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Habitat and population estimates of Príncipe flagship species: Príncipe thrush *Turdus xanthorhynchus*, and Obô giant snail *Archachatina bicarinata*.

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“When we save species, we’re actually saving ourselves.” – Joel Sartore

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RESUMO ALARGADO

O número de espécies ameaçadas de extinção tem crescido rapidamente devido às atividades humanas, estimando-se que o rácio de extinções tenha aumentado entre 100 a 1000 vezes em relação aos tempos anteriores ao surgimento do ser humano. A alteração do uso do solo é considerada a maior ameaça para a sobrevivência de muitas espécies, com a agravante de facilitar o aparecimento de muitas outras ameaças, como a proliferação de espécies invasoras. Atualmente assistimos a uma rápida alteração dos usos do solo, como tal é urgente identificar áreas prioritárias para conservação, em especial nos trópicos, onde se concentra grande parte da biodiversidade e onde as alterações antropogénicas se têm acentuado mais rapidamente nas últimas décadas. Neste contexto, conhecer a distribuição das espécies e as suas associações ambientais é essencial para desenvolver medidas de conservação.

A ilha do Príncipe, no Golfo da Guiné, faz parte de um hotspot de biodiversidade a nível global, e é uma reserva da biosfera da UNESCO. A maior parte destes reconhecimentos deve-se à sua biodiversidade, que apesar da sua reduzida dimensão é muito rica em endemismos, com pelo menos 9 espécies de aves e 29 espécies de moluscos terrestres endémicas. Entre estas, contam-se algumas espécies particularmente carismáticas, como o tordo-do-Príncipe e o búzio-d'Obô. O tordo-do-Príncipe, *Turdus xanthorhynchus*, é uma espécie "Criticamente Ameaçada" endémica do Príncipe, que ocorre sobretudo em floresta nativa, desde o nível do mar até aos 800 m de altitude. O búzio-d'Obô, *Archachatina bicarinata*, é uma espécie "Vulnerável" endémica de São Tomé e Príncipe, que também está fortemente associada à floresta nativa. Ambas as espécies têm sido utilizadas como bandeira para consciencializar os habitantes locais para a perda de biodiversidade e para a degradação das florestas. Apresentam distribuições semelhantes à escala da ilha, acabando por sofrer pressões antropogénicas também semelhantes, sendo assim importante integrar os conhecimentos obtidos sobre ambas as espécies de forma a poder tomar as melhores decisões de conservação ao nível da floresta nativa.

Este estudo tem como objetivo modelar a distribuição do tordo-do-Príncipe e do búzio-d'Obô, de forma a avaliar as suas preferências ambientais e fazer estimativas populacionais. Tudo isto para poder apoiar com informação os atuais planos de conservação destas duas espécies, propondo ações concretas para promover não só a sua conservação, como do ecossistema do qual dependem.

Para modelar a distribuição das espécies e compreender as suas preferências ambientais foram utilizados modelos lineares generalizados tendo como base variáveis ambientais potencialmente relevantes, como a altitude, a pluviosidade, a topografia, a rugosidade, a distância à costa, o tipo de uso do solo, a inacessibilidade, o declive e a proporção de copas grandes. Esta análise foi feita a duas escalas: para a ilha completa e apenas para a zona de floresta nativa, onde se concentra o maior número de observações de ambas as espécies. No caso do tordo foram recolhidos dados de variáveis ambientais locais (número de árvores, número de árvores mortas, número de árvores grandes, número de palmeiras arbustivas, cobertura de copa, densidade do subcoberto, percentagem de solo coberta por vegetação, percentagem de solo coberta por pedras, percentagem de solo coberta por manta morta e percentagem de solo nu), para avaliar o seu efeito na presença da espécie no sul da ilha. A população das duas espécies foi estimada com dados recolhidos em transetos que estão localizados dentro da área de ocorrência destas espécies, cada um dos transetos foi amostrado por duas vezes, uma em junho e outra em dezembro.

Ao nível da ilha a presença do tordo-do-Príncipe estava fortemente associada à floresta nativa, enquanto que dentro desta mostrava uma preferência por zonas mais remotas, afastadas da floresta mais degradada, a altitudes mais elevadas e com menor cobertura de copa. A área estimada como adequada à presença da espécie foi de cerca de 15.4 km^2. Estas associações entre o tordo e o habitat são principalmente atribuídas à vulnerabilidade da espécie à pressão da caça e a espécies invasoras, e não

tanto devido a uma dependência a floresta bem preservada, apesar de não se poder descartar que a espécie pode estar dependente de certas características ecológicas da floresta nativa.

A estimativa populacional do tordo foi de 86 indivíduos (IC 95%: 34 a 180) em junho, e de 314 indivíduos (IC 95%: 201 a 477) em dezembro. Esta variação sazonal era expectável, uma vez que em geral o pico de atividade e conspicuidade das aves corresponde à época de reprodução que na maioria das aves de São Tomé e Príncipe ocorre durante a época das chuvas. Tendo como base dados de pontos de contagem obtidos de estudos anteriores sobre a distribuição e abundância das espécies de aves presentes na floresta nativa do Príncipe, foi feita uma correlação entre a abundância observada e a densidade corrigida de cada espécie, a partir da qual se tentou estimar a população de tordo existente na ilha. Esta análise apontou para uma população entre 178 e 259 indivíduos.

À escala da ilha, a presença do búzio-d'Obô apresentou-se fortemente associada à floresta nativa e a elevadas altitudes, enquanto que dentro da floresta nativa esteve associado a as zonas de meia encosta, seguidas de zonas planas e vales. Tal como para o tordo, pensamos que a distribuição do búzio se deve não tanto a características ecológicas da floresta nativa, mas sobretudo a fatores externos como a pressão antropogénica e a sensibilidade a espécies invasoras, nomeadamente quando até há poucos anos a espécie era abundante por toda a ilha. A área estimada como adequada para a presença da espécie foi de cerca de 32 km^2. Estimou-se uma população de 8881 indivíduos em junho (IC 95 %: 7874 a 9963), e de 4440 indivíduos em dezembro (IC 95%: 3736 a 5213). O maior número de indivíduos em junho foi um resultado surpreendente, pois era expectável que a maior atividade e abundância fosse durante a época das chuvas quando existe mais alimento disponível.

É importante realçar que os resultados obtidos para ambas as espécies devem ser interpretados com grande cuidado, devido especialmente a uma amostragem pequena e potencialmente enviesada; especialmente no sul da ilha, onde o terreno é muito acidentado, houve certamente uma amostragem mais intensiva nas zonas mais acessíveis, o que pode enviesar as estimativas de abundância, as associações com variáveis ambientais e os mapas de probabilidade de ocorrência.

Os resultados obtidos indicam que a sobrevivência de ambas espécies está fortemente dependente da proteção dos ecossistemas de floresta nativa, localizados quase exclusivamente no Parque Natural do Príncipe, que para isso precisa de um reforço nas capacidades de fiscalização e implementação. Para além do parque funcionar como refúgio para espécies ameaçadas, foi também possível perceber que estas espécies não ocupam esta área uniformemente, pelo que se mostra relevante compreender os complexos padrões de distribuição de ecossistemas ao longo do parque para permitir uma atuação mais focada nas áreas e nas ameaças mais importantes a curto prazo. Além disso, estes resultados sugerem que o estatuto do tordo deve ser mantido como "Criticamente Ameaçado" dentro dos critérios atuais, enquanto que o do búzio deveria ser reavaliado para pelo menos "Em Perigo", devido a ter uma área de ocorrência inferior a 5000 km^2 e estar limitada a duas localizações (Príncipe e São Tomé) onde está a decorrer um declínio ao nível da ocorrência, área de ocupação, qualidade do habitat e do número de subpopulações. Para garantir a adequação de medidas específicas de conservação, a monitorização é extremamente importante, pelo que a extensão e frequência da monitorização deveriam ser aumentadas. Recomendamos ainda que estudos futuros se dediquem a compreender a ecologia destas espécies, em particular ao nível da reprodução e da alimentação, bem como ao desenvolvimento de trabalhos que visem perceber o impacto das espécies invasoras nas espécies endémicas, com um foco particular na interação entre o búzio-d'Obô e o búzio-vermelho, *Archachatina marginata*, que foi introduzido no Príncipe nas últimas décadas. Finalmente, encorajamos o desenvolvimento de programas de educação ambiental em que estas duas espécies sejam utilizadas como bandeira para que os habitantes do Príncipe possam estar informados sobre a situação atual da biodiversidade da ilha, e sobre a importância das florestas e das espécies endémicas, para continuar a promover a alteração de atitudes e comportamentos em relação ao ambiente.

Palavras-chave: Endemismo, espécies ameaçadas, floresta nativa, Golfo da Guiné, Modelação da distribuição de espécies.

ABSTRACT

Habitat change is the main cause for biodiversity loss, and namely for the decline of bird and land snail populations. Thus, preventing and reversing population declines requires information on how species use different ecosystems.

The “Critically Endangered” Príncipe thrush, *Turdus xanthorhynchus,* and the “Vulnerable” Obô giant snail are two endemic species that occur on Príncipe Island, in the Gulf of Guinea. They are reported to be almost restricted to the less accessible southern forests, for which that have been used as flagship species for the conservation of the native forests of the island, but very little is known about their ecology. This study aims to model the distribution, to assess habitat preferences, across the island and within native forest, and to estimate population size for both of these species.

Species distribution models for the full island showed that the thrush occurs over an area of about 15.4 km^2 and is strongly associated to native forest. Within this forest type, it preferred remote areas away from degraded forest, at higher altitudes, and with lower canopy cover. Using data obtained in transects that have been surveyed systematically, the species was estimated to have 86 individuals (95% CI: 34 to 180) in June, and 314 individuals (95% CI: 201 to 477) in December. Using data from point counts, population estimates ranged from 178 to 259 individuals.

Using similar analyses, the snail was shown to occur over an area of about 32 km^2. At island level, it was clearly associated to native forest, while within native forest it preferred middle slopes, followed by valleys and flat plain areas. We estimated that the species had a population of 8881 individuals (95% CI: 7874 to 9963) in June, and 4440 individuals (95% CI: 3736 to 5213) in December.

It is important to note that these results must be interpreted with great care, not only because the data available is relatively scarce, but also because difficulties of access due to the rugged terrain may have spatially biased data collection.

The survival of these species relies on effective protection of the Príncipe Natural Park, supplemented by additional pro-active conservation actions. We advise that the conservation status of the thrush is kept as “Critically Endangered” and that the snail should be reassessed and classified at least as “Endangered”. We recommend future studies on the breeding and feeding ecology of these species. Finally, local environmental education programs are encouraged to continue using these species to raise awareness regarding the importance and threats to the biodiversity of Príncipe.

Keywords: Endemism, Gulf of Guinea, native forest, species distribution modelling, threatened species.

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AICc: Akaike Information Criterion corrected for small sample sizes
a.s.l.: above sea level
AUC: Area Under the Curve
CR: Critically Endangered
GIS: Geographical Information System
GLM: Generalized Linear Model
CI: Confidence Interval
PNP: Príncipe Natural Park
ROC: Receiving Operating Characteristic
RVI: Relative Variable Importance
SDM: Species Distribution Model
sp. nov: Species nova
SRTM: Shuttle Radar Topography Mission
TPI: Topography Position Index
UNESCO: United Nations Educational, Scientific and Cultural Organization
VIF: Variance Inflation Factors
WGS: World Geodetic System

GENERAL INTRODUCTION

Recent extinction rates are 100 to 1000 times higher than their pre-human levels (Pimm 1995), and the number of species threatened with extinction looks set to become rapidly worse (Myers et al. 2000). Large scale land use changes pose a major threat to the survival of many species, by reducing habitat quality, and increasing ecosystem fragmentation, isolation, and degradation, while promoting the expansion of exotic species (Foley 2005). Usually multiple threats co-occur and interact with each other, even facilitating the rise of other threats such as invasive species, habitat degradation, pollution, altered climate, hydrology, or fire regimes (Gutiérrez et al. 2014). The ongoing rapid habitat modification in many tropical regions urges for the quick identification of conservation areas (Oke & Omoregie 2012), for which it is key to understand species distribution and habitat associations (Sutherland et al. 2004). Habitat change is the main cause of population decline in bird and land snail species, and all other threats are associated with it. Preventing and reversing population decline requires information on the importance of different habitats for each species, as well as on the threats to those habitats, to inform species conservation and management (Gunnarsson et al. 2006; Idohou et al. 2013).

The conservation of populations of animals requires information on where they are, why they are there, and where else they could be (Aarts et al. 2008). Animals are exposed to many factors, such as the need to acquire food, find mates, rear offspring, defend limited resources and avoid predators. The habitat, which is mostly heterogeneously distributed in space, influences all those factors. Environmental variables can be dynamic or static and may be positively or negatively associated with the presence of a species. Together they make unique combinations across the landscape influencing the distribution of a species (Beyer et al. 2010). Habitat preference is the use of habitat relative to its availability of all possible habitat (Aarts et al. 2008). By analysing how animals use the habitat, we can begin to understand its patterns and to develop more efficient conservation efforts (Beyer et al. 2010).

To identify target areas for intervention and protection, monitor population trends, manage habitat, and tackle threats it is vital to understand the distribution of the species. In this regard, both generalised linear models (GLMs) and species distribution models (SDMs) have been widely used (e.g. Heinänen et al. 2012; De Lima et al. 2017). Generalised linear models consists of three steps: i) the distribution of the response variable; ii) the specification of the systematic component in terms of explanatory variables; iii) the link between the mean of the response variable and the systematic part (Zuur 2009). These models have the advantage of being easily constructed and estimated (Li 1994). SDMs are numerical tools that combine observations of species occurrence or abundance with environmental estimates, to allow for the prediction of species distribution across the landscape (Elith & Leathwick 2009). This technique is derived from correlation and projects the probability of species occurrence based on the distribution of environmental characteristics across the landscape. SDMs allow to reduce the effects of sampling biases, because the projection of the probability of occurrence of the species is based on environmental characteristics that are mapped for the landscape. This technique is often used to support conservation decisions (Guisan et al. 2013). Statistical limitations and limited understanding of biological systems can introduce errors, but these can be partly reduced by advances in statistical modelling techniques (Van Echelpoel et al. 2015).

Estimating population sizes is also key in nature conservation. They are invaluable to monitor population trends and to understand how threatened a species might be. In most estimates, animals are counted in part of their area of occurrence and the population size is then extrapolated for the entire area, which is cheaper and less time consuming (Eikelboom et al. 2019). One of the most used techniques for estimating the size of wild populations is variable distance line transect sampling (Hedley & Buckland 2004). In this technique, an observer moves along a line through a study area, looking to both sides searching for the species of interest, and the perpendicular distances to all detected items of interest are recorded. Combining these data with the assumption that all items close to the line are detected, it is possible to correct the estimates of abundance per unit area for the items not detected (Díaz-Gamboa & Navarro 2015).

