sampled between 17h43 and 22h11 GMT during the long dry season, and between 18h00 and 21h43 GMT during the short dry season. The time interval between sunset and the start time of the transect was maintained between transects, repeated in both field surveys to avoid bias while assessing seasonality. Rainy or windy nights were avoided, as these conditions are likely to have a significant negative effect on detectability and on the vocal activity of owls (Kavanagh *et al.* 1995).

At each sampling point, owl calls were registered during the first two minutes. When no owl was heard, a one-minute playback was used to stimulate responses, using a speaker (Mini Amplifier/Speaker, RadioShack Technologies, Fort Worth, TX, USA) and an iPod (iPod Touch 4th Generation, Apple In., Cupertino, CA, USA). Whenever an individual was stimulated by the recorder, the playback was stopped to prevent the bird from moving from its initial position. Information recorded at each sampling point included: start and end time of the count, number of individuals detected and, for each individual, the estimated distance to the sampling point, the direction, and whether it was recorded before or after the playback. Distances up to 10 m were rounded to the nearest 1 m, up to 50 m were rounded to the nearest 5 m, and above 50 m were rounded to the nearest 10 m, based on the volume of the call. Bias in estimation was reduced by training the observer with owl recordings played at different distances. Detections outside the sampling points were also registered, including information on the number of individuals, distance, and direction of call. These additional records were used in all subsequent analyses. Information on distance and direction was used to assess if individuals were being double counted in subsequent points. Whenever possible, the vocalisations were recorded using a recorder (Edirol R-09HR, Roland, Shizuoka, Japan) frequency response: 20–40 Hz, and a microphone (MKE 400, Sennheiser, Wennebostel, Germany).

### Characterising spatially explicit variables

To model the distribution of the Principe Scops-owl at the island scale, eight variables were assessed using Quantum GIS (QGIS

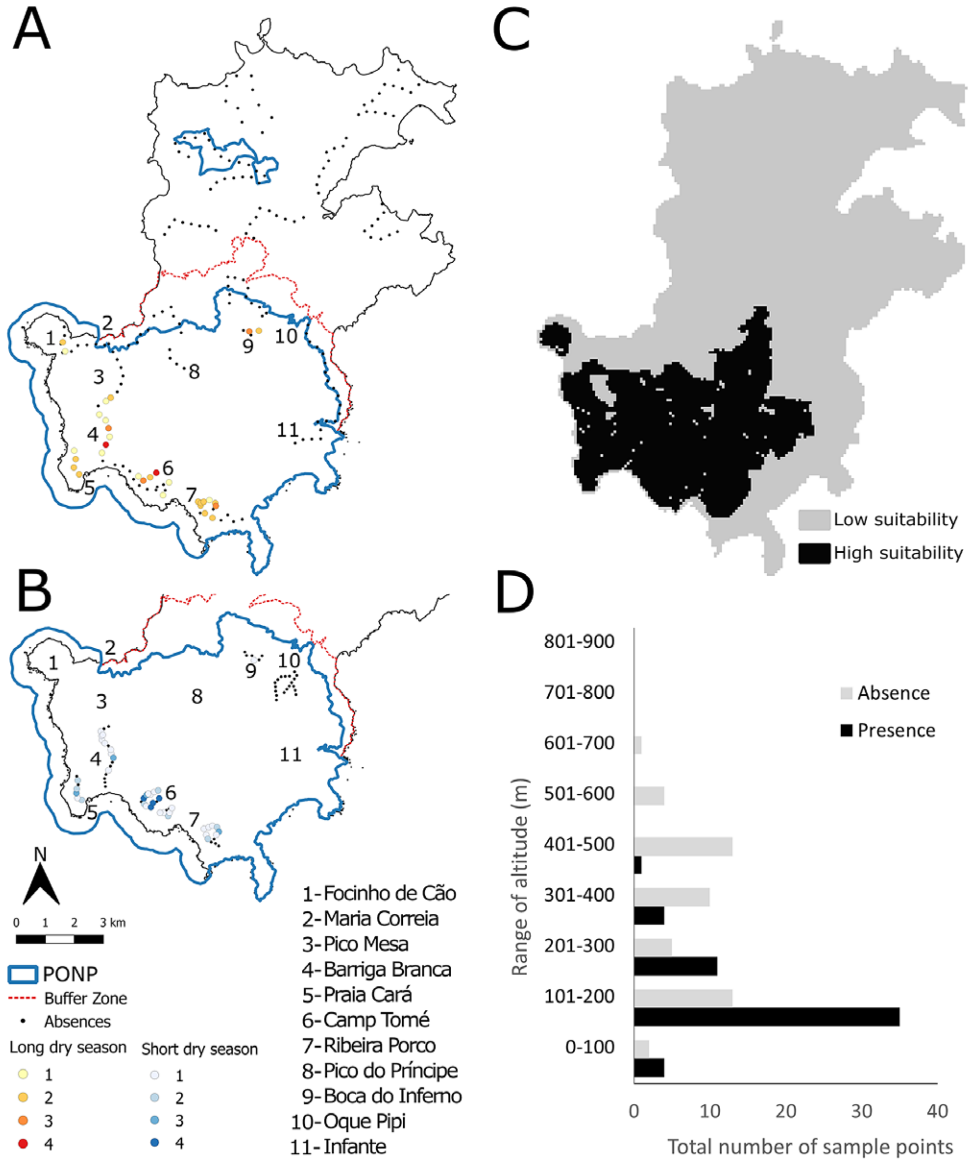


**Figure 2.** Location of sampling points on Príncipe Island during the long dry season (A) and the short dry season (B), specifying the sampling locations of the south and using colours to show the number of individuals detected at each point; (C) binary predicted habitat suitability for the Principe Scops-owl (high suitability area = 34.4 km$^2$); (D) proportion of records (absence or presence) in native forest along the altitudinal range (both seasons). PONP: Príncipe Obô Natural Park.