Species ranges on islands are often naturally small, making it difficult to encompass dramatic range shifts due to changing climate, geology, and subtle shifts in environmental tolerance making them excellent models to understand ecological processes (Warren et al. 2015). Island fauna and flora are extremely vulnerable to the introduction of predators, diseases, and other threats since, unlike continental species, they have evolved in isolation often in ecosystems where these components were absent. As a result, a larger fraction of island species are at risk of extinction, compared to continental species, and an even greater fraction has gone extinct (Manne et al. 1999). Additionally, the lower genetic diversity on islands limits the potential for island species to adapt to changing environmental conditions including competition, parasitism, and predation by invasive species (Hofman & Rick 2017). Islands are crucial for bird and snail conservation, with approximately 20% of bird species restricted to islands and over 90% of bird extinctions and 70% of mollusc extinctions during historic times occurring on islands (Johnson & Stattersfield 2008; Régnier et al. 2009). Their biggest immediate threats are the invasive species, and the loss of native forest and habitat changes (Johnson & Stattersfield 2008).

Príncipe Island, in the Gulf of Guinea, has a remarkably high degree of endemism of terrestrial fauna and flora, particularly birds, terrestrial molluscs, angiosperms, reptiles, and amphibians (Jones 1994; Fundação Príncipe 2019), especially taking into consideration its small size. For instance, it is a critical priority for the conservation of birds at a global level (Buchanan et al. 2011). The island is part of one of the 25 global biodiversity hotspots (Myers et al. 2000), and it is a UNESCO Biosphere reserve since 2012 (UNESCO 2012). Its forests are also an Important Bird Area (Fishpool & Evans 2001), and part of the Guinean Forests of West Africa Hotspot (Fundação Príncipe 2019). In Príncipe, at least 9 bird species (Freitas 2019; Fundação Príncipe 2019) and 29 terrestrial mollusc species (Holyoak et al. 2020) are endemic to São Tomé and Príncipe. Príncipe has 3 animal species recognized as threatened (IUCN 2020), but most of its species have not been assessed at all. Its threatened species include the "Critically Endangered" Príncipe thrush, *Turdus xanthorhynchus*, the "Endangered" Príncipe white-eye, *Zosterops ficedulinus*, and the "Vulnerable" Obô giant snail, *Archachatina bicarinata* (IUCN 2020).

This study aims to contribute to the conservation of Príncipe's native forest by studying the ecology and distribution of the two flagship species of Príncipe, the Príncipe thrush, and the Obô giant snail. Both are threatened species, and present similar distribution patterns, relying on the remote native forest from the south of the island to persist (Dallimer & Melo 2010; Dallimer et al. 2010).

Flagship species are used to raise funds and awareness for biodiversity loss, often providing a face for ecosystems or larger environmental problems (Verissimo et al. 2011). Most successful conservation organizations have developed effective marketing departments. The cooperation between conservationists and marketeers ensures that campaigns consider the larger conservation picture and take a more effective and balanced approach. Considering the conservation target and identifying target stakeholders will be a great approach to select a flagship species that fits the specific situation. However, there are still many approaches to select a flagship species some of which may result in a poor selection. An example of a great option is creating a new flagship species, selecting a flagship species that was never used for this purpose could ensure the accumulation of the benefits that arise from promoting that species. In contrast, commonly used flagship species, are used by a wide range of organizations which divides potential contributions and makes them less effective at raising attention and funds (Verissimo et al. 2011).

The first chapter is dedicated to the thrush, and we model its distribution, to assess habitat preferences, across the island and within native forest, and estimate population size. In the second chapter we assess the same parameters for the Obô giant snail. This information is vital to support conservation activities, and we will discuss the implications of our findings in that regard, proposing concrete actions to promote a better future for each of these species and for the ecosystems on which they rely.

GENERAL METHODS

STUDY AREA

Príncipe Island (1°32'N - 1°43'N, 7°20'E - 7°28'E) is 139 km^2, being 17 km long by 8 km wide, and lies 220 km west of the African coast and 146 km northeast of São Tomé Island, in the Gulf of Guinea (Central Africa) (Jones & Tye 2006). These two oceanic islands form the Democratic Republic of São Tomé and Príncipe (Fig. 0.1). Príncipe Island comprises two distinct regions: a relatively flat, low-lying basalt platform in the north with small hillocks below 180 m, which contrasts sharply with the mountainous centre and south. The main peaks, Pico (948 m), Mencorne (935 m) and Carriote (830 m) form a topographic barrier between the two parts of the island (Fitton & Hughes 1977; Jones & Tye 2006). The high relief of the island intercepts the prevailing moist wind from the southwest throughout the year, so that annual rainfall in the southwest exceeds 5000 mm, while in the north is around 2000 mm. The rainy season lasts from September to May and the dry season, known as *gravana*, from July to August. There is also a smaller dry period between December and mid-January, known as *gravanito*. At sea-level maximum temperatures range from 22º C to 33º C, and a mean humidity of 80% (Jones 1992; Jones & Tye 2006). The monthly mean temperature ranges from 26º C to 28º C (Chou et al. 2020).

Almost all social and economic life unfolds from its geographical centre to the north, notably in the city of Santo António, its surroundings, and the Airport area (PNUD e Governo Regional do Príncipe 2008). Due to high rainfall, poor quality and lack of maintenance, the roads in Príncipe degrade very quickly. The result is that the regional road network is very deteriorated. Since most of the human population and agricultural land are in the north of the island, most of the south has barely been affected by human activities and remains covered by native forest (Fauna & Flora International 2018), most of which is within the Príncipe Natural Park (PNP), created in 2006 (Direcção Geral do Ambiente 2006). The remaining forest consists of: i) Northern secondary forest – a rare forest type, since most of the north is being used for plantations; ii) Old secondary forest –corresponding to logged forest found at low elevation (50-300 m), mostly in the PNP; iii) Coastal and lowland mature forest –the most diverse forest in the island, found at low elevation (100-400 m); iv) Central forest around Pico Príncipe – found at medium to high elevation (250-650 m), which is poorly surveyed, but shares species with type iii, indicating that the two are related (Fauna & Flora International 2018). Forests cover 59.2% of Príncipe, while the remaining area is covered by shade plantations (29.1%) and non-forested areas (11.7%) (Fundação Príncipe 2019). Almost all the accessible regions of the island were once cleared and planted, mostly with cocoa, coffee, coconuts, and bananas (Jones & Tye 2006), although many of these plantations have been abandoned.

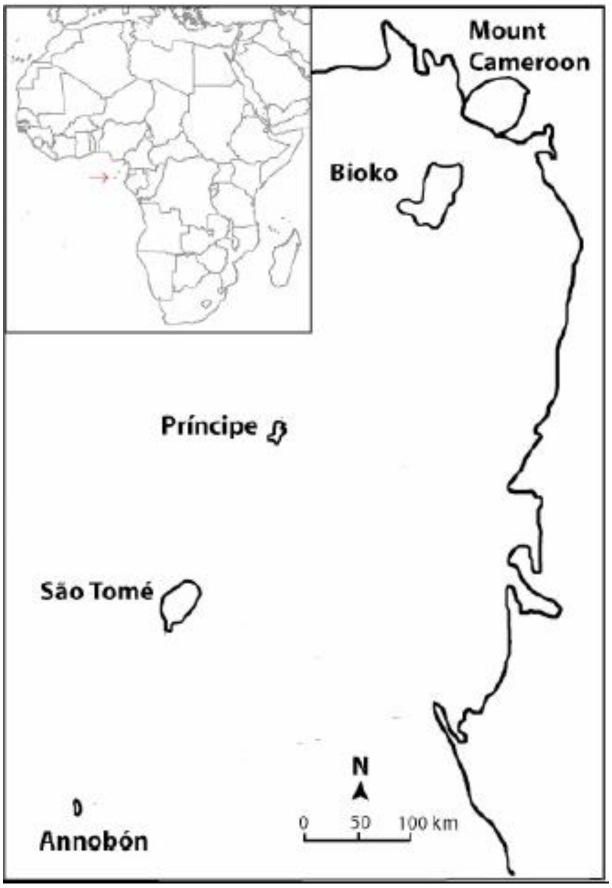

Figure 0.1 - Location of São Tomé and Príncipe Islands in the Gulf of Guinea. The inset on the top left shows the location in Africa (Melo & Dallimer 2008).

DATA COLLECTION

Landscape variables

We obtained raster layers of relevant environmental variables, for which we had spatially-explicit information at island level: Altitude, Ruggedness, Slope, Topography Position Index (TPI), Land-use, Distance to coast, Rainfall and Remoteness index (Table 0.1 – Freitas 2019; Soares 2019). Then, we used the "point sampling tool" QGIS plugin (QGIS Development Team 2019) to extract values for sampling points across the island. We also created an additional variable, proportion of large canopies, identifying areas covered by large canopies, based on visual interpretation of satellite images (Google Earth 2020), using the "Add Polygon Feature" tool (QGIS Development Team 2019). The resulting shapefile was converted to a raster file, where each cell value represented the percentage of that cell covered by large canopies. The cell size was 0.000833º x 0.000833º to match the cell size of other raster layers. To avoid that extreme values affected modelling outcomes, we converted each continuous variable to four ordinal categories.

Table 0.1 – Description of predictor landscape variables used in species distribution modelling. *All variables were built in Quantum GIS, are in raster format and projected coordinate reference system, WGS 84 (EPSG 4326). Cell size is 0.000833º x 0.000833º. We created "Proportion of large canopies" variable, while all the remaining already existed (Freitas 2019; Soares 2019).*

Variable	Description	Type	Units
Altitude	Digital Elevation Model based on NASA's Shuttle Radar Topography Mission (SRTM) with ~92.4227 meters of horizontal resolution	Continuous	Meters
Ruggedness	Ruggedness Index calculated from the Digital Elevation Model with 92.4227 meters of resolution	Continuous	-
Slope	Slope calculated from the Digital Elevation Model	Continuous	Decimal degrees
Topography position index	Index representing the position of each cell regarding the mean elevation of a neighbourhood within a 250 meters radius	Categorical	Flat plain areas and Valleys (1); Middle slope (2); Upper slope (3); Ridges (4)
Land-use	Land use map built from satellite images, drone-based images, historical land-use maps, and local knowledge of Fundação Príncipe staff	Categorical	Native forest (1); Secondary forest (2); Shade plantation (3); Non forested areas (4)
Rainfall	Vectorised map obtained from a map with 30 years of mean annual precipitation data throughout the island. Smoothed with a circular filter with a 20 cells radius.	Continuous	Millimetres
Distance to coast	Minimum linear distance between each cell and the nearest point in coastline	Continuous	Decimal degrees
Remoteness index	Cost accumulated surface created with a friction surface derived from slope and weighted by the population density	Continuous	-
Proportion of large canopies	Percentage of large trees in each cell, estimated using satellite images	Continuous	Percentage

Transects

To collect additional systematic data on the occurrence of target species, we sampled five transects, which follow established but rarely used footpaths within the distribution area of those species, namely in *Morro de Leste*, *Pico Príncipe*, *Barriga Branca*, *Praia Seca* and *Rio São Tomé* (Fig. 0.2). According to the existing methodology (Fauna & Flora International 2019), observers moved along a predetermined fixed route at constant pace and recorded snails or thrushes seen or heard on each side of the route, took a GPS waypoint, and measured/estimated the distance between the animal and the route. A survey team only completed one transect each day, aiming to commence at 6 am. Transects were not conducted during rainfall. When it rained during a transect the surveyors paused until the rain had completely stopped. If it was not possible to commence or finish a transect due to rainfall, it was abandoned, and restarted on a subsequent day. Disturbance that might frighten or attract the focal animals was minimized during the transect, and when approaching the transect before starting. All transects were sampled twice, in June and in December 2019.

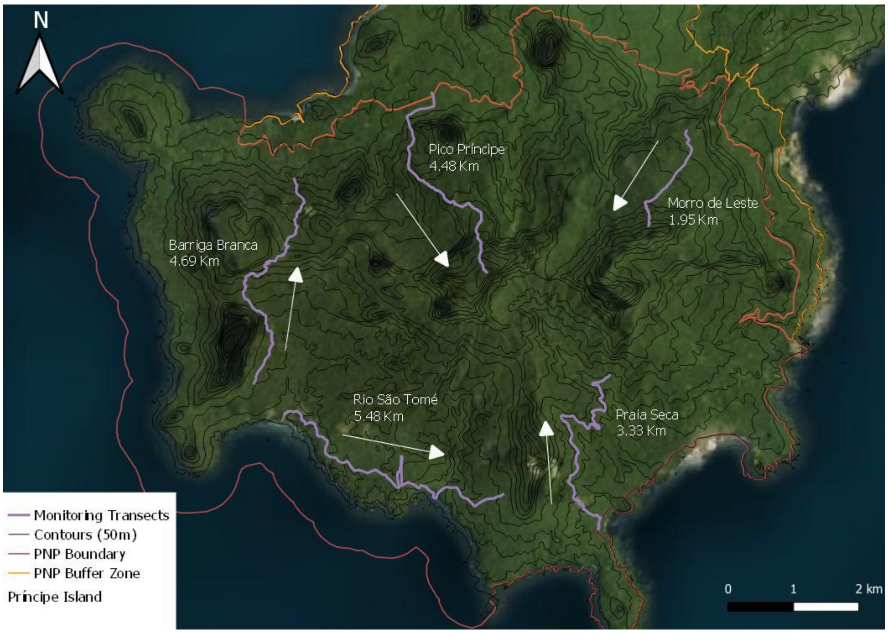

Figure 0.2 - The location of the five monitoring transects used to sample the target species in the south of Príncipe. *Arrows indicate the direction in which they were done.*

DATA ANALYSES

All statistical analyses were made in R (R Core Team 2019) and spatial analyses were made in QGIS (QGIS Development Team 2019).

Landscape environmental associations

Boxplots and Cleveland dotplots built using the “vegan” package (Oksanen et al. 2019) were used to identify outliers in each numeric variable. Multicollinearity was evaluated using Spearman’s rank correlation coefficient, and variables that were strongly correlated were excluded according to: i) presence of outliers; ii) lower correlation with the presence of the target species. To double-check multicollinearity, Variance Inflation Factors (VIF) were calculated using “car” package (Fox & Weisberg 2019).

Presence and absence data from both the full island and the native forest were used to build generalized linear models (GLMs) with binomial distribution (Zuur 2009), and to identify which landscape variables best explain the presence of each species.

All possible models were created and ranked based on the Akaike information criterion (AICc), ΔAICc and Akaike weights, and to use all the data to select the best model the results were bootstrapped using the “dredge” and “bootWeights” functions from the “MuMIn” package (Barton 2019). To identify which variables contribute the most to explain the distribution of each species, the Relative Variable Importance (RVI) was obtained with the “sw” function from the “MuMIn” package (Barton 2019).

The goodness of fit was assessed using the bootstrapped results, and McFadden’s index from the “pscl” package (Jackman 2017) and Hosmer-Lemeshow test from “ResourceSelection” package (Lele et al. 2019). We calculated receiving operating characteristic (ROC) curve and area under the curve (AUC) to assess model performance, using the “ROCR” package (Sing et al. 2005).

Species distribution modelling

Based on the best landscape model for the full island and for the native forest, we represented the potential distribution of each species using the raster layers for the variables included in the best model, using the “raster” package (Hijmans 2020), and the “predict” function from the “stats” package (R Core Team 2019). For the native forest map, Youden’s J Index (Youden 1950) was used to define a threshold to represent this map in a binary map of probable presence or absence, using the “optimalCutoff” function from the “InformationValue” package (Prabhakaran 2016).

Population estimates

We divided the transects in 1 Km long sections, and estimated thrush and snail densities for each section based on a Poisson distribution, for June and December transects separately, estimating the distance of detectability, and calculating 95% confidence intervals. We used thrush and snail densities to calculate population sizes, based on estimated areas of occurrence resulting from the binary map obtained from the species distribution model.

CHAPTER I: Habitat and population estimates for the endemic and Critically Endangered Príncipe thrush *Turdus xanthorhynchus*.

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ABSTRACT

The “Critically Endangered” Príncipe thrush, *Turdus xanthorhynchus,* is endemic to Príncipe island in the Gulf of Guinea. It is reported to be almost restricted to the less accessible native forest of the south, but very little is known about its ecology. This study aims to model the distribution, to assess habitat preferences, across the island and within native forest, and to estimate population size of the Príncipe thrush to support its conservation.

Species distribution models at island scale showed that the thrush occurred over an area of 15.4 km^2 and was strongly associated to native forest. Within this forest type, it preferred remote areas away from degraded forest, at higher altitudes, and with lower canopy cover. The species was estimated to have about 86 individuals (95% CI: 34 to 180) with data from transects sampled in June, while for December’s data the estimate was about 314 individuals (95% CI: 201 to 477) revealing an expected clear seasonal difference. Using data from point counts, the estimate ranged from 178 to 259 individuals.

We recommend the implementation of extended and improved monitoring, to follow population trends. We also advise that the thrush is kept as “Critically Endangered” under criteria: extremely small population, estimated of between 50 to 249 mature individuals, occupying an extremely small range, estimated to be less than 60km^2, and restricted to a single island, which is susceptible to the introduction of alien species. Its survival relies on the effective protection of the Príncipe Natural Park, supplemented by additional pro-active conservation actions. Future studies should focus on the breeding and feeding ecology preferences, but also on understanding the impact of invasive species o the endemic species, such as the thrush. Finally, local environmental education programs are encouraged to raise awareness regarding the importance and threats to the biodiversity of Príncipe.

Keywords: Endemism, Gulf of Guinea, native forest, species distribution modelling, threatened species.

INTRODUCTION

Thrushes belong to an Old-World family which most probably originated in central or southern Asia. Today they are found in all major land masses except Antarctica and New Zealand, the latter of which has an introduced species from Europe. All thrushes are chiefly forest dwellers or have in the recent past emerged from being forest-dwelling birds and adapted to more open types of habitat. However, very few live in areas completely devoid of some kind of tree or tree-scrub cover. Thrushes are highly vocal birds and are one of the more active, visible, and excitable group of birds in their territorial and sexual displays. Thrushes have two moulting periods during the year, one complete moult involving the replacement of all feathers after the breeding season, and a partial moult at the end of winter or non-breeding season. Most thrushes are probably best described as omnivorous; they are perhaps more adapted as insectivorous, but readily take to a wide variety of berries, fruits, and seeds. Within this large range of food they are largely opportunistic, and will take what is more readily available (Clement & Hathway 2000). The genus *Turdus* has 87 species including six threatened, four “Vulnerable”, and the “Critically Endangered” Príncipe thrush, *Turdus xanthorhynchus,* and Taita thrush, *Turdus helleri* (IUCN 2020).

The Príncipe thrush is a bird species endemic to the island of Príncipe (Birdlife International 2014). It was originally described as a full species (Salvadori 1901), but later on (Sclater 1924) considered a subspecies of the São Tomé thrush, *Turdus olivaceofuscus* (Peet & Atkinson 1994). Due to this fact, its fragile conservation status was masked by the abundance of the São Tomé thrush, and considered overall “Near threatened” (Dallimer et al. 2010). More recently, genetic evidence showed that it is a distinct species, constituting a clearly independent evolutionary lineage from that of the São Tomé thrush (Melo et al. 2010). Phenotypic evidence corroborated these results: Príncipe thrushes have a smaller body size and bill length, but a larger bill width and depth; Príncipe thrushes also have longer middle toes (Melo et al. 2010). In São Tomé, the throat is dusky-brown with off-white streaking, with the upper to mid-breast dusky-brown in a broad band that breaks down on the lower breast and belly into off-white with narrow dusky-brown barring. In Príncipe, the throat is off-white with dark brown streaking, ending in an off-white crescent-shaped patch on the uppermost breast, with a narrow dark-brown breast-band that breaks down on the lower breast and belly into off-white with coarse dark-brown scaling. The former pattern is subtle, the latter bold. This distinction is further emphasized by the dusky bill and legs and brown eyes of the São Tomé thrush contrasting with the bright yellow bill, dull yellow legs, bluish-white eyes and narrow yellow eye-ring of the Príncipe thrush (Melo et al. 2010). In addition, the Príncipe thrush utters a low call, previously not recorded in the genus Turdus (Melo et al. 2010). In the Príncipe species, sexes are similar, and the juvenile looks like adult, both having light buff flecking above and blotched brown below (BirdLife International 2020). The species has been recorded in native forest from the lowlands up to c. 800 m a.s.l., although most records were obtained above 400 m (Dallimer et al. 2010). The Príncipe Thrush actively approaches humans and is readily killed by forest dwellers, such as hunters, parrot collectors and snail harvesters. This may explain why the highest densities are restricted to the most inaccessible areas within the native forest, as it seems to happen with the endemic giant land snail *Archachatina bicarinata* (Dallimer & Melo 2010). With no records since 1920s, the Príncipe thrush was considered extinct, but was rediscovered in 1997 (Jones & Tye 2006). It is currently classified as “Critically Endangered” (CR) due to an extremely small population, estimated of between 50 to 249 mature individuals, occupying an extremely small range, estimated to be less than $60km^2$, and restricted to a single island, which is susceptible to the introduction of alien species (IUCN 2020). The extent and quality of the habitat are in decline, which, together with a plausible threat from hunting, is thought to be driving a continuing decline of the population (BirdLife International 2018a). This is based on a previous population estimate of 364 individuals (95% CI: 186 to 887) in 40.1 km^2 (Dallimer et al. 2010): Despite this estimate being useful, it has some limitations: assumptions about the area of occurrence and a relationship between density and elevation were made with sparse data, and the detection function used in the distance analysis was based on data on the São Tomé Thrush, due to insufficient records of the Príncipe thrush. The use of a non-specific detection function will likely have affected density estimates, as the two species have notable differences in behaviour and habitat utilization, both of which can influence detectability (Dallimer et al. 2010). The species has been associated to the native forest, in particular the higher altitudes and most remote areas (Dallimer & Melo 2010; Dallimer et al. 2010; BirdLife International 2018)

Increasing the understanding of ecology, population size and distribution of the species was a key goal of the Príncipe thrush action plan (Birdlife International 2014). This study is part of the projects “Understanding the remarkable biodiversity of Príncipe Island” and “Implementing the Action Plan for the Critically Endangered Príncipe Thrush”, that aim to increase the understanding and distribution of Príncipe species, and in particular, the Príncipe thrush. This study aims to model the distribution of the Príncipe thrush, to assess habitat preferences, across the island and within native forest, and estimate population size. This information is vital to support conservation activities, and we will discuss the implications of our findings in that regarding, proposing concrete actions to promote a better future for this species and for the ecosystems on which it relies.

METHODS

Data collection

Thrush occurrence

We compiled the location of all records of the thrush from the last 5 years (Fundação Príncipe 2019). Many of these records result from surveys of Príncipe bird species, which sampled 760 point counts across the island between July 2018 and July 2019 (Fundação Príncipe 2019). The models required both presence and absence points. We selected absences in the southern part of the island since the species is restricted to that area (Fig. 1.1; Dallimer & Melo 2010; Dallimer et al. 2010). For these absence points, we randomly selected a number of bird counting points where the species had not been registered (Fundação Príncipe 2019). To guarantee independence between points, we only used presences with a minimum distance of 50 m from each other, and absences with a minimum distance of 300 m from the closest presence. Whenever a thrush was observed in the field and fulfilled the previous criteria, the presence was added to the list of records. This resulted in 81 presences and 81 absences.

Using the same criteria described above, we selected absences for the full island and only for the native forest, resulting in a total of 3 datasets: i) Full Island (81 presences and 81 absences); ii) South of the Island (81 presences and 81 absences); iii) Native forest (66 presences and 66 absences).

From the bird surveys, we also gathered information on bird species densities in the native forest, obtained using two different methods: One, based on the number of birds within and beyond a 20 m radius of the point count, and the other based on distance bands and detectability thresholds where it is assumed that all birds inside the 20 m radius circle were detected. Thus, this method presumed the detectability of observers was flawless (Fundação Príncipe 2019).

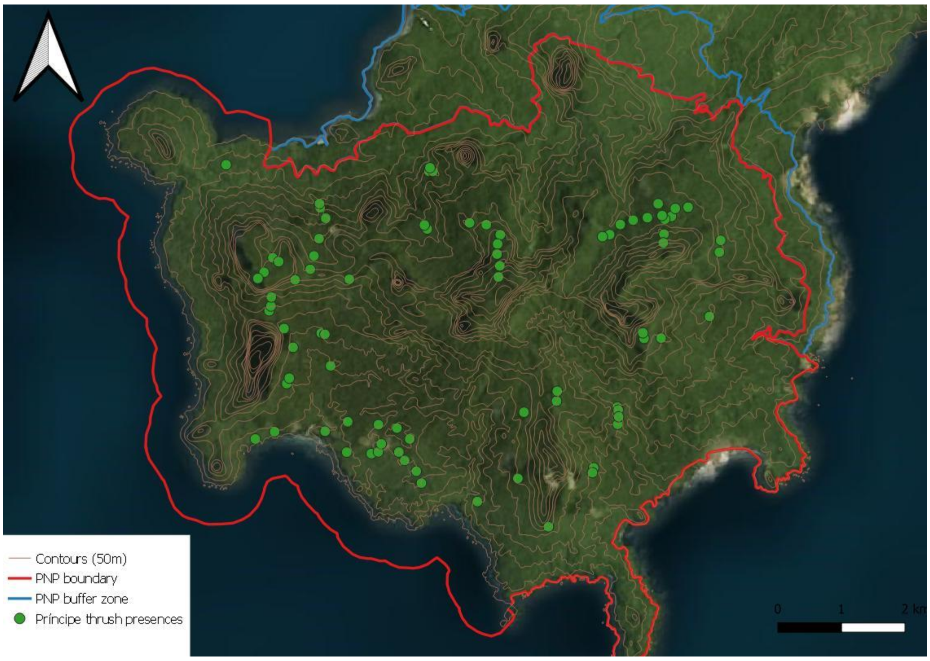

Figure 1.1 – Map of the south of Príncipe Island showing the location of all Príncipe thrush observations since 2014 (Fundação Príncipe 2019).

Field variables

To identify the relationship between thrush presence and local environmental factors, we characterized the abovementioned 81 presences and 81 absences for the south of the island. Points were sampled between October 2019 and January 2020, and we measured 10 environmental variables representing a variety of vegetation and substrate characteristics that might affect the occurrence of the thrush (Table 1.1).

Table 1.1 - List of environmental factors used to identify habitat characteristics that might affect the occurrence of the Príncipe thrush at the local level.

Variable	Measurement
Number of Trees	Count of trees (trees with a diameter at breast height of at least 20cm, including palm trees but not shrubby palms) in a 50 m transect 4 m wide. Using a measuring tape.
Number of Dead Trees	Count of dead trees (standing and fallen with a diameter at breast height of at least 20cm) in a 50m transect 4m wide. Using a measuring tape.
Number of Large Trees	Count of trees with a diameter at breast height over 40 cm in a 20 m radius.
Number of shrubby palms	Count of shrubby palms in a 50 m transect 4m wide. Using a measuring tape.
Canopy Cover	Percentage of canopy cover measured with a convex spherical densiometer. The mean between 4 measurements collected around the point was used.
Understorey density	Classified in a 20m radius according five classes: 1-None or very sparse; 2-Sparse; 3-Medium; 4-Dense; 5-Very dense (De Lima et al. 2013, 2017; Panisi 2017).
% of soil covered with vegetation	Percentage estimated in a 20 m radius.
% of soil covered in rock	Percentage estimated in a 20 m radius.
% of soil covered in forest litter	Percentage estimated in a 20 m radius.
% of bare soil	Percentage estimated in a 20 m radius.

Data analyses

Local environmental associations

We followed the same procedure as for the landscape variables, to assess local environmental associations.

Population estimates

For the approach mentioned in the general methods, we used a detectability distance of 30m for each side of the transect. Despite the number of presences at smaller distance being higher, to avoid biases we used a longer distance because the thrushes actively approach humans.

Beside that approach, we also estimated thrush densities using point count data from other bird species in native forest. To do so, we made a linear correlation between the number of individuals recorded for each species and estimated density (Fundação Príncipe 2019) and used it to extrapolate thrush density. We did this for both methods densities estimates for the birds of Príncipe (Fundação Príncipe 2019). We compared thrush densities obtained from both methods, and used them to calculate population sizes, based on estimated areas of occurrence resulting from the binary species distribution model.

RESULTS

Landscape environmental associations

Full island

No outliers were identified. Slope and ruggedness (correlation coefficient = 0.9), altitude and distance to coast (correlation coefficient = 0.7), and land-use and remoteness (correlation coefficient = - 0.7) were strongly correlated, resulting in the exclusion of slope, distance to coast and remoteness since they had a lower correlation with the presence of the thrush (Fig. S1). After the exclusion of these variables all VIFs were good (VIF < 3).

Modelling using spatially explicit variables showed that altitude and land-use were strongly associated with the presence of the species (Table 1.2). Altitude and native forest were positively correlated with the presence of the species (Fig. S2 & S3). These were the only two variables included in almost all the best models, namely the best model, which only included altitude and land-use (Table S1 - weight = 0.26). The best model also showed good model fit (McFadden index = 0.4; AUC = 0.87).

Native forest

No outliers were identified. Slope and ruggedness (correlation coefficient = 0.9) and altitude and distance to coast (correlation coefficient = 0.8) were strongly correlated, resulting in the exclusion of ruggedness and distance to coast since they had a lower correlation with the presence of the thrush (Fig. S4). After the exclusion of these variables all VIFs were good (VIF<3).

Modelling using spatially explicit variables showed that altitude and remoteness were strongly associated (Table 1.2) and positively correlated with the presence of the species (Fig. S5 & S6). This was confirmed by these being the only two variables included in all best models. The best model included altitude, remoteness, and slope (Table S2 - weight = 0.25). The best model showed fair model fit (McFadden index = 0.155; AUC = 0.75).