Development Team 2009a): altitude, ruggedness, slope, distance to the coast, topography, remoteness, rainfall, and land use (Soares 2019) (see Supplementary Material Figure S1 and Table S1). Altitude was used as proxy for temperature, for which Príncipe has no reliable spatial information (Flick and Hijmans 2017).

The eight variables were standardised to a common raster grid, using the nearest neighbour sampling method, the altitude raster as the geometric reference, and the "align rasters" tool (QGIS Development Team 2009b) to generate 163 × 210 cells rasters with 92.4227 m resolution. Each point count was characterised for each environmental variable using the "point sampling tool" plugin (QGIS Development Team 2009c).

All subsequent data analyses were carried out using R (R Core Team 2017) in RStudio 1.1.447 (RStudio Team, 2015).

### *Species distribution modelling and island-wide habitat associations*

To model the potential distribution of the Principe Scops-owl and assess island-wide habitat associations, all point counts were used, including both seasons and additional records. For each spatially explicit variable, boxplots were drawn to identify outliers and analyse variance homogeneity, using the "vegan" package (Oksanen *et al.* 2019). Multicollinearity of continuous variables was tested using Spearman's rank correlation coefficient and a correlogram built with the "corrgram" package (Wright 2018). Multicollinearity between categorical and continuous variables was tested using polyserial correlation, and between categorical variables using polychoric correlation, both applying the "polycor" package (Fox 2016). Variance Inflation Factors (VIF) were

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subsequently used to double-check multicollinearity, using the "car" package (Fox and Weisberg 2019).

Generalised Linear Models (GLMs) with binomial distribution were used to explain the presence of the owl, based on all possible combinations of the abovementioned spatially explicit variables. The data were divided in training and testing sets, using the "caTools" package: 70% of the points were used for the GLM (Zuur *et al.* 2009, Bolker *et al.* 2009), and the remaining 30% were used to validate the model (Tuszynski 2019). GLMs were ranked based on the Akaike Information Criterion corrected for small sample sizes (AICc) using the "dredge" function from the "MuMIn" package (Barton 2016). Goodness of fit was assessed using the Hosmer–Lemeshow test in the "ResourceSelection" package (Lele *et al.* 2019), and McFadden's index (McFadden 1974) in the "pscl" package (Jackman 2017). Predicted values were validated, and the receiving operating characteristic (ROC) curve and area under the curve (AUC) were calculated to examine model performance using the "ROCR" package (Sing *et al.* 2005). To identify which variables best explained the presence of this species, general dominance was explored using the "dominanceanalysis" package (Navarrete and Soares 2019).

The predictions from the best model were mapped using the "raster" package (Hijmans 2019), and the rasters of the variables included in that model. The threshold to classify average continuous probabilities into a map of probable presences or absences was defined using Youden's Index, obtained from the "Information Value" package (Prabhakaran 2016), which accounts for both false-positive and false-negative rates.

Sampling points within the general area of occurrence of the species were subsequently used to assess suitability within this smaller area, repeating the same modelling procedures.

### *Population size*

Population density was estimated using distance sampling on DISTANCE, version 7.2, release 1 (Thomas *et al.* 2010) on the data obtained during the short dry season, which should coincide with the breeding season (Jones and Tye 2006, Melo et al. 2022), when the vocal activity is expected to be higher. As point counts were established at a distance that avoided double counting, the 71 point counts with potential suitable habitat were considered independent and used as sampling units.

To estimate the detection function, the models with the smallest AICc value were selected among the uniform, half-normal, and hazard-rate models with cosine, hermite, or simple polynomial adjustments. The negative-exponential key function was excluded due to the shape criterion (Buckland *et al.* 2001). Models with similar low AICc values were examined more carefully, considering goodness-of-fit tests and truncation of the 5% and 10% longest distances. The population size was calculated by extrapolating estimated density to the area of suitable habitat identified by the island-wide species distribution model.

### *Conservation status*

To propose a conservation threat category following IUCN criteria (IUCN 2012), we used our results and assessed the extent of occurrence (EOO) and the area of occupancy (AOO) of the Principe Scops-owl. EOO and AOO were calculated using the Geospatial Conservation Assessment Tool (Bachman *et al.* 2011). The AOO is a function of the scale at which it is measured and should be appropriate for the taxon being studied (IUCN 2012). Considering the restricted distribution of this species (see Results), we considered the IUCN default value of 2 km (4 $km^2$) inadequate for this species. Instead, AOO was based on the "auto-value" function, which provides a scaled grid cell width based on the size of the EOO, which in this case was 1 km (1 $km^2$).

## Results

### *Distribution*

During the first field survey, 24 transects of variable length were sampled, totalling 83.2 km and 192 point counts (Figure 2A). These included 51 points in native forest, 82 points in secondary forest, 46 points in plantations, and 13 points in non-forested areas. This survey returned 51 records from 27 points, of which 24 were in native forest and three in secondary forest near native forest. Nine additional records were made outside the sampling points: three in native forest, one in secondary forest, and one in a non-forested area. All the records were inside the PONP, namely near Praia Cará, Barriga Branca, Camp Tomé, Ribeira Porco, Focinho de Cão, and Boca do Inferno (Figure 2A).

The second field survey focused on the PONP (Figure 2B), repeating seven transects and creating three new ones: one in Camp Tomé and two in Oque Pipi. In total, 19.6 km of transects and 80 sampling points were sampled, all in native forest, apart from 10 that were in secondary forest. In this second survey, 65 records were made in 37 points, of which 33 were in native forest and four in secondary forest. Three additional records were made outside the sampling points: two in native forest (Camp Tomé and Ribeira Porco), and one in secondary forest (Barriga Branca). The presence of the owl was confirmed in all transects visited during the first survey, but just in one of the new transects, in Camp Tomé (Figure 2A and B).

The owl was detected from 62 m asl at Praia Cará to 402 m asl near Pico Mesa, even though the sampling points ranged from 13 m to 607 m asl. In native forest, the detections were mostly at low altitudes (Figure 2D), and 61.2% of records were only obtained after playback.

### *Species distribution modelling*

While modelling the distribution of the Principe Scops-owl at the island level, two sampling points were outliers: one for ruggedness and slope, and another one for land use, and were removed from subsequent analyses. Rainfall and ruggedness were also excluded from further analyses for being strongly correlated (correlation coefficients higher than 0.8) to remoteness and slope, respectively, but less correlated to owl presence than the latter variables (Supplementary Material Figure S2). VIF values higher than 10 further confirmed the need to exclude ruggedness or slope.

The model with smaller AICc included altitude, distance to the coast, land use, and remoteness (AICc = 108.88) (Supplementary Material Figure S3). The Hosmer–Lemeshow test ($\chi^2 = 11.961$, df = 8, $P$ value = 0.153) and the McFadden's index (0.507) indicated a good fit, and the ROC plot exhibited high AUC (0.941). Using this model, a map with continuous probabilities of occurrence was obtained, from which a binary map was produced (Youden's Index = 0.323), identifying 34.4 $km^2$ of suitable area (Figure 2C) that included 23 points where the presence of the owl had not been confirmed and did not contained five presence points.

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**Table 1.** Average density estimates for the Principe Scops-owl and key function comparisons. The models in bold were used to estimate population densities. AICc: Akaike's Information Criterion corrected for small sample sizes; GOF: goodness of fit; *N*obs: number of observations; EDR: effective detection radius; D: average density; LCL: lower confidence limit; UCL: upper confidence limit; CV: coefficient of variation.

| Key function | Adjustment serie | Right truncation (%) | AICc | χ2 p GOF | *N*obs. | EDR (m) | Density (ind./km$^2$) *D* | 95% LCL | 95% UCL | CV (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Uniform** | **Cosine** | **–** | **704.82** | **0.38** | **67** | **94.85** | **33.39** | **23.63** | **47.19** | **17.61** |
| Half-normal | Hermite polynomial | – | 706.09 | 0.40 | 67 | 94.78 | 33.44 | 23.59 | 47.40 | 17.78 |
| **Half-normal** | **Cosine** | **–** | **704.88** | **0.67** | **67** | **80.45** | **46.42** | **29.27** | **73.61** | **23.61** |
| Hazard rate | Simple polynomial | – | 704.90 | 0.53 | 67 | 90.32 | 36.82 | 22.46 | 60.37 | 25.36 |
| Half-normal | Cosine | 5 | 653.91 | 0.09 | 64 | 88.27 | 36.83 | 24.98 | 54.30 | 19.82 |
| Half-normal | Cosine | 10 | 623.36 | 0.18 | 62 | 86.66 | 37.01 | 24.69 | 55.47 | 20.67 |

Considering the general dominance analysis, remoteness presented the highest average contribution value (0.268), followed by land use (0.186), distance to the coast (0.029), and altitude (0.025). The owl responded negatively to distance to the coast, but positively to all other continuous variables. Regarding land use, the owl clearly preferred native forest, with decreasing frequency of occurrence in secondary forest, where it only occurred when it was adjacent to native forest.

For the modelling focusing solely on the general area of occurrence of the species, slope was excluded due to a strong correlation to ruggedness, while distance to the coast was excluded due to having a VIF higher than 10. The model with smaller AICc contained rainfall only. The McFadden's index (0.079) and AUC (0.500) showed that predictions of this model are no better than random, so we refrained from modelling owl presence at this scale of analysis.

### *Population size*

In total, 67 observations were included in the analysis to estimate the detection function. The lowest AICc values for the detection curve were obtained by the uniform model with cosine adjustment, half-normal with cosine adjustment, and hazard-rate with simple polynomial adjustment (Table 1). The histograms and goodness-of-fit measures revealed that the half-normal model with cosine adjustment was the best detection function. Truncation of the data at 5% and 10% resulted in low $\chi^2$ *P* values of goodness of fit and in poor fitted cumulative distribution function, so it was not applied. Considering the half-normal model with cosine adjustment, owl density is estimated at 46.4 individuals/km$^2$ (95% CI: 29.3–73.6) (Table 1), which leads to an estimated population size of 1,597 individuals (95% CI: 1,007–2,533). Considering a more conservative model (i.e. the uniform model with cosine adjustment), owl density is estimated at 33.4 individuals/km$^2$ (95% CI: 23.6–47.2) (Table 1), leading to an estimated population size of 1,149 individuals (95% CI: 813–1,623) (Table 1). As these two models had the lowest and similar AICc values but resulted in quite distinct density estimates, both were used.

### *IUCN Red List category*

Since the existence of the Principe Scops-owl has only been confirmed recently, there are no data to assess population trends or the probability of extinction, which prevents us from applying IUCN Red List criteria A and E for the assessment of its threat category and further hampers the application of other criteria.