*Table 1.2 - **Relative variable importance (RVI) and Spearman's rank correlation coefficient (rho).** RVI values for the explanatory variables. Values range from 0 to 1, 0 meaning the variable does not improve the models, and 1 meaning the variable is included in all the best models. Rho is the response of the species presence to each variable. Differences were considered significant when p-value < 0.05. "*" p-value ≤ 0.05; "**" p-value ≤ 0.01; "***" p-value ≤ 0.001*

Variables	**RVI**	**rho**
Landscape environmental associations in the entire island		
Land-use	1	-0.62***
Altitude	0.92	0.50***
Proportion of large canopies	0.44	0.11
Ruggedness	0.26	0.31***
TPI	0.27	0.16*
Landscape environmental associations in Native forest		
Remoteness	0.98	0.27**
Altitude	0.98	0.35***
Slope	0.63	-0.12
Proportion of large canopies	0.30	0.16
TPI	0.47	0.06
Local environmental associations		
Canopy cover	0.86	-0.19*
Altitude	0.69	0.17*
Number of dead trees	0.3	0.06
% of soil covered in forest litter	0.3	0.07
% of bare soil	0.3	-0.03
Slope	0.29	0.03
Number of shrubby palms	0.28	0.05
Number of Large Trees	0.27	0.03
Understorey density	0.27	0.07
% of soil covered in rock	0.27	-0.05
% of soil covered with vegetation	0.26	0.02

Species distribution modelling

Species distribution modelling suggests that the thrush is restricted to the south of the island. It also showed that it was strongly associated to the native forest, to the point that, even within this forest type, it avoids, the coast and areas close to degraded forest (Fig. 1.2 & 1.3).

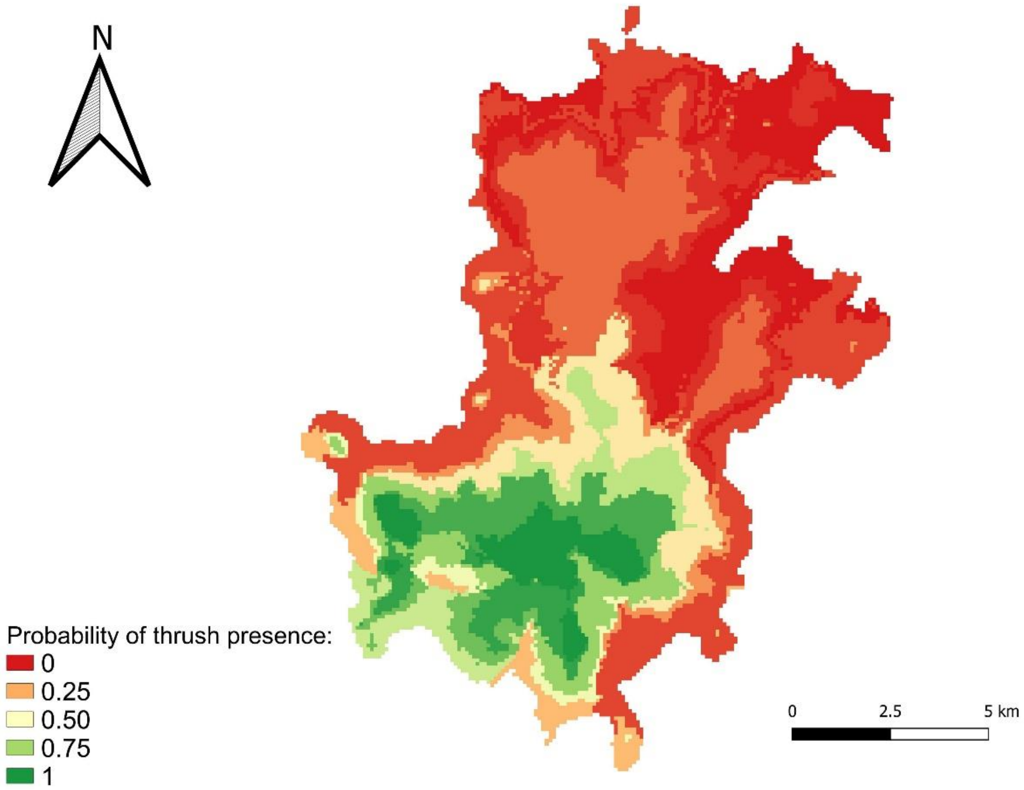

Figure 1.2 - Potential distribution of the Príncipe thrush in the Príncipe Island

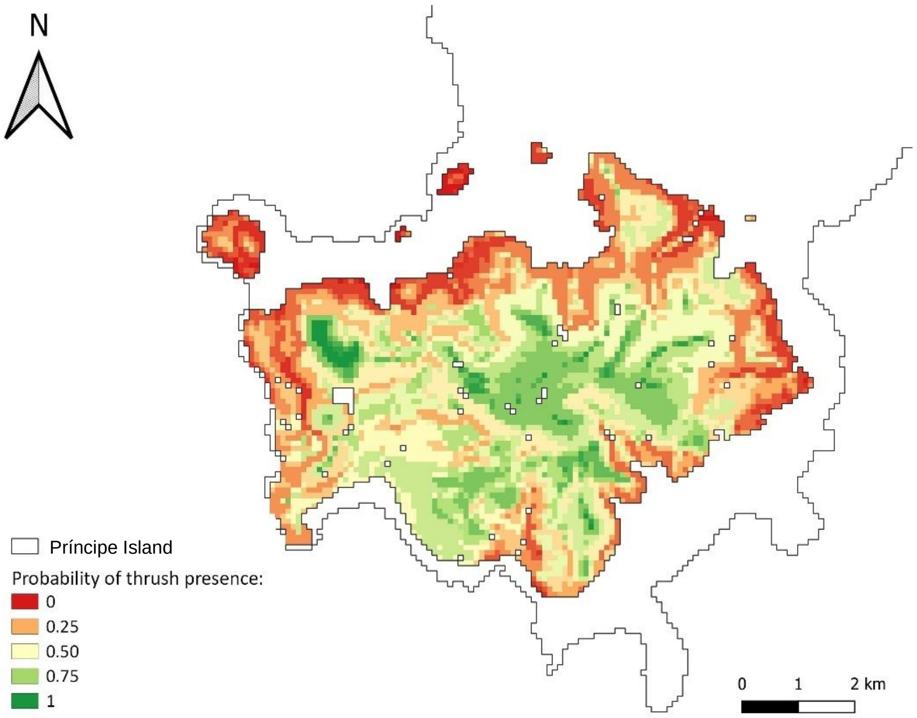

Figure 1.3 - Potential distribution of the Príncipe thrush within the area of native forest in Príncipe Island

Local environmental associations

No outliers or multicollinearity were identified, and all VIFs were good (VIF < 3). Modelling using variables measured at a local scale showed that canopy cover was the most important variable to explain the occurrence of the thrush, followed by altitude (Table 1.2). Canopy cover was negatively correlated with the presence of the species, while altitude was positively correlated (Fig. S7 & S8). All the remaining variables had little importance (Table 1.2). The best model included canopy cover and altitude (Table S3 - weight = 0.08) but had a poor model fit (McFadden index = 0.054; AUC = 0.65).

Population estimates

Using the transects within the area of occurrence of the species, we estimated densities of 5.6 thrushes/Km^2 (95% CI: 2.2 to 11.7) in June, and 20.4 (95% CI: 13.0 to 30.9) in December. Using only the point counts, which were done in the native forest, densities ranged from 11.53 to 16.75 thrushes/km^2.

Based on the transects, we estimated a population size of 86 individuals in June (95% CI: 34 to 180), and 314 in December (95% CI: 201 to 477) in 15.4 km^2. Using the point counts, the estimated number of individuals ranged from 178 to 259 in 15.4 km^2.

DISCUSSION

The presence of the Príncipe thrush was strongly associated to native forest. Within this forest type, it preferred remote areas away from degraded forest, at higher altitudes, and with lower canopy cover.

Population estimates using data from transects sampled in June estimated 86 individuals (95% CI: 34 to 180) and 314 individuals (95% CI: 201 to 477) in December, in 15.4 km^2. While using data from point counts population estimates ranged from 178 to 259 individuals.

Habitat associations

Our data shows that the Príncipe thrush is clearly reliant on the native forest that persists in the south of the island, as it has been reported since its description (Dallimer et al. 2010). This area, characterized by mountainous terrain, has been little affected by human activities (Jones et al. 1991).This association has in the literature been attributed to the species vulnerability to hunting pressure rather than to its ecological dependence on well-preserved forest (Dallimer et al. 2010), because the Príncipe thrush is the tamest of São Tomé and Príncipe birds, actively approaching humans and, as a result, is readily killed by forest users, such as hunters, parrot collectors and snail harvesters (Dallimer & Melo 2010). Its tameness should make it vulnerable to introduced species, which should be less abundant in native forest when compared to areas closer to human populations. This does not discard that the species might be reliant on the unique ecological characteristics of the native forest. However, since the ecology of the species and of the native forest remain mostly unknown (Fundação Príncipe 2019), and hunting pressure decreases in native forest, we cannot fully untangle the role of human disturbance and habitat preferences to explain the strong association between the Príncipe thrush and native forest. These preferences may be linked with the availability of food since from what is currently known the thrush feeds mainly on invertebrates and fruits, which should differ between forest types (Birdlife International 2014; Fauna & Flora International 2018).

Our data also shows a preference for remote areas and higher altitudes, as suggested in previous studies (Dallimer et al. 2010). Once again, this might be explained by a combination of habitat specialization, and human pressure, since higher elevations have a distinct forest type (Fauna & Flora International 2018) but are also in some of the least accessible portions of the island. A cause for the association with altitude might be the three different forest types that exist in the south part of the island, at different altitudes. Old secondary forest, the lowland and medium elevated mature forest and the central sub montane mature forest present from 250 m to 650 m (Fauna & Flora International 2018). The sub montane forest possesses a unique flora, with many unidentified species and has many huge trees that allow bird breeding (Fauna & Flora International 2018), with such different ecological characteristics, and with 44 out of the 66 presences of the species in the native forest being at elevations higher than 250 m, we may be in the case of a species preference for this type of forest.

The habitat associations of the Príncipe thrush are somewhat distinct of those of the closely related São Tomé thrush, endemic to São Tomé Island. This species occupies a wide spectrum of habitats, even though it is still more frequent in forests than in plantations (Soares et al. 2020). Unlike its Príncipe counterpart, the São Tomé thrush seems to prefer locations at lower altitudes that are further away from the coast (Soares 2017). This difference might be attributed to the remarkable tameness of the Príncipe thrush making it more vulnerable to hunting (Dallimer et al. 2010), but it is difficult to know without knowing more about the ecology of both species. From 87 *Turdus* species, only 2 are "Critically Endangered", the Príncipe thrush and the Taita thrush (BirdLife International 2018b), and none is "Endangered" (IUCN 2020). Both "Critically Endangered" *Turdus* have restricted distribution and strong associations to well-preserved forest and higher altitudes. Taita thrush inhabits continental Africa, but is confined to small patches of forest in the Taita hills in Kenya with almost no migration between populations (Galbusera et al. 2000), which are almost functional islands because of the population isolation, with the situation aggravating as the species' montane forest habitat continues to decline in both extent and quality to the point that it is severely fragmented.

The recently discovered and yet undescribed Príncipe scops owl, *Otus* sp. nov., is also almost entirely restricted to native forest suggesting that the restricted distribution of both species to the south of the island might be related to negative effects of proximity to humans (Melo & Dallimer 2008, 2009; Freitas 2019). Nevertheless, it prefers lower altitudes, which is possibly related to different forest types (Fauna & Flora International 2018).

At local scale, reduced canopy cover was apparently the most important characteristic to explain the occurrence of the thrush, followed by higher altitude. This result is surprising and difficult to explain, especially because this was the first study to assess the species local environmental associations. However, forests at higher altitudes normally have lower canopy cover which might explain the association. Future studies should focus on gaining a better understanding of the ecology of the species to confirm this unexpected association. Finally, it is important to note that both the analysis at island and forest scales are weakened by the small number of observations of the thrush, and by potential spatial biases in the distribution of these observations, as accessible routes are more easily sampled. These problems are likely to affect the results of the associations of environmental variables with the presence of the thrush, as well as the maps with the probability of occurrence. A more thorough and spatially unbiased sampling would be very desirable, although it is difficult to obtain because of the ruggedness of the terrain.

Range and population estimates

Our estimates using data from transects suggest a population size of 86 individuals (95% CI: 34 to 180) in June and 314 individuals (95% CI: 201 to 477) in December, while using data from point counts estimates ranged from 178 to 259 individuals in a total area of 15.4 km^2, which matches the only previous estimate of 364 individuals (95% CI: 186 to 887) in 40.1 km^2 (Dallimer et al. 2010). Species distribution modelling suggests that the species does not occupy all areas inside native forest uniformly, reinforcing that the previous estimate might have been an overestimate, as it had been previously suggested to precautionarily assume that the species has fewer than 250 mature individuals. This decision is also reinforced by our results, especially considering that the species might have a reduced proportion of mature individuals (Dallimer et al. 2010).

It is important to note that these population estimates should be interpreted with great care, because they may suffer from potentially important sources of error. One potential problem is the assumption that the thrush is present at homogeneous densities throughout its forest range. The other potential sources of error are in the density estimates. For example, the location of the transects used to estimate density may be biased towards the most accessible terrain, and the fact that the birds are apparently attracted to the observers may inflate its numbers.

There is a clear seasonal variation in the numbers of thrushes encountered; far more were encountered in December than in June. However, this result should be interpreted with care because the data available is only from one survey in each season; more data is needed to fully understand this result. Despite needing more data and not having information about the seasonality or breeding of this species, this result matches our expectations. Most bird species from São Tomé and Príncipe breed during the rainy seasons with a peak during *gravanito* (Madeira 2018). The breeding season normally matches with a peak in activity rates, because it is the time of the year with more juveniles and when adults are more active searching for food. This implies that birds will be more conspicuous during this part of the year, resulting in a higher number of encounters while sampling.

Conservation implications

The Príncipe thrush has an extremely small population restricted to PNP in the south of the island, and is heavily reliant on native forest, preferring higher elevations. Since the species and the ecosystems on which it relies are likely to be highly susceptible to the introduction of alien species and to the effects of climate change (Fundação Príncipe 2019), it should be kept as "Critically endangered" under criteria B1ab(ii,iii,v); C2a(ii) (BirdLife International 2018a).

To ensure the survival of this species monitoring is extremely important, and the extent and frequency of this monitoring should be increased (Fauna & Flora International 2019). We recommend that more transects are created and that these are sampled at least every two months, to detect population trends and gain a better understanding of seasonal variations. To focus conservation efforts, it is also important to study the breeding and feeding ecology of the species, which remain almost entirely unknown and are crucial to interpret habitat associations (Fundação Príncipe 2019). Assessing the threat posed by introduced animal species, including potential nest predators, the black rat, *Rattus rattus,* and the Mona monkey, *Cercopithecus mona*, and potential active predators, feral cats, dogs, and African civets, *Civettictis civetta*, should also be a priority (Fundação Príncipe 2019).

Finally, it is crucial to ensure effective protection of the ecosystems on which the species depends. With at least 9 endemic bird species and 29 endemic terrestrial molluscs species (Freitas 2019; Fundação Príncipe 2019; Holyoak et al. 2020), the PNP needs effective implementation, supplemented by additional pro-active conservation actions targeting this species. At the same time, it is extremely important to develop environmental education programs for locals so they can be made aware of the current biodiversity situation on the island, and the importance of the forests and endemic species, and start to change attitudes and behaviours.