The habitat suitability map showed that the Principe Scops-owl is restricted to a continuous area entirely located inside the PONP, so we considered it to occur in a single location. The EOO was estimated to be 33.0 km$^2$, and the AOO 15 km$^2$. Even though the area where it occurs is under formal protection, the species remains under pressure, namely from introduced species (Dutton 1994) and infrastructure development. Therefore, we considered that there is a reasonable chance of a continuing decline in the extent of occurrence and area of occupancy, habitat quality, and the number of mature individuals. As such, the species fulfils criteria B1ab(i, ii, iii, v) for the "Critically Endangered" category, and criteria B2ab(i, ii, iii, v) for the "Endangered" category.

It classifies as "Endangered" considering the scenario of decline and a population size ranging from 813 to 2,533 (95% CI for both models), following criteria C2a(ii).

If the scenario of decline is not considered, it classifies as "Vulnerable" under criterion D1, if we consider it might have fewer than 1,000 mature individuals, and under criterion D2, considering the EOO and AOO estimates, and that it has a single population.

Based on these data, and having taken into account that the threat category of greatest concern prevails when multiple criteria fit, the Principe Scops-owl classifies as "Critically Endangered" under criteria B1ab(i, ii, iii, v).

## Discussion

This study provides the first data on the ecology of the recently described Principe Scops-owl (Melo *et al.* 2022). The estimated range of the species is restricted to 34.4 km$^2$, occurring in native forest and in its vicinities, in the most remote areas of Príncipe Island, and showing a preference for lower altitudes. Although it can be locally abundant, our data suggest that it classifies as "Critically Endangered", considering a likely scenario of decline, and its small range, restricted to a single location.

### *Distribution and habitat associations*

Field records and species distribution modelling showed that the Principe Scops-owl is most likely restricted to the PONP, in the south of Príncipe Island. This distribution coincides with a previous map of the calls, which were then suspected to belong to a candidate species of scops-owl (Melo and Dallimer 2009), namely at Ribeira Porco, Camp Tomé, and Boca do Inferno. The presence of the Principe Scops-owl was now also confirmed near Praia Cará, Barriga Branca, and Focinho de Cão.

The owl seems to be restricted to native forest and vicinities, in remote rugged terrain where the effects of human presence are limited. Indeed, remoteness and land use were the most important variables to explain its presence, suggesting that low human disturbance drives its current distribution. Even though there was some significant historical land-use change across the entire island (Jones *et al.* 1991), the south has always been the least affected by human disturbance. In the past, human presence in the south was mainly restricted to the establishment of coconut groves along parts of the coast, which are now abandoned. Currently, human presence in the southern forests is restricted to a couple of temporary coastal settlements of fishermen and to the occasional visit by tourists or hunters. No owl was recorded at Oque Pipi, although the area is covered by native forest and less than 1 km away from Boca do Inferno, where the Principe Scops-owl is present. This might be because of current or past human disturbance. In the latter case, its absence may be a consequence of the campaign for the eradication of the tsetse fly, which led to the destruction of significant areas of forest, including at Oque Pipi (Costa 1913). This location is inside the PONP but, being at its northern boundaries, it is close to human settlements, easily accessible, and often visited by hunters and tourists.

Besides being detected in native forest, the owl was occasionally found in mature secondary forests surrounded by native forest. It was not recorded in areas of younger secondary forest, such as those forests near Infante or Maria Correia (Figure 2A). This suggests that the species is heavily reliant on native forests as has been shown for other threatened species including the "Critically Endangered" Principe Thrush, *Turdus xanthorhynchus* Salvadori, 1901, and the "Vulnerable" Obo Giant Snail, *Archachatina bicarinata* Bruguière, 1792 (Rebelo 2020), which further highlights the need to ensure effective conservation of the PONP. This strong dependency on native forest is expected, since the endemic-rich native avifauna of these oceanic islands evolved in a forest-dominated landscape, which is now itself being threatened by anthropogenic impacts (Jones *et al.* 1991). Interestingly, the Sao Tome Scops-owl, *Otus hartlaubi* (Giebel, 1849), seems to cope better with land-use intensification, being frequent in native and secondary forests (Soares *et al.* 2020).

The Principe Scops-owl was mostly detected at lower altitudes and closer to the coast, even though it avoided the immediate proximity of the coast. Both altitude and distance to the coast may be proxies for other abiotic factors, such as temperature, rainfall, and geomorphology, which influence biotic factors that are much harder to map, such as the distribution of fauna and flora (Lewis *et al.* 2018). As most scops-owls, this species is likely to feed on insects (König *et al.* 2008), so its distribution is most certainly influenced by their abundance, which tends to increase at intermediate altitudes in tropical regions (Brehm *et al.* 2007). The Principe Scops-owl seems to be associated with large trees (Freitas 2019), which are mostly absent at higher altitudes (Bosco *et al.* 2018), and from the coastal fringe, which has extensive sections dominated by abandoned coconut groves. Therefore, the altitudinal preferences of this species might be linked to the coastal lowland to medium elevation mature forest (100–400 m asl), which is characterised by the occurrence of large trees and for being the most diverse forest type of Príncipe Island (Bosco *et al.* 2018). The higher altitudinal limit of the owl distribution range may have been underestimated due to the difficulty in surveying areas of higher elevations, which are mostly restricted to steep cliffs or difficult to access areas.

### Population size

Distance sampling analysis estimated a population density of 46.4 individuals/km$^2$ (95% CI: 29.3–73.6), using the half-normal model with cosine adjustment, or 33.4 individuals/km$^2$ (95% CI: 23.6–47.2), using the uniform model with cosine adjustment. Both estimates are consistent with previous claims that the species can be locally abundant (Melo and Dallimer 2009). These are much higher than estimates for other widespread species of the genus *Otus*, like the Eurasian Scops-owl, *Otus scops* (Linnaeus, 1758), which can have 3.2–3.9 territories/km$^2$ (Marchesi and Sergio 2005). However, it matches the "density compensation" pattern observed in many oceanic island populations (MacArthur *et al.* 1972), which has been shown for other insular owl populations, such as the Anjouan Scops-owl, *Otus capnodes* (Gurney, 1889), with 55–87 individuals/km$^2$ (Green *et al.* 2014), and the Grand Comoro Scops-owl, *Otus pauliani* Benson, 1960, with 27.04 individuals/km$^2$ (Ibouroi *et al.* 2019).

Considering a suitable area of 34.4 km$^2$, these population densities correspond to a population size between 1,597 (95% CI: 1,007–2,533) and 1,149 individuals (95% CI: 813–1,623). As the presence of the owl was not confirmed for some of this area, we call for caution and suggest that further efforts should be made to improve these estimates. For instance, if it is confirmed that the owl does not occur above 500 m, the population size estimate would drop by over 200 individuals (Freitas 2019).

### IUCN Red List category

The small EOO, being restricted to a single location, and the inferred distribution, habitat, and population declines indicate that the Principe Scops-owl is "Critically Endangered" (B1ab(i, ii, iii, v)). The species is not persecuted as it is only known by a handful of people, most of whom are involved in the efforts to study it. Nevertheless, its tight association with native forest shows that it is highly sensitive to forest degradation and human disturbance, similarly to the co-occurring "Critically Endangered" Principe Thrush. Direct threats are likely to come from introduced species, which often have strong negative impacts on island species (Holmes *et al.* 2019). Many are known to occur on Príncipe Island (Dutton 1994, Figueiredo *et al.* 2011), of which the mammal predators are likely to be particularly problematic for a cavity-nesting bird such as the Principe Scops-owl. The Mona monkey, *Cercopithecus mona* (Schreber, 1774), and the Black rat, *Rattus rattus* (Linnaeus, 1758), are likely to prey on the nests (eggs and chicks) and even on nesting adults (Guedes *et al.* 2021). The high abundance of the Grey Parrot, *Psittacus erithacus* Linnaeus, 1758, may represent an additional threat, since they are likely to compete with the owl for nesting sites (Melo 1998, Valle *et al.* 2021).

Only around one quarter of Príncipe Island (34.4 km$^2$) was deemed suitable for the owl, making it the smallest known range of any *Otus* species, even lower than that of the "Endangered" Seychelles Scops-owl, *Otus insularis* (Tristram, 1880), which has a distribution range of 46 km$^2$ (BirdLife International 2016). The Principe Scops-owl is restricted to a single area inside the PONP, with an effective area of occupancy estimated at only 15 km$^2$. Although under formal protection, this area remains under pressure from pervasive threats such as introduced species (Dutton 1994) and the plans to build a hydro-electric dam in the Papagaio river. These are particularly worrisome, considering that the dam and its supporting infrastructures will be built inside the PONP next to the northernmost records for this species (Boca do Inferno).

## Future work

Being highly threatened, the Principe Scops-owl should be prioritised for conservation, namely through a Species Action Plan, as has already been made for all other "Critically Endangered" bird species in the country (e.g., BirdLife International 2014, Fundação Príncipe *et al.* 2021). This plan should integrate current knowledge on the ecology of the species with ongoing conservation efforts, namely regarding monitoring (Fauna & Flora International, 2019), which will be key to determining population trends, and thus to improving future assessments of conservation status and to allow adjustments of conservation actions.

Upcoming research should be conservation-oriented, focusing on identifying key threats, and on the breeding and feeding ecology of the species, all of which remain virtually unknown despite being crucial to guide conservation. Knowledge on the distribution and habitat associations of the owl should also be improved, namely by surveying areas that were considered suitable for the species but have not yet been visited. Most of these are in mid to high altitudes, where the very steep slopes and high annual rainfall make nocturnal work challenging. The use of automatic sound recorders may help to overcome these challenges (Darras *et al.* 2019). Gathering more information on relevant environmental variables at multiple scales would be useful: a previous attempt to identify associations with the traits of vegetation at local scale did not allow for robust analyses (Freitas 2019), and a detailed vegetation map for the island would most certainly enhance the predictive accuracy of this and other species distribution models.

As this species is unknown to most islanders, the announcement of its discovery should be made to promote the awakening of pride and affection. Until very recently, the Principe Thrush was also unknown to most people living on the island (Melo *et al.* 2010), but the species is now a flagship species for the conservation of the native forest (Fundação Príncipe 2019, Rebelo 2020). Raising awareness for the uniqueness of the Principe Scops-owl and the forests on which it depends should further boost support for the conservation of the endemic-rich forests of Príncipe, both locally and globally. Guaranteeing a proper implementation and management of the PONP will be the single most important measure to ensure the survival of the owl and the forests it inhabits, but this will only be achieved if there is widespread support for biodiversity conservation in Príncipe.

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Analyses reported in this article can be reproduced using the data provided in https://osf.io/4b37v/ (Freitas et al. 2022).

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## References

Bachman, S., Moat, J., Hill, A., de la Torre, J. and Scott, B. (2011) Supporting Red List threat assessments with GeoCAT: geospatial conservation assessment tool. *ZooKeys* **150**: 117–126.