Overall, this work helped filling in some gaps in what was known about the Príncipe thrush, while also reinforcing indications from previous studies. Hopefully, it will help raising awareness for the urgent need of working towards the conservation of this species and the unique biodiversity of Príncipe. Our findings underline the importance of protecting the forests of Príncipe and the crucial role of the Natural Park in this regard.

CHAPTER II: Habitat and population estimates for the endemic and Vulnerable Obô giant snail *Archachatina bicarinata*.

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ABSTRACT

Preventing and reversing population decline requires information on how species use different ecosystems.

The "Vulnerable" Obô giant snail, *Archachatina bicarinata*, is a species endemic to Príncipe Island, in the Gulf of Guinea. It is reported to be almost restricted to the poorly accessible native forest of the south, but very little is known about its ecology. This study aims to model the distribution, to assess habitat preferences across the island and within native forest, and to estimate population size of this flagship species of Príncipe.

Species distribution models for the full island showed that the snail occurred over an area of 32 km^2 and its presence was clearly associated with native forest and high altitudes at the island level, while within native forest it preferred middle slopes, followed by valleys and flat plain areas. We estimate that the species has a population of about 8881 individuals (95% CI: 7874 to 9963) using the data from June's transects, while for transects sampled in December, we estimated a population of about 4440 individuals (95% CI: 3736 to 5213), revealing a surprising clear seasonal difference.

We advise that the snail should be reassessed at least as "Endangered" due to an area of occurrence estimated to be less than 5000 km^2, being limited to two locations where there is a continuous decline in its extent of occurrence, area of occupancy, quality of habitat, and number of subpopulations. Its survival relies on the effective protection of the Príncipe Natural Park, supplemented by additional species-specific conservation actions. We recommend future studies focusing on the ecology of the Obô giant snail, particularly on the breeding and feeding ecology. Finally, local environmental education programs are encouraged to raise awareness regarding the importance and threats to the biodiversity of Príncipe, so locals can start to change attitudes and behaviours.

Keywords: Endemism, Gulf of Guinea, native forest, species distribution modelling, threatened species.

INTRODUCTION

Nonmarine molluscs belong to the second most diverse animal phylum. They receive much less publicity than vertebrates, the most popular phylum, and attract much less research effort. Molluscs have the highest number of documented extinctions of any major taxonomic group and only 2% of all known mollusc species have had their conservation status properly assessed (Lydeard et al. 2004). More than 70% of molluscs extinctions have occurred on oceanic islands, because of their restricted distribution and their evolution under reduced predation pressure (Régnier et al. 2009). Terrestrial land snails are one of the most important groups of invertebrates in ecosystems. In forest ecosystems, they contribute to soil production and calcium concentration of the soil, to the plant litter decomposition process, and are targeted to be very useful indicators of environmental conditions, such as the structure and texture of the soil, and the health of the environment (Idohou et al. 2013). The main threats to land molluscs are habitat changes and the introduction of alien species, especially on oceanic islands (Lydeard et al. 2004; Chiba & Cowie 2016).

The Obô giant snail, *Archachatina bicarinata*, was first described in 1792 by Bruguière and can easily be identified by the combination of sinistral coiling and very large shell size, along with the broad blunt apex of the shell, characteristic of the genus *Archachatina.* Adults can be recognised by the thick dark to blackish-purple shell coloration, marked with obscure brown waves with a bluish-white interior of the aperture; it also has six to seven shell whorls, an arched columella and the shell length can reach up to 15.6 cm (Panisi 2017; Panisi et al. 2020). The species is endemic to São Tomé and Príncipe, being restricted to the centre and west of São Tomé Island associated with higher altitudes and valleys and to native and secondary forests in the south of Príncipe Island, with a potential occupancy area estimated of 181 Km^2 for São Tomé (Panisi 2017) and 61 Km^2 for Príncipe (Fundação Príncipe 2019). The species functions in the ecosystems of São Tomé and Príncipe have not yet been studied. However, it is known that the species is mainly diurnal, which is uncommon for African giant land snails. From observations in captivity, it has been found that it can feed on a wide variety of fruits and leaves which it finds on the ground. Mating and egg-laying has been observed in the wet seasons. The snail also has cultural importance for the locals who use it as food and for traditional medicine (Panisi et al. 2020).

Observations from previous expeditions, local guides and snail harvesters, suggest that the species used to be relatively common, especially in the forest, and that it has suffered a drastic decline over the last 20 years, both in abundance and extent (Dallimer & Melo 2010). Despite evidence of the ongoing decline on both islands, there are no population estimates (Panisi et al. 2020). This decrease has been associated with the introduction of the West African giant land snail, *Archachatina marginata*, which has benefited from habitat disturbance (Panisi 2017). The invasive giant snail threat over the native snail might be related to a disease to which the endemic snail has no resistance, to aggressive behaviour or to the production of mucus that inhibits the growth and behaviour of other conspecifics or closely related species (Panisi 2017). The Obô giant snail is currently "Vulnerable" under criteria A1cde, B1 +2b, suspected population reduction based on a decline in its extent of occurrence, area of occupancy, quality of habitat, number of locations, potential levels of exploitation, and effects of introduced taxa (Clarke & Naggs 1996), but this assessment was done 20 years ago and all recent studies advise an urgent update to at least "Endangered" (Panisi et al. 2020).

METHODS

Data collection

Snail occurrence

We compiled information on all giant snail records, obtained between July 2018 and December 2019 (Fig. 2.1; Fundação Príncipe 2019). To generate pseudo absences, we used the 760 point counts surveyed throughout the island between July 2018 and July 2019 (Fundação Príncipe 2019) in QGIS (QGIS Development Team 2019), and selected random point counts where the species had not been registered to be used as absences (Fundação Príncipe 2019). To guarantee independence between points, we only used presences with a minimum distance of 50 m from each other, and absences with a minimum distance of 100 m from the closest presence. This resulted in 2 datasets of presences and absences, one for the whole island (196 presences and 196 absences), and one just for the native forest (159 presences and 136 absences).

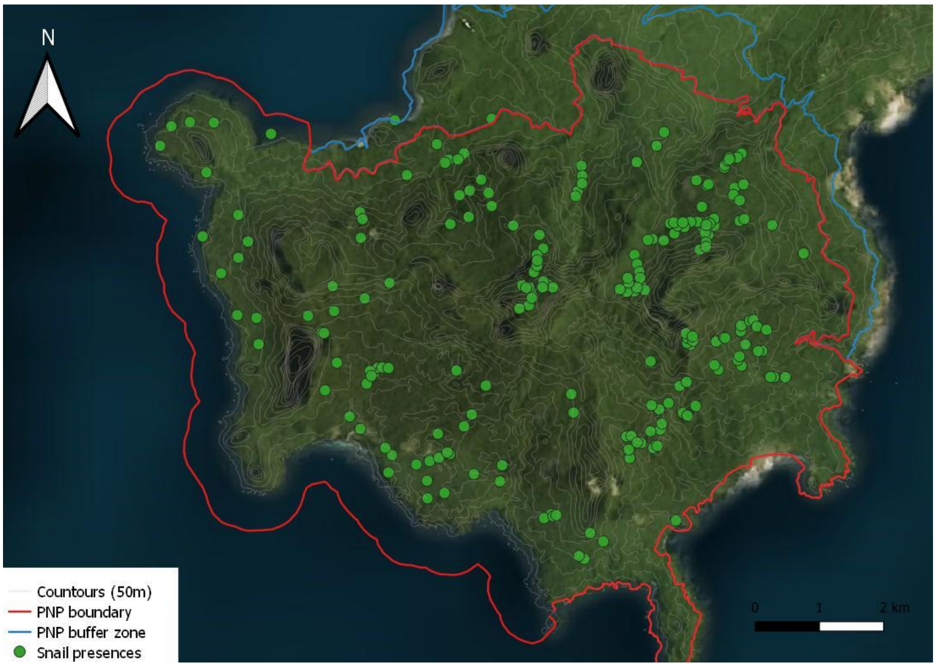

Figure 2.1 - Map of the south of Príncipe Island showing the location of all Obô giant snail observations between July 2018 and December 2019 (Fundação Príncipe 2019).

RESULTS

Landscape environmental associations

Full island

None of the variables had outliers. Slope and ruggedness (correlation coefficient = 0.9), altitude and distance to coast (correlation coefficient = 0.8), land-use and remoteness (correlation coefficient = - 0.7), and rainfall and remoteness (correlation coefficient = 0.8) were strongly correlated, resulting in the exclusion of slope, distance to coast, rainfall, and remoteness since they had a lower correlation with the presence of the snail (Fig. S10). After the exclusion of these variables all VIFs were good (VIF < 3).

Modelling using spatially explicit variables showed that altitude and land-use were strongly associated with the presence of the species (Table 2.1). Altitude and native forest were positively correlated with the presence of the species (Fig. S11 & S12). This was confirmed by these being the only two variables included in almost all the best models, namely the best model, which included altitude, land-use, ruggedness and TPI (Table S4 - weight = 0.35). The best model also showed good model fit (McFadden index = 0.39; AUC = 0.87).

Table 2.1 - Relative variable importance (RVI) and Spearman's rank correlation coefficient (rho). *RVI values for the explanatory variables. Values range from 0 to 1, 0 meaning the variable does not improve the models, and 1 meaning the variable is included in all the best models. Differences were considered significant when p-value < 0.05. "*" p-value ≤ 0.05; "**" p-value ≤ 0.01; "***" p-value ≤ 0.001.*

Variables	RVI	rho
Landscape environmental associations in the entire island		
Land-use	1	-0.62***
Altitude	0.99	0.47***
TPI	0.59	0.01
Ruggedness	0.49	0.29***
Landscape environmental associations in Native forest		
TPI	0.91	-0.14*
Distance to coast	0.64	0.09
Proportion of large canopies	0.63	-0.08
Rainfall	0.27	-0.05

Native forest

None of the variables had outliers. Slope and ruggedness (correlation coefficient = 0.9), TPI and slope (correlation coefficient = 0.9), ruggedness and TPI (correlation coefficient = 0.8), altitude and distance to coast (correlation coefficient = 0.8) and remoteness and rainfall (correlation coefficient = 0.6), were strongly correlated, resulting in the exclusion of ruggedness, slope, remoteness, and altitude since they had a lower correlation with the presence of the snail (Fig. S13). After the exclusion of these variables all VIFs were good (VIF<3).

Modelling using spatially explicit variables showed that TPI was strongly associated (Table 2.1) with the presence of the species (Fig. S14). The presence was mostly associated to middle slope, followed by valleys and flat plain areas. This was confirmed by being the only variable included in almost all best models. The best model included TPI, distance to coast, and Proportion of large canopies (Table S5 - weight = 0.30) but showed poor model fit (McFadden index = 0.042; AUC = 0.63).

Species distribution modelling

Species distribution modelling showed that the snail was restricted to the south of the island. It also showed that it was strongly associated to the native forest, avoiding most coastal areas (Fig. 2.2 & 2.3).

Population estimates

Using the transects within the area of occurrence of the species, and a detectability of 1m for each side of the transect, we estimated densities of 277.8 snails/km^2 (95% CI: 246.3 to 311.6) in June, and 138.9 (95% CI: 116.9 to 163.0) in December. Extrapolating for an area of occurrence of 32 km^2, we estimated a population size of 8881 individuals in June (95% CI: 7874 to 9963), and 4440 in December (95% CI: 3736 to 5213).

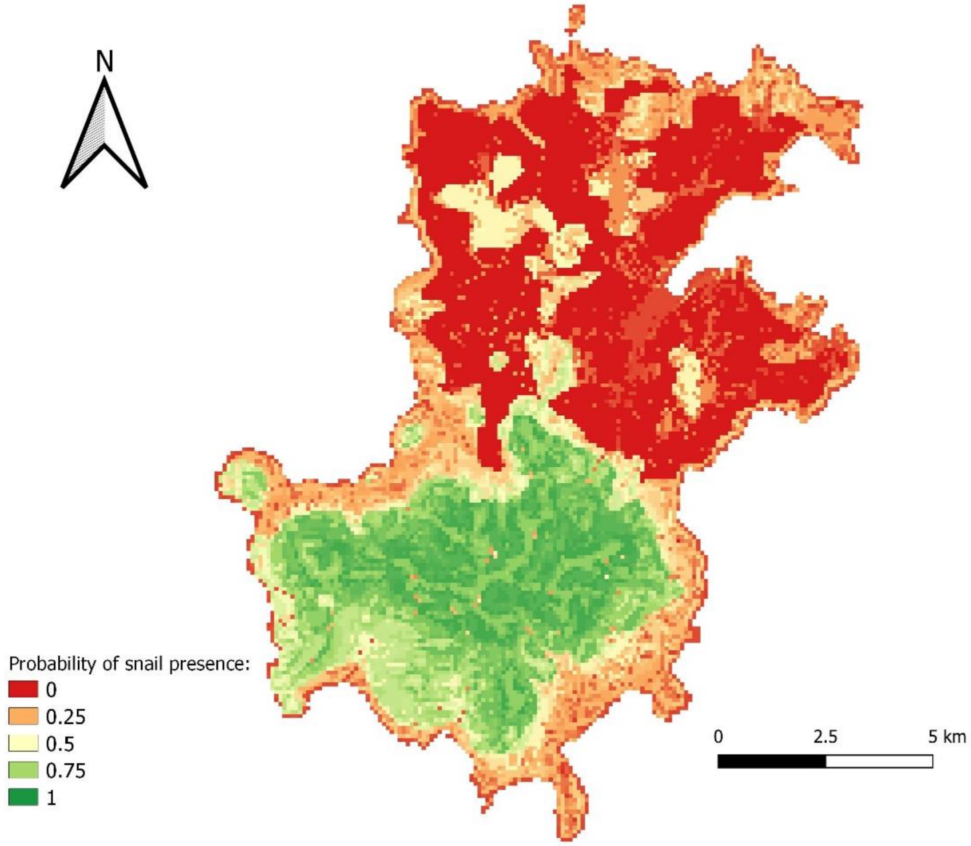

Figure 2.2 - Potential distribution of the Obô Giant Snail in the Príncipe Island.