Barton, K. (2016). MuMIn: Multi-model Inference. R package version 1.15.6. Available at https://CRAN.R-project.org/package=MuMIn.

BirdLife International (2014) *International Action Plan for the conservation of Critically Endangered birds on São Tomé: 2014–2018.* Santo Antonio, São Tomé and Príncipe: BirdLife International.

BirdLife International (2016) *Otus insularis.* The IUCN Red List of Threatened Species 2016: e.T22688667A93205310. Available at http://www.iucnredlist.org/details/22688667/0.

Bolker, B. M., Brooks, M. E., Clark, C. J., Geange, S. W., Poulsen, J. R., Stevens, M. H. H. and White, J.-S. S. (2009) Generalized linear mixed models: a practical guide for ecology and evolution. *Trends Ecol. Evol.* **24**: 127–135.

Borges, S. H., Magalli Henriques, L. and Carvalhaes, A. (2004) Density and habitat use by owls in two Amazonian forest types. *J. Field Ornithol.* **75**: 176–182.

Bosco, L. B., Stévart, T. and Dias, D. (2018) *Príncipe Island botanical sampling follow up work.* Santo Antonio, São Tomé and Príncipe: Fauna & Flora International and Fundação Príncipe.

Brehm, G., Colwell, R. K. and Kluge, J. (2007) The role of environment and mid-domain effect on moth species richness along a tropical elevational gradient. *Glob. Ecol. Biogeogr.* **16**: 205–219.

Buckland, S. T., Anderson, D. R., Burnham, K. P., Laake, J. L., Borchers, D. L. and Thomas, L. (2001) *Introduction to distance sampling: estimating abundance of biological populations.* Oxford, UK: Oxford University Press.

Ceríaco, L. M. P., Marques, M. P. and Bauer, A. M. (2018) Miscellanea Herpetologica Sanctithomae, with a provisional checklist of the terrestrial herpetofauna of São Tomé, Príncipe and Annobon islands. *Zootaxa* **4387**: 91.

Collen, B., Pettorelli, N., Baillie, J. E. M. and Durant, S. M. (2013) *Biodiversity monitoring and conservation: bridging the gap between global commitment and local action.* Oxford, UK: Wiley–Blackwell.

Costa, B. F. B. da (1913) *Trabalhos sobre a doença do sono: Saneamento, Estatística, Serviços Hospitalares e Brigada Official na Ilha do Príncipe.* Limited edition. Lisbon.

Crooks, K. R., Burdett, C. L., Theobald, D. M., King, S. R. B., Di Marco, M., Rondinini, C. and Boitani, L. (2017) Quantification of habitat fragmentation reveals extinction risk in terrestrial mammals. *Proc.Natl Acad. Sci. U S A* **114**: 7635–7640.

Darras, K., Batáry, P., Furnas, B. J., Grass, I., Mulyani, Y. A. and Tscharntke, T. (2019) Autonomous sound recording outperforms human observation for sampling birds: a systematic map and user guide. *Ecol. Appl.* **29**: e01954.

Dutton, J. (1994) Introduced mammals in São Tomé and Príncipe: possible threats to biodiversity. *Biodivers. Conserv.* **3**: 927–938.

Exell, A. W. (1944) *Catalogue of the vascular plants of S. Tomé (with Príncipe and Annobón).* London, UK: British Museum (Natural History).

Fauna & Flora International (2019) *Príncipe thrush and Obô snail monitoring protocol.* Cambridge, UK: Fauna & Flora International.

Figueiredo, E., Paiva, J., Stévart, T., Oliveira, F. and Smith, G. F. (2011) Annotated catalogue of the flowering plants of São Tomé and Príncipe. *Bothalia* 41: **41**–82.

Flick, S. E. and Hijmans, R. J. (2017) WorldClim 2: new 1km spatial resolution climate surfaces for global land areas. *Int. J. Climatol* **37**: 4302–4315.

Fox, J. (2016) polycor: Polychoric and Polyserial Correlations. R package version 0.7-9. Available at https://CRAN.R-project.org/package=polycor.

Fox, J., and Weisberg, S. (2019) *An R companion to applied regression.* Third edition. Thousand Oaks, CA, USA: Sage.

Freitas, B. (2019) *The mystery Scops owl of Príncipe Island: combining evidence for a species description and assessment of its conservation status.* M.Sc.

dissertation. University of Porto, Porto, Portugal. Available at https://hdl.handle.net/10216/124021

Freitas, B., Melo, M., do Bom Jesus, C., da Costa, S. R., dos Santos, Y., Crottini, A. and de Lima, R. F. (2022) Data from: The recently discovered Principe Scops-owl is highly threatened: distribution, habitat associations and population estimates. Available at https://doi.org/10.17605/OSF.IO/4B37V

Fundação Príncipe (2019) *Understanding the remarkable biodiversity of Príncipe Island*. Scientific Report. Santo Antonio, São Tomé and Príncipe: Fundação Príncipe.

Fundação Príncipe, Fauna & Flora International, SPEA & BirdLife International (2021) *Segundo Plano de Ação para a conservação do Tordo-do-Príncipe* Turdus xanthorhynchus *2021–2025, Santo Antonio*. Available at https://www.cepf.net/sites/default/files/action-plan-for-Príncipe-thrush-2021-2025-portuguese.pdf

Green, K. E., Daniel, B. M., Lloyd, S. P., Said, I., Houmadi, A., Salim, D. M., M'Madi, S., Doulton, H. and Young, R. P. (2014) Out of the darkness: the first comprehensive survey of the Critically Endangered Anjouan Scops Owl *Otus capnodes*. *Bird Conserv. Int.* **25**: 322–334.

Guedes, P., dos Santos, Y., de Lima, R. F. and Bird, T. L. F. (2021) Introduced Mona monkey is a key threat to the Critically Endangered Príncipe thrush. *Oryx* **55**: 809.

Hijmans, R. J. (2019) raster: Geographic Data Analysis and Modeling. R package version 2.9.5. Available at https://CRAN.R-project.org/package=raster.

Holmes, N. D., Spatz, D. R., Oppel, S., Tershy, B. *et al.* (2019) Globally important islands where eradicating invasive mammals will benefit highly threatened vertebrates. *PLoS One* **14**: e0212128.

Holyoak, D., Holyoak, G. A., de Lima, R. F., Panisi, M. and Sinclair, F. (2020) A checklist of the land Mollusca (Gastropoda) of the islands of São Tomé and Príncipe, with new records and descriptions of new taxa. *Iberus (Madr.)* **38**: 219–319.

Ibouroi, M. T., Hassane, N. A., Moindjié, S., Ombade, M., Mohamed, N., Saidou, M. H., Abderemane, K., Cheha, A. and Chiffard, J. (2019) The first comprehensive survey of habitat suitability and population size for the endangered Grande Comoro Scops Owl (*Otus pauliani*): implications for its conservation. *J. Ornithol.* **160**: 1121–1132.

IPBES (2019) *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (Version 1). Zenodo. Available at https://doi.org/10.5281/zenodo.3831674

IUCN (2012) *IUCN Red List Categories and Criteria: Version 3.1*. Second edition. Gland, Switzerland and Cambridge, UK: International Union for Conservation of Nature.

Jackman, S. (2017) pscl: Classes and Methods for R Developed in the Political Science Computational Laboratory. R package version 1.5.2. United States Studies Centre, University of Sydney, Sydney. Available at https://github.com/atahk/pscl/.

Jones, P. and Tye, A. (2006) *The birds of São Tomé and Príncipe, with Annobón: islands of the Gulf of Guinea*. Oxford, UK: British Ornithologists' Union.

Jones, P. J. (1994) Biodiversity in the Gulf of Guinea: an overview. *Biodivers. Conserv.* **3**:772–784.

Jones, P. J., Burlison, J. P. and Tye, A. (1991) *Conservação dos ecossistemas florestais na República Democrática de São Tomé e Príncipe*. Gland, Switzerland: International Union for Conservation of Nature.

Kavanagh, R., Debus, S., Tweedie, T. and Webster, R. (1995) Distribution of nocturnal forest birds and mammals in North-Eastern New South Wales: relationships with environmental variables and management history. *Wildl. Res.* **22**: 359.

König, C., Weick, F. and Becking, J.-H. (2008) *Owls of the world*. Second edition. New Haven, CT, USA: Yale University Press.

Le Saout, S., Hoffmann, M., Shi, Y., Hughes, A., Bernard, C., Brooks, T. M., Bertzky, B., Butchart, S. H. M., Stuart, S. N., Badman, T. and Rodrigues, A. S. L. (2013) Protected areas and effective biodiversity conservation. *Science* **342**: 803–805.

Lele, S. R., Keim, J. L. and Solymos, P. (2019) ResourceSelection: Resource Selection (Probability) Functions for Use-Availability Data. R package version 0.3-4. Available at https://CRAN.R-project.org/package=ResourceSelection.

Lewis, T. C., Melo, M., de Lima, R. F. and Bremner-Harrison, S. (2018) Habitat associations of the critically endangered São Tomé Fiscal *Lanius newtoni*: comparing standard and playback-confirmed point counts. *Afr. J. Ecol.* **56**: 404–408.

de Lima, R. F. and Melo, M. (2021) A revised bird checklist for the oceanic islands of the Gulf of Guinea (Príncipe, São Tomé and Annobón). *Bull.Br. Ornithol. Club* **141**: 179–198.

Loiseau, C., Melo, M., Lee, Y., Pereira, H., Hanemaaijer, M. J., Lanzaro, G. C. and Cornel, A. J. (2019) High endemism of mosquitoes on São Tomé and Príncipe Islands: evaluating the general dynamic model in a worldwide island comparison. *Insect Conserv. Divers.* **12**: 69–79.

MacArthur, R. H., Diamond, J. M. and Karr, J. R. (1972) Density compensation in island faunas. *Ecology* **53**: 330–342.

Marchesi, L. and Sergio, F. (2005) Distribution, density, diet and productivity of the Scops Owl *Otus scops* in the Italian Alps. *Ibis* **147**: 176–187.

Mayr, E. (1965) Avifauna: turnover on islands. *Science* **150**: 1587–1588.

McFadden, D. (1974) The measurement of urban travel demand. *J. Public Econ.* **3**: 303–328.

Melo, M. (1998) *Differentiation between Príncipe Island and mainland populations of the African Grey Parrot* Psittacus erithacus: *genetic and behavioural evidence and implications for its conservation*. Cape Town, South Africa: Percy FitzPatrick Institute, University of Cape Town

Melo, M. (2007) *Bird speciation in the Gulf of Guinea*. Edinburgh, UK: Institute of Evolutionary Biology, University of Edinburgh. Doi: 10.13140/RG.2.1.4249.7768.

Melo, M., Bowie, R. C. K., Voelker, G., Dallimer, M., Collar, N. J. and Jones, P. J. (2010) Multiple lines of evidence support the recognition of a very rare bird species: the Príncipe thrush. *J. Zool.* **282**: 120–129.