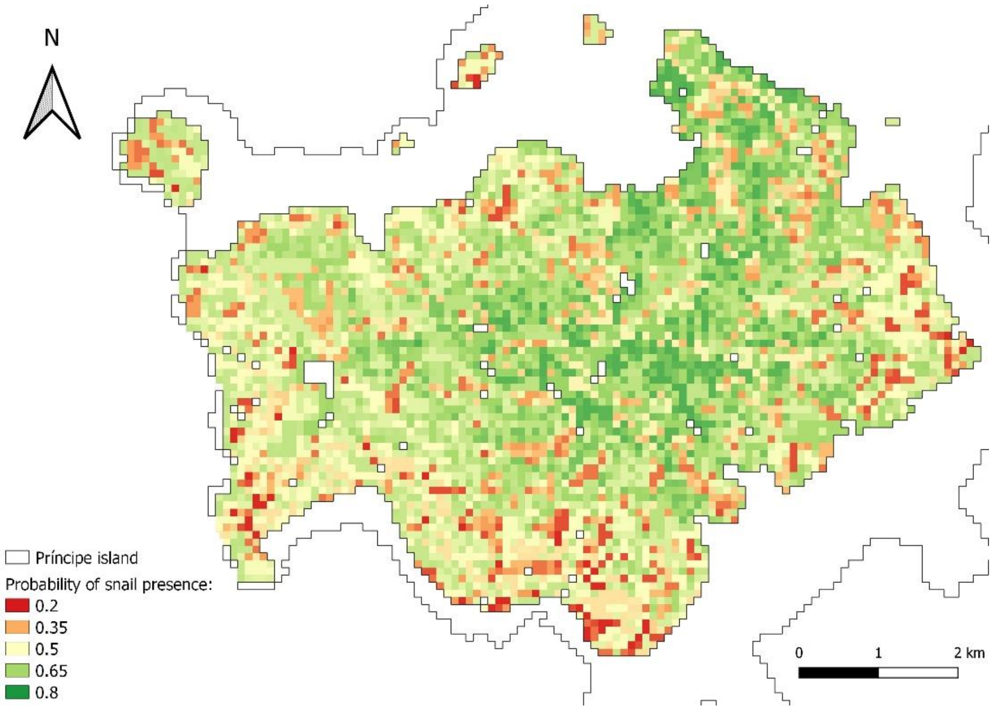

Figure 2.3 - Potential distribution of the Obô Giant Snail in the native forest of Príncipe Island.

DISCUSSION

The Obô giant snail was clearly associated to native forest and higher altitudes at the island level, while within native forest it preferred middle slopes, followed by valleys and flat plain areas. We estimate that the species occupies an area of 32 km^2 and has a population of 8881 individuals (95% CI: 7874 to 9963) based on transects sampled in June and 4440 (95% CI: 3736 to 5213) for transects sampled in December.

Habitat associations

The snail was clearly reliant on native forests and higher elevations at the island scale, just as it had been previously shown for both Príncipe (Dallimer & Melo 2010), and São Tomé (Panisi 2017). This association with the most remote areas of the island might be related to its vulnerability to invasive species and human pressure, and not so much on an ecological dependence on well-preserved forests. Especially, when until a few decades ago the species was abundant throughout the island (Dallimer & Melo 2010; Panisi et al. 2020). With more accessible parts of the native forest losing almost their entire populations it seems clear that a combination human pressure and the introduction of invasive species, particularly the West African giant snail, is the biggest reason for this drastic reduction in the abundance of the Obô sail. The invasive West African giant snail has been suggested as the biggest threat for the endemic snail, and even though it is not clear how. It has been suggested that it might be through direct competition, or through the introduction of a parasite or disease to which the endemic snail is sensitive (Dallimer & Melo 2010). Other potential serious threats include opportunistic collection for food, traditional medicine, and trade (Dallimer & Melo 2010), and predation by invasive mammals (Panisi et al. 2020).

Inside native forest, the Obô giant snail was mostly associated to middle slope, followed by valleys and flat plain areas. These results are not entirely surprising since the species has been associated to valleys in São Tomé (Panisi 2017), although our results do not match exactly this, the two slope categories represent similar or proximal topographies. Future studies should try to clarify these associations by focusing on smaller scales, which are probably more meaningful for the species. The inadequacy of our scale of analysis might help explain why the native forest models did not have a good fit.

Species distribution modeling suggests that the snail avoids areas close to the edge of the forest, once again suggesting that the species is restricted to locations where direct and indirect human pressure is lower. This cannot discard that the species might be reliant on the unique ecological characteristics of the native forest, however it is less likely due to how abundant throughout the island the species used to be a few decades ago (Dallimer & Melo 2010).

All these results should be interpreted with care since the rugged terrain in the south of the Island causes many challenges for the surveyors. It results in spatial biases since the more accessible areas are being sampled more frequently and consequently having more opportunistic observations. These problems will likely bias the resulting habitat associations and maps of the potential distribution of the Obô giant snail.

Range and population estimates

Our estimates suggest a density of 278 snails/km^2 for June and 139 snails/km^2 for December, resulting in a population of approximately 8881 individuals (95% CI: 7874 to 9963) in June and 4440 individuals (95% CI: 3736 to 5213) in December, for an area of 32 km^2 of suitable native forest habitat. This is the first population size estimates for the Obô snail (Panisi et al. 2020), so we advise to be interpreted carefully, since we only had data from two rounds of monitoring transects (Fauna & Flora International 2019) and their location is probably biased to the most accessible areas. These estimates also assumed that the snail density is homogeneously distributed throughout its area of occurrence, which may be a source of errors. Comparing to other giant land snail species, these density estimates seem extremely low: *Achatina fulica* (50 700 snails/km^2), *A.marginata* (11 000 snails/km^2), and *Limicolaria flammea* (49 000 snails/km^2) in Benin (Idohou et al. 2013), and *Powelliphanta traversi* (50 000 snails/km2) in New Zealand (Standish et al. 2002). Even though these results are alarming, especially considering the abundance of the species until recently, future studies should obtain more precise estimates and monitor population trends.

Our estimates also revealed a clear seasonal difference in numbers, with much more snails found in June than in December. We cannot daw big conclusions from these results since they were estimated with data from only one survey of each transect for each season. However these results are surprising since we would expect a peak in activity and therefore in the number of encounters, during the rainy season in December, since there is more food available with increased rainfall (Hau et al. 2008).

Conservation implications

The Obô giant land snail is currently classified as "Vulnerable" but this assessment is more than 20 years old (Clarke & Naggs 1996). Our estimates and the severe distribution and population decline reported on both Príncipe and São Tomé (Dallimer & Melo 2010; Panisi 2017) suggests that the species should be reassessed, and most likely should receive a higher degree of threat, at least to "Endangered", since it has an area of occurrence estimated to be less than 5000 km^2, it is limited to two locations where there is a continuous decline in its extent of occurrence, area of occupancy, quality of habitat, and number of subpopulations (Panisi et al. 2020).

The association between the Obô giant snail and the native forest shows that these less accessible mountainous forests that have been little affected by human activities (Jones et al. 1991) are acting as a refuge for Príncipe threatened endemic species, away from human influence. This has also been suggested for the Príncipe thrush, (Dallimer et al. 2010), the yet undescribed Príncipe scops owl, *Otus* sp. nov (Freitas 2019), and multiple plant species (Fauna & Flora International 2018). Considering this, it is crucial to ensure the protection of the ecosystems on which this species depend. For that the PNP needs effective implementation, supplemented by additional pro-active conservation actions targeting this species.

Our results and previous studies show that the species not only has a very small population, but it is also declining fast. This species has been reported as an indicator of the effectiveness of the protected areas for biodiversity conservation (Dallimer & Melo 2010), its clear and fast decline reinforces the importance of protecting this forests. It is also key to gain a better understanding of the ecology of the species, especially its vulnerability to introduced species, with a special focus on the West African giant snail and all the factors associated with its introduction, but also on the introduced mammals, including the black rat, *Rattus rattus,* the Mona monkey, *Cercopithecus mona*, feral cats, dogs, and African civets, *Civettictis civetta* (Fundação Príncipe 2019). A better knowledge of breeding and feeding ecology would also be useful to support conservation, namely if *ex situ* efforts are to be continued (Panisi et al. 2020). Monitoring is extremely important to ensure the survival of this species (Fauna & Flora International 2019), but its extent and frequency should be increased. We recommend that more transects are created and that these are sampled at least every two months, to detect population trends and gain a better understanding of seasonal variations. A study to estimate with precision the population size on both islands should also be prioritized.

At the same time, it is extremely important to develop environmental education programs for locals so they can be made aware of the current biodiversity situation on the island, and the importance of the forests and endemic species, to start to change attitudes and behaviours. Allowing the Obô giant snail to be used as a flagship species for the conservation of the unique native forests of São Tomé and Príncipe, as recent studies have done (Panisi et al. 2020), would be a good step in that direction.

Overall, our work helped filling in some gaps in what was known about the Obô giant snail, while also reinforcing indications from previous studies. Combining the small density with an also small suitable area and with all the potential threats, we believe that there are reasons to really focus conservation efforts on the Obô giant snail and its ecosystem.

FINAL CONSIDERATIONS

This study provides further evidence that the less accessible native forest in the south of Príncipe island acts as refuge for threatened species, such as the Príncipe thrush or the Obô giant snail. Additionally, these results suggest that the restricted distribution of these species is probably explained by human pressure, and all associated threats, such as land-use changes and invasive alien species. Almost all areas that were found to be important for these species are inside the PNP, so considering that the resources are limited, protecting, monitoring, and focusing conservations efforts on the park will be key to keep the unique fauna and flora of the island.

Although both species are clearly reliant on the PNP and its protection, they do not occupy all the areas uniformly, even within native forest (Fig. 3.1). This shows that the PNP should not be handled as a whole, but as a complex area with different interactions between environmental factors and different anthropogenic pressures. Future efforts should try to start unravelling the complex patterns of ecosystems distribution within the PNP to allow future actions to especially target the most important areas and the most alarming short-term threats. Integrating both species action plans and the PNP management plan would allow better planning and the best use of limited resources.

This was the first study to estimate the population size of the Obô giant snail and the second for the Príncipe thrush. Our estimates are alarming, suggesting that the work towards the conservation of both species needs to be addressed seriously and immediately. These estimates can be used as basis for future studies not only to obtain more precise estimates, but also to guide ongoing monitoring of population trends.

The two species are currently being used as flagship species for the conservation of the forests of the island. According to our knowledge and previous studies, they are excellent flagship species, since they are two of the most threatened species of Príncipe that are simultaneously charismatic for the inhabitants of the island. Having the support of local communities is key to help conserving not only these species but also the forests on which they rely. Most of the local population recognizes the threats to the biodiversity of the island, especially in the case of the snail due to its historical importance for food, traditional medicine, and trade. Locals have a clear idea that the species is becoming rarer every year, making it an excellent flagship species for biodiversity conservation in environmental education programs. Using the two species as flagships can help not only raising awareness for the urgent need to protect the park, but also to alert the inhabitants of Príncipe for the importance of the forests and the endemics of the island, hopefully engaging them in their protection, and supporting the ongoing change of attitudes and behaviours towards the environment.

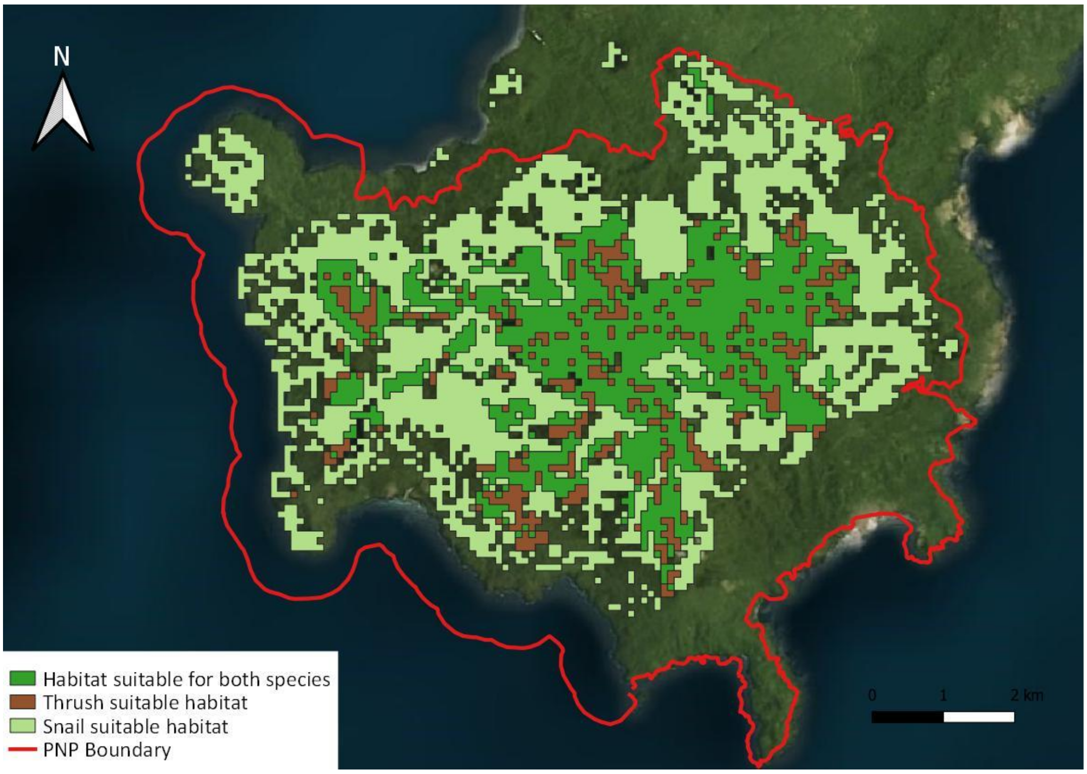

Figure 3.1 - Map of the suitable habitat for the Príncipe thrush and the Obô giant snail. *Map resulting from the binary species distribution models representing the best suited areas for the species occurrence. Red line representing the boundary of Príncipe Natural Park.*

REFERENCES

(Following Conservation Biology guidelines)

Aarts G, MacKenzie M, McConnell B, Fedak M, Matthiopoulos J. 2008. Estimating space-use and habitat preference from wildlife telemetry data. Ecography **31**:140–160.

Barton K. 2019. MuMIn: Multi-model inference. R package version 1.43.15. Available from https://cran.r-project.org/web/packages/MuMIn/MuMIn.pdf (accessed February 5, 2020).

Beyer HL, Haydon DT, Morales JM, Frair JL, Hebblewhite M, Mitchell M, Matthiopoulos J. 2010. The interpretation of habitat preference metrics under use–availability designs. Philosophical Transactions of the Royal Society B: Biological Sciences **365**:2245–2254.

Birdlife International. 2014. Single species action plan for the conservation of the Príncipe thrush *Turdus xanthorhynchus*. Technical Report. Birdlife International, Cambridge, UK. Available from http://rgdoi.net/10.13140/RG.2.1.4295.3121 (accessed February 13, 2020).

BirdLife International. 2018a. *Turdus xanthorhynchus*. The IUCN Red List of Threatened Species 2018: e.T22736414A131458830. Available from http://dx.doi.org/10.2305/IUCN.UK.2018-2.RLTS.T22736414A131458830.en (accessed February 13, 2020).

BirdLife International. 2018b. *Turdus helleri* (amended version of 2016 assessment). The IUCN Red List of Threatened Species 2018: e.T22708740A128039456. Available from http://dx.doi.org/10.2305/IUCN.UK.2016-3.RLTS.T22708740A128039456.en (accessed February 28, 2020).

BirdLife International. 2020. Species factsheet: *Turdus xanthorhynchus*. Available from http://www.birdlife.org (accessed March 16, 2020).

Buchanan GM, Donald PF, Butchart SHM. 2011. Identifying priority areas for conservation: A global assessment for forest-dependent birds. PLoS ONE **6**:10.

Chiba S, Cowie RH. 2016. Evolution and extinction of land snails on oceanic islands. Annual Review of Ecology, Evolution, and Systematics **47**:123–141.

Chou SC et al. 2020. Downscaling projections of climate change in São Tomé and Príncipe Islands, Africa. Climate Dynamics **54**:4021–4042.