Melo, M. and Dallimer, M. (2009) Is there an undiscovered endemic scops owl *Otus* sp. on Príncipe Island? Malimbus **31**: 109–115.

Melo, M., Freitas, B., Verbelen, P., da Costa, S. R., Pereira, H., Fuchs, J., Sangster, G., Correia, M. N., de Lima, R. F. and Crottini, A. (2022) A new species of scops-owl (Aves, Strigiformes, Strigidae, *Otus*) from Príncipe Island (Gulf of Guinea, Africa) and novel insights into the systematic affinities within *Otus*. *Zookeys* **1126**: 1–54. doi.org/10.3897/zookeys.1126.87635

Mendes, L. F. and Bivar de Sousa, A. (2012) New account on the butterflies (Lepidoptera: Rhopalocera) of São Tomé e Príncipe. *Bol. SEA* **51**: 157–186.

Mora, C., Tittensor, D. P., Adl, S., Simpson, A. G. B. and Worm, B. (2011) How many species are there on earth and in the ocean? *PLoS Biol.* **9**: e1001127.

Navarrete, C. B. and Soares, F. C. (2019) dominanceanalysis: Dominance Analysis. R package version 1.0.0. Available at https://CRAN.R-project.org/package=dominanceanalysis.

Oksanen, J., Blanchet, G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P. R., O'Hara, R. B., Simpson, G. L., Solymos, P., Stevens, M. H. H., Szoecs, E. and Wagner, H. (2019) vegan: Community Ecology Package. R package version 2.5.5. Available at https://cran.r-project.org/web/packages/vegan/index.html.

Pilla, P., Puan, C. L., Lim, V.-C., Azhar, B. and Zakaria, M. (2018) Sunda Scops-Owl density estimation via distance sampling and call playback. *Sains Malaysiana* **47**: 441–446.

Prabhakaran, S. (2016) InformationValue: Performance Analysis and Companion Functions for Binary Classification Models. R package version 1.2.3. Available at https://CRAN.R-project.org/package=InformationValue.

QGIS Development Team (2009a) QGIS Geographic Information System. Open Source Geospatial Foundation Project. Available at http://qgis.osgeo.org.

QGIS Development Team (2009b) Raster Terrain Analysis Plugin. Open Source Geospatial Foundation Project. Available at https://docs.qgis.org/2.18/en/docs/user_manual/plugins/plugins_raster_terrain.html.

QGIS Development Team (2009c) Point sampling tool. Open Source Geospatial Foundation Project. Available at https://plugins.qgis.org/plugins/pointsamplingtool/.

R Core Team (2017) *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing.

Rebelo, G. R. V. (2020) *Habitat and population estimates of Príncipe flagship species*: *Príncipe thrush* Turdus xanthorhynchus, *and Obô giant snail* Archachatina bicarinata. *MSc Thesis*. Faculdade de Ciências da Universidade de Lisboa, Lisbon. Available at: http://hdl.handle.net/10451/48598.

RStudio Team (2015) *RStudio: Integrated Development Environment for R*. Boston, MA, USA: RStudio, Inc.

Sing, T., Sander, O., Beerenwinkel, N. and Lengauer, T. (2005) ROCR: visualizing classifier performance in R. *Bioinformatics* **21**: 3940–3941.

Soares, F. C. (2019) Analyses of bird field survey data from Príncipe Island. Work report.

Soares, F. C., Panisi, M., Sampaio, H., Soares, E., Santana, A., Buchanan, G. M., Leal, A. I., Palmeirim, J. M. and de Lima, R. F. (2020) Land-use intensification promotes non-native species in a tropical island bird assemblage. *Anim. Conserv.*: acv.12568.

Stattersfield, A. J., Crosby, M. J., Long, A. J. and Wege, D. C. (1998) *Endemic bird areas of the world: priorities for biodiversity conservation*. Cambridge, UK: BirdLife International.

Thomas, L., Buckland, S. T., Rexstad, E. A., Laake, J. L., Strindberg, S., Hedley, S. L., Bishop, J. R. B., Marques, T. A. and Burnham, K. P. (2010) Distance software: design and analysis of distance sampling surveys for estimating population size. *J. Appl. Ecol.* **47**: 5–14.

Tuszynski, J. (2019) caTools-package: Tools: Moving Window Statistics, GIF, Base64, ROC AUC, etc.

UNEP-WCMC (2021) Protected Area Profile for Parque Natural Obô do Príncipe from the World Database of Protected Areas. Protected Planet. Available at https://www.protectedplanet.net/555592842.

UNESCO (2012) The Island of Príncipe. Available at http://www.unesco.org/new/en/natural-sciences/environment/ecological-sciences/biosphere-reserves/africa/sao-tome-and-Pincipe/the-island-of-Principe.

Valle, S., Collar, N. J., Melo, M. and Marsden, S. J. (2021) What can the abundance of Grey Parrots on Príncipe Island tell us about large parrot conservation? *J. Trop. Ecol.* **36**: 293–297.

Verbelen, P., Melo, M., Sangster, G. and Spina, F. (2016) A 90-year-old mystery solved: a potentially new species of owl from Príncipe. *Oryx* **50**: 581.

Wright, K. (2018) corrgram: Plot a Correlogram. R package version 1.13. Available at https://CRAN.R-project.org/package=corrgram.

Zuur, A. F., Ieno, E. N., Walker, N. J., Saveliev, A. A. and Smith, G. M. (2009) *Mixed effects models and extensions in ecology with R*. New York, USA: Springer