Clarke D, Naggs F. 1996. *Archachatina bicarinata*. International Union for Conservation of Nature. Available from http://www.iucnredlist.org/details/2039/0 (accessed November 23, 2020).

Clement P, Hathway R. 2000. Thrushes. Christopher Helm, London, UK.

Dallimer M, Melo M. 2010. Rapid decline of the endemic giant land snail *Archachatina bicarinata* on the island of Príncipe, Gulf of Guinea. Oryx **44**:213–218.

Dallimer M, Melo M, Collar NJ, Jones PJ. 2010. The Príncipe thrush *Turdus xanthorhynchus*: a newly split, 'Critically Endangered', forest flagship species. Bird Conservation International **20**:375–381.

De Lima RF et al. 2017. Distribution and habitat associations of the critically endangered bird species of São Tomé Island (Gulf of Guinea). Bird Conservation International **27**:455–469.

De Lima RF, Dallimer M, Atkinson PW, Barlow J. 2013. Biodiversity and land-use change: understanding the complex responses of an endemic-rich bird assemblage. Diversity and Distributions **19**:411–422.

Díaz-Gamboa R, Navarro J. 2015. Line transect sampling. Pages 47–61 in B. Manly and J. Alberto, editors. Introduction to ecological sampling. FL CRC Press 2014, Boca Raton, US.

Direcção Geral do Ambiente. 2006. Lei do Parque Natural do Obô (Lei n.6/2006). Ministério dos Recursos Naturais e Ambiente, São Tomé e Príncipe.

Eikelboom JAJ, Wind J, van de Ven E, Kenana LM, Schroder B, de Knegt HJ, van Langevelde F, Prins HHT. 2019. Improving the precision and accuracy of animal population estimates with aerial image object detection. Methods in Ecology and Evolution **10**:1875–1887.

Elith J, Leathwick JR. 2009. Species distribution models: Ecological explanation and prediction across space and time. Annual Review of Ecology, Evolution, and Systematics **40**:677–697.

Fauna & Flora International. 2018. Príncipe island botanical sampling follow up work. Work report.

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

Fishpool LDC, Evans MI. 2001. Important Bird Areas in Africa and associated islands: Priority sites for conservation. BirdLife International Cambridge, Cambridge, UK.

Fitton JG, Hughes DJ. 1977. Petrochemistry of the volcanic rocks of the Island of Príncipe, Gulf of Guinea. Contr. Mineral. and Petrol **64**:257–272.

Foley JA. 2005. Global consequences of land use. Science **309**:570–574.

Fox J, Weisberg S. 2019. An R companion to applied regression, 3rd edition. Sage, Thousand Oaks, CA, US.

Freitas BB. 2019. The mystery Scops owl of Príncipe Island: combining evidence for a species description and assessment of its conservation status. MSc dissertation. Faculdade de Ciências da Universidade do Porto, Porto, Portugal.

Fundação Príncipe. 2019. Understanding the remarkable biodiversity of Príncipe Island. Scientific Report. Fundação Príncipe, Santo António, Príncipe Island. Available from www.fundacaoprincipe.org.

Galbusera P, Lens L, Schenck T, Waiyaki E, Mattyhsen E. 2000. Genetic variability and gene flow in the globally, critically-endangered Taita thrush. Conservation Genetics **1**:45–55.

Google Earth. 2020. Google Earth Pro version 7.3.3.7786. Available from https://www.google.com/intl/pt-PT/earth/download/gep/agree.html (accessed April 15, 2020).

Guisan A et al. 2013. Predicting species distributions for conservation decisions. Ecology Letters **16**:1424–1435.

Gunnarsson TG, Gill JA, Appleton GF, Gíslason H, Gardarsson A, Watkinson AR, Sutherland WJ. 2006. Large-scale habitat associations of birds in lowland Iceland: Implications for conservation. Biological Conservation **128**:265–275.

Gutiérrez JL, Jones CG, Sousa R. 2014. Toward an integrated ecosystem perspective of invasive species impacts. Acta Oecologica **54**:131–138.

Hau M, Perfito N, Moore IT. 2008. Timing of breeding in tropical birds: mechanisms and evolutionary implications. Ornitologia Neotropical **19**:39–59.

Hedley SL, Buckland ST. 2004. Spatial models for line transect sampling. Journal of Agricultural, Biological, and Environmental Statistics **9**:181–199.

Heinänen S, Erola J, von Numers M. 2012. High resolution species distribution models of two nesting water bird species: a study of transferability and predictive performance. Landscape Ecology **27**:545–555.

Hijmans RJ. 2020. Geographic data analysis and modeling. R package version 3.0-12. Available from https://cran.r-project.org/web/packages/raster/raster.pdf (accessed April 14, 2020).

Hofman CA, Rick TC. 2017. Ancient biological invasions and island ecosystems: Tracking translocations of wild plants and animals. Journal of Archaeological Research **26**:65–115.

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

Idohou R, Djagoun CAMS, Kassa B, Assogbadjo AE, Codjia JTC. 2013. Soil factors affecting density of three giant land snail species in different habitats of Dassa-Zoumè district (Central Benin). QScience Connect **2013**:31.

IUCN. 2020. The IUCN red list of threatened species. Version 2020-2.

Jackman S. 2017. pscl: Classes and methods for R. developed in the political science computational laboratory. R package version 1.5.2. Available from https://github.com/atahk/pscl/ (accessed February 5, 2020).

Johnson TH, Stattersfield AJ. 2008. A global review of island endemic birds. Ibis **132**:167–180.

Jones P. 1992. São Tomé and Príncipe. Pages 240–243 in J. Sayer, C. Harcourt, and N. Collins, editors. The Conservation Atlas of Tropical Forests Africa. Springer, London, UK.

Jones P, Tye A. 2006. The birds of São Tomé & Príncipe, with Annobón, islands of the Gulf of Guinea: an annotated checklist. British Ornithologists' Union, Oxford, UK.

Jones PJ. 1994. Biodiversity in the Gulf of Guinea: An overview. Biodiversity and Conservation **3**:772–784.

Jones PJ, Burlison JP, Tye A. 1991. Conservação dos ecossistemas florestais na República Democrática de Sao Tomé e Príncipe. IUCN, Gland, Switzerland.

Lele SR, Halliday AN, Fitton J JG, Poli G. 2019. Resource selection (probability) functions for use-availability data. R package version 0.3-5. Available from https://cran.r-project.org/web/packages/ResourceSelection/ResourceSelection.pdf (accessed April 14, 2020).

Li WK. 1994. Time series models based on generalized linear models: Some further results. International Biometric Society **50**:506–511.

Lydeard C et al. 2004. The global decline of nonmarine mollusks. BioScience **54**:321.

Madeira B. 2018. Sexual dimorphism and reproductive phenology of common birds in São Tomé Island – conservation implications. MSc dissertation. Faculdade de Ciências da Universidade de Lisboa, Lisboa, Portugal.

Manne LL, Brooks TM, Pimm SL. 1999. Relative risk of extinction of passerine birds on continents and islands. Nature **399**:258–261.

Melo M, Bowie RCK, Voelker G, Dallimer M, Collar NJ, Jones PJ. 2010. Multiple lines of evidence support the recognition of a very rare bird species: the Príncipe thrush. Journal of Zoology **282**:120–129.

Melo M, Dallimer M. 2008. The status of a rare and recently described endemic bird species (the Príncipe thrush *Turdus* [*olivaceofuscus*] *xanthorhynchus*) and a search for an as yet undescribed 'owl.' Work report.

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

Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Kent J. 2000. Biodiversity hotspots for conservation priorities. Nature **403**:853–858.

Oke CO, Omoregie CE. 2012. Land snail species richeness in cocoa agro-forest in Ile-Oluji, Ondo state, Nigeria. Zoologist **10**:40–47.

Oksanen J et al. 2019. Vegan: community ecology package. R package version 2.5.6. Available from https://CRAN.R-project.org/package=vegan (accessed February 18, 2020).

Panisi M. 2017. Biological invasion and the conservation of endemic island species: São Tomé Archachatina giant land snails (Pulmonata: Achatinidade). MSc dissertation. Faculdade de Ciências da Universidade de Lisboa, Lisboa, Portugal.

Panisi M, Sinclair F, Santos Y. 2020. Single species action plan for the conservation of the Obô giant snail *Archachatina bicarinata*, 2021-2025. SSC Mid-Atlantic Island Invertebrate Specialist

Group. Available from http://www.maiisg.com/resources/publications/ (accessed December 1, 2020).

Peet B, Atkinson W. 1994. The biodiversity and conservation of the birds of São Tomé and Príncipe. Biodiversity & Conservation **3**:851–867.

Pimm L. 1995. The future of biodiversity. Science **269**:347–350.

PNUD e Governo Regional do Príncipe. 2008. 1º Plano de desenvolvimento regional 2009-2013. Governo Regional do Príncipe, Príncipe, São Tomé e Príncipe.

Prabhakaran S. 2016. InformationValue: Performance analysis and companion functions for binary classification models. R package version 1.2.3. Available from https://cran.r-project.org/web/packages/InformationValue/InformationValue.pdf (accessed October 25, 2020).

QGIS Development Team. 2019. QGIS Geographic Information System version 3.8.1. Open Source Geospatial Foundation. Available from http://qgis.osgeo.org/ (accessed January 1, 2020).

R Core Team. 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available from https://www.R-project.org/ (accessed January 15, 2020).

Régnier C, Fontaine B, Bouchet P. 2009. Not knowing, not recording, not listing: Numerous unnoticed mollusk extinctions. Conservation Biology **23**:1214–1221.

Salvadori T. 1901. Due nuove specie di uccelli dell'Isola di S. Thomé e dell'Isola del Principe. raccolte dal Sig. Leonardo Fea. Boll. Mus. Zool. Anat. Comp. **16**:1–2.

Sclater WL. 1924. Systema avium ethiopicarum. British Ornithologists' Union, London, UK.

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

Soares F. 2017. Modelling the distribution of São Tomé bird species: Ecological determinants and conservation prioritization. MSc dissertation. Faculdade de Ciências da Universidade de Lisboa, Lisboa, Portugal.

Soares FC. 2019. Analyses of bird field survey data from Príncipe Island. Work report.

Soares FC, Panisi M, Sampaio H, Soares E, Santana A, Buchanan GM, Leal AI, Palmeirim JM, Lima RF. 2020. Land-use intensification promotes non-native species in a tropical island bird assemblage. Animal Conservation **23**:573–584.

Standish RJ, Bennett SJ, Stringer IAN. 2002. Habitat use of *Tradescantia fluminensis* by *Powelliphanta traversi*. Science for Conservation **195A**:26.

Sutherland WJ, Newton I, Green R. 2004. Bird ecology and conservation: a handbook of techniques. OUP Oxford, Oxford, US.

UNESCO. 2012. The Island of Príncipe. Available from http://www.unesco.org/new/en/natural-sciences/environment/ecological-sciences/biosphere-reserves/africa/sao-tome-and-principe/the-island-of-principe (accessed December 11, 2020).

Van Echelpoel W, Boets P, Landuyt D, Gobeyn S, Everaert G, Bennetsen E, Mouton A, Goethals PLM. 2015. Species distribution models for sustainable ecosystem management. Pages 115–134 in S. Jorgensen and M. Gromiec, editors. Developments in Environmental Modelling. Elsevier, Toulouse, France.

Verissimo D, MacMillan DC, Smith RJ. 2011. Toward a systematic approach for identifying conservation flagships. Conservation Letters **4**:1–8.

Warren BH et al. 2015. Islands as model systems in ecology and evolution: prospects fifty years after MacArthur-Wilson. Ecology Letters **18**:200–217.

Youden WJ. 1950. Index for rating diagnostic tests. Cancer **3**:32–35.

Zuur AF, editor. 2009. Mixed effects models and extensions in ecology with R. Springer, New York, US.

SUPPLEMENTARY MATERIAL

Section I: Tables and figures

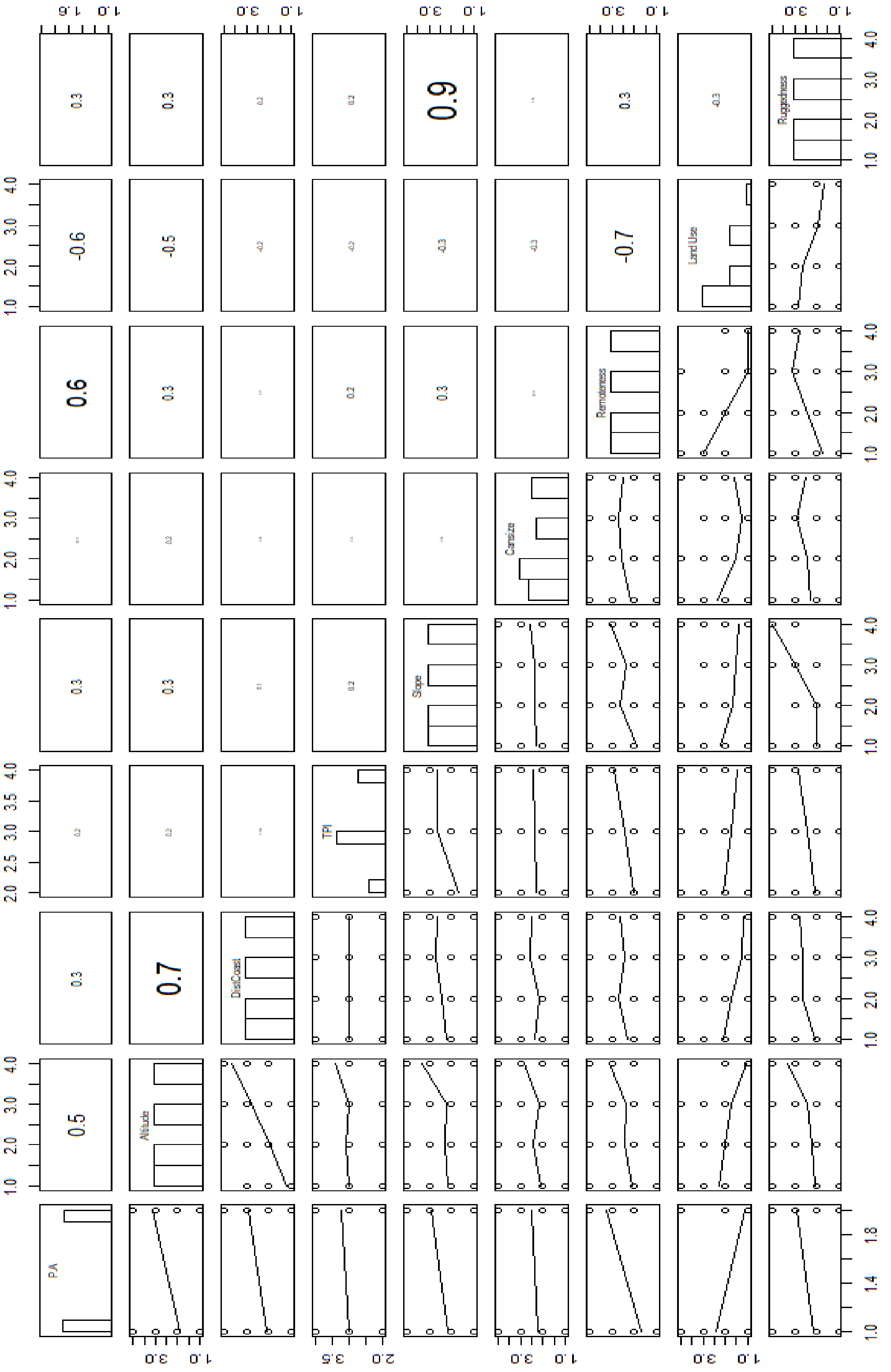

Figure S1 - Spearman rank correlation coefficient panel. Between environmental variables and presence and absence of the Príncipe thrush for the entire Príncipe island.

Table S1 - Top 10 models for the Príncipe thrush landscape associations at island scale. *Models are ranked based on the Akaike Information Criterion for the bootstrapped weights corrected for small sample sizes (AICc). Each line represents a model. Weight is the number of trials when the response is the proportion of successes.*

Altitude	**Proportion of large canopies**	**Land-use**	**Ruggedness**	**TPI**	**Df**	**Bootstrapped Weights**
0.6376		+			5	0.26
0.6862	-0.30490	+			6	0.25
0.6598		+		+	7	0.11
0.5893		+	0.1699		6	0.1
0.7046	-0.28900	+		+	8	0.09
0.6448	-0.28760	+	0.1375		7	0.06
0.6112		+	0.1807	+	8	0.03
		+	0.3092		5	0.03
0.6625	-0.27210	+	0.1540	+	9	0.02
		+			4	0.02

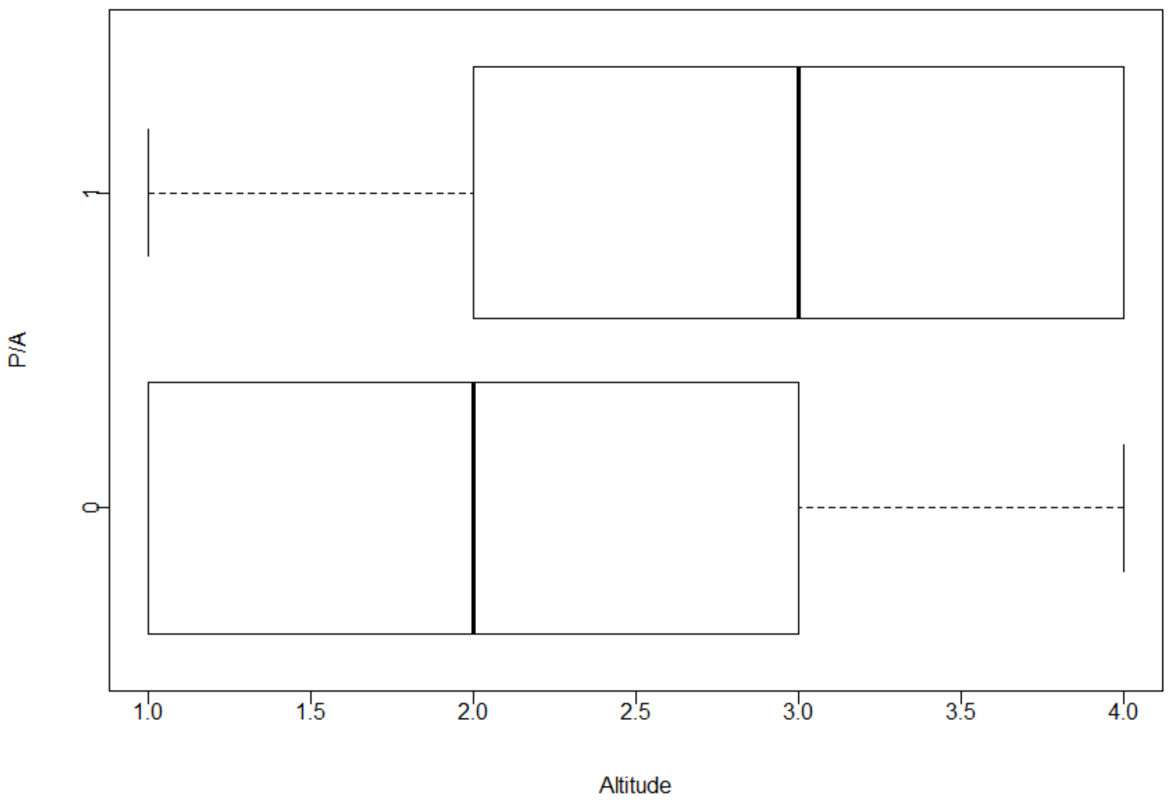

Figure S2 - Variation of the presence of the Príncipe thrush with altitude. *Boxplot representing the variation of the presence of the species with altitude. Absence (0); Presence (1). Lower altitude category (1) to the highest altitude (4).*

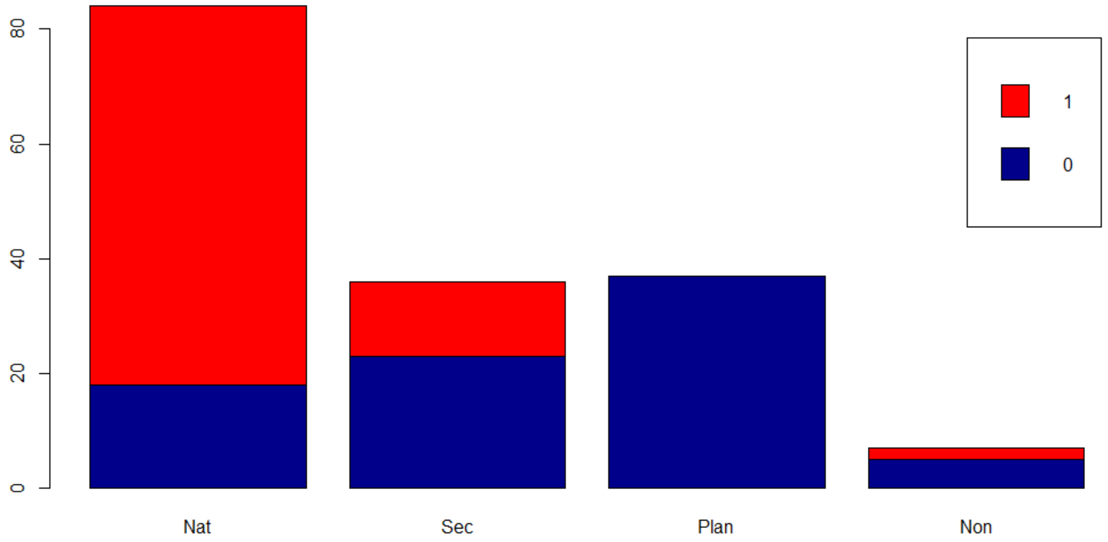

Figure S3 - Variation of the presence of the Príncipe thrush with land-use. *Stacked plots representing the variation of the presence of the species with land-use. Absence (0); Presence (1). Native forest (Nat); Secondary forest (Sec); Shade plantation (Plan); Non forested (Non)*

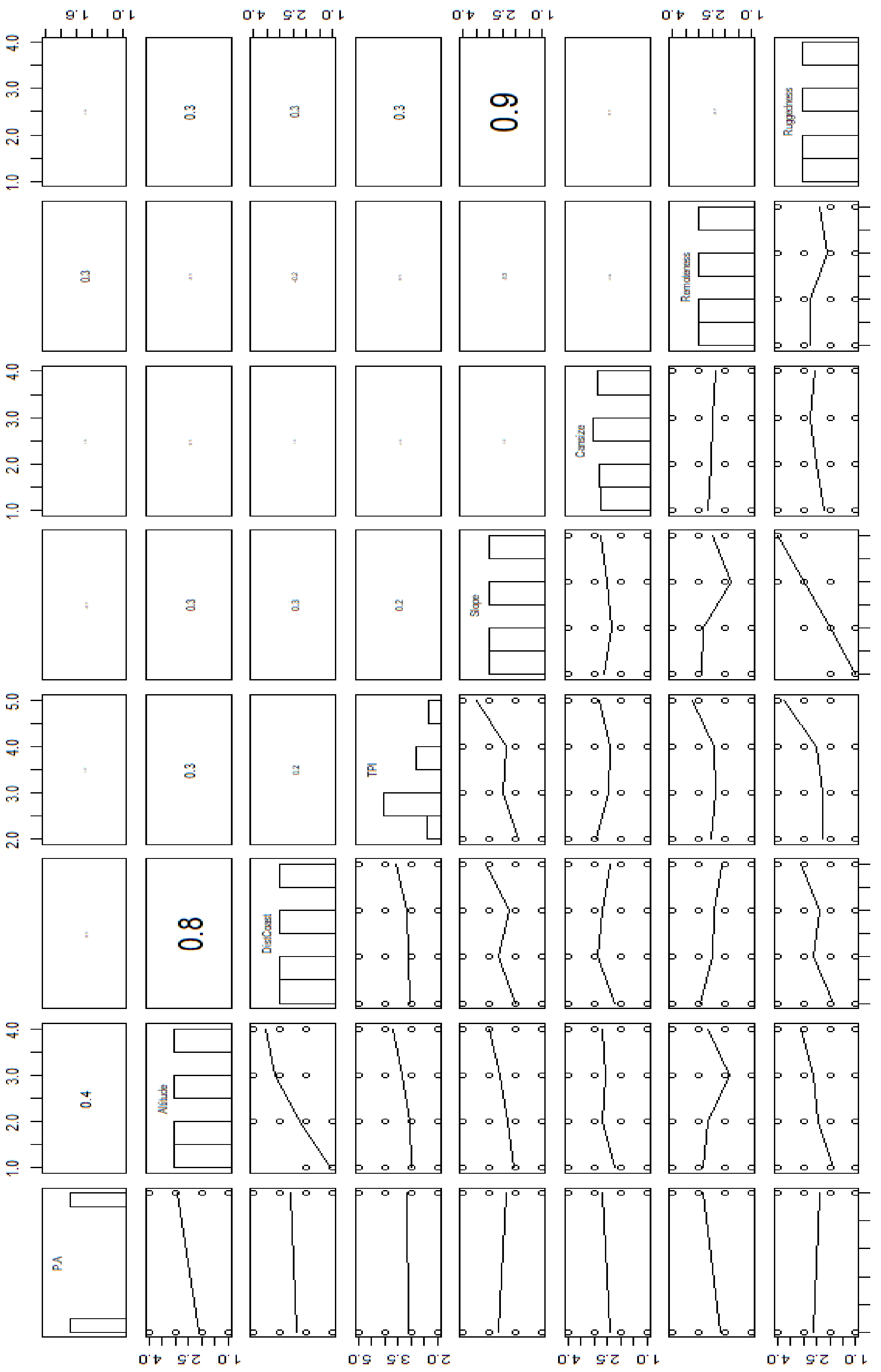

Figure S4 - Spearman rank correlation coefficient panel. Between environmental variables and presence and absence of the Príncipe thrush for the native forest in the Príncipe island.

Table S2 - Best models for the Príncipe thrush landscape environmental associations in the native forest. *Models are ranked based on the Akaike Information Criterion for the bootstrapped weights corrected for small sample sizes (AICc). Each line represents a model. Weight is the number of trials when the response is the proportion of successes.*

Altitude	Proportion of large canopies	Remoteness	Slope	TPI	Df	Bootstrapped Weights
1.0240		0.6700	-0.44860		4	0.25
1.1550		0.7962	-0.39150	+	7	0.23
1.0490		0.8651		+	6	0.13
0.9898	0.2289	0.6874	-0.41560		5	0.11
0.8490	0.2842	0.7413			4	0.08
1.0160	0.2036	0.8619		+	7	0.07
0.8883		0.7382			3	0.07
1.1250	0.1545	0.8015	-0.36830	+	8	0.04

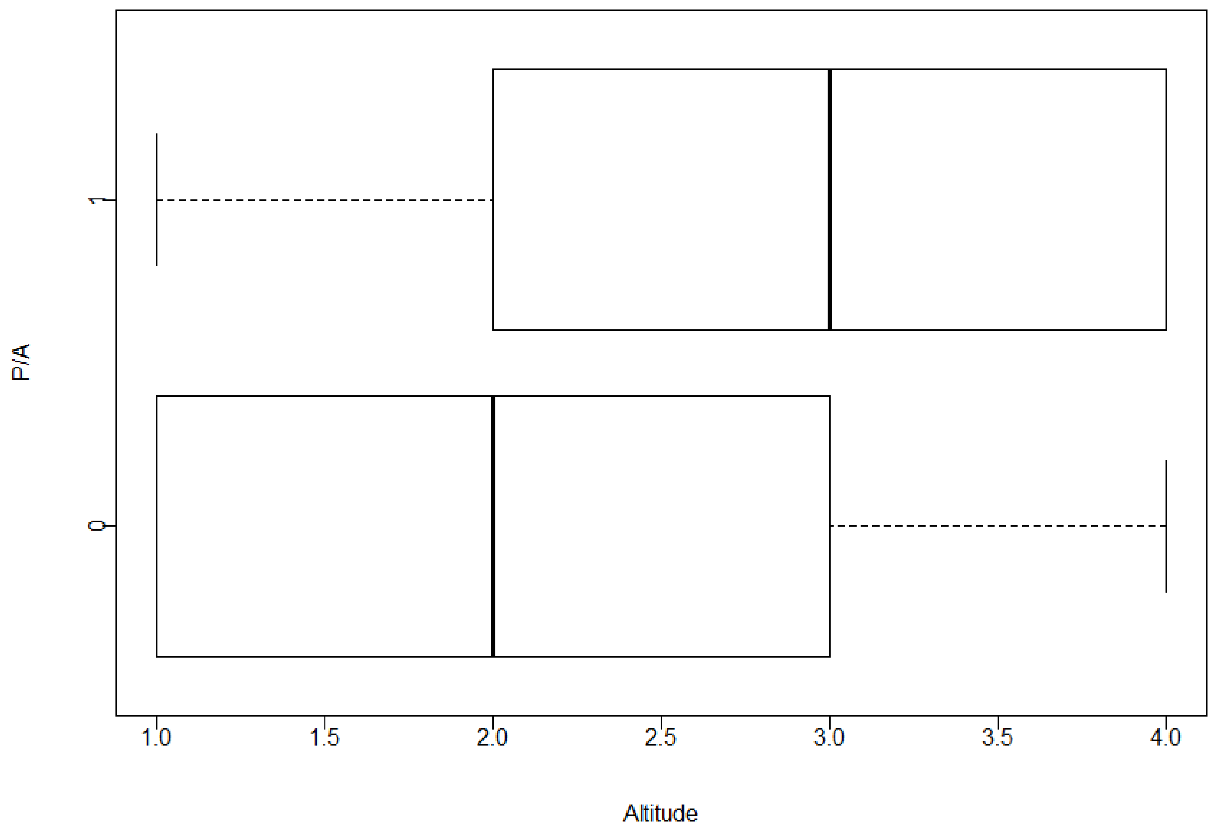

Figure S5 - Variation of the presence of the Príncipe thrush with altitude in native forest. *Boxplot representing the variation of the presence of the species with altitude. Absence (0); Presence (1). Lower altitude category (1) to the highest altitude (4).*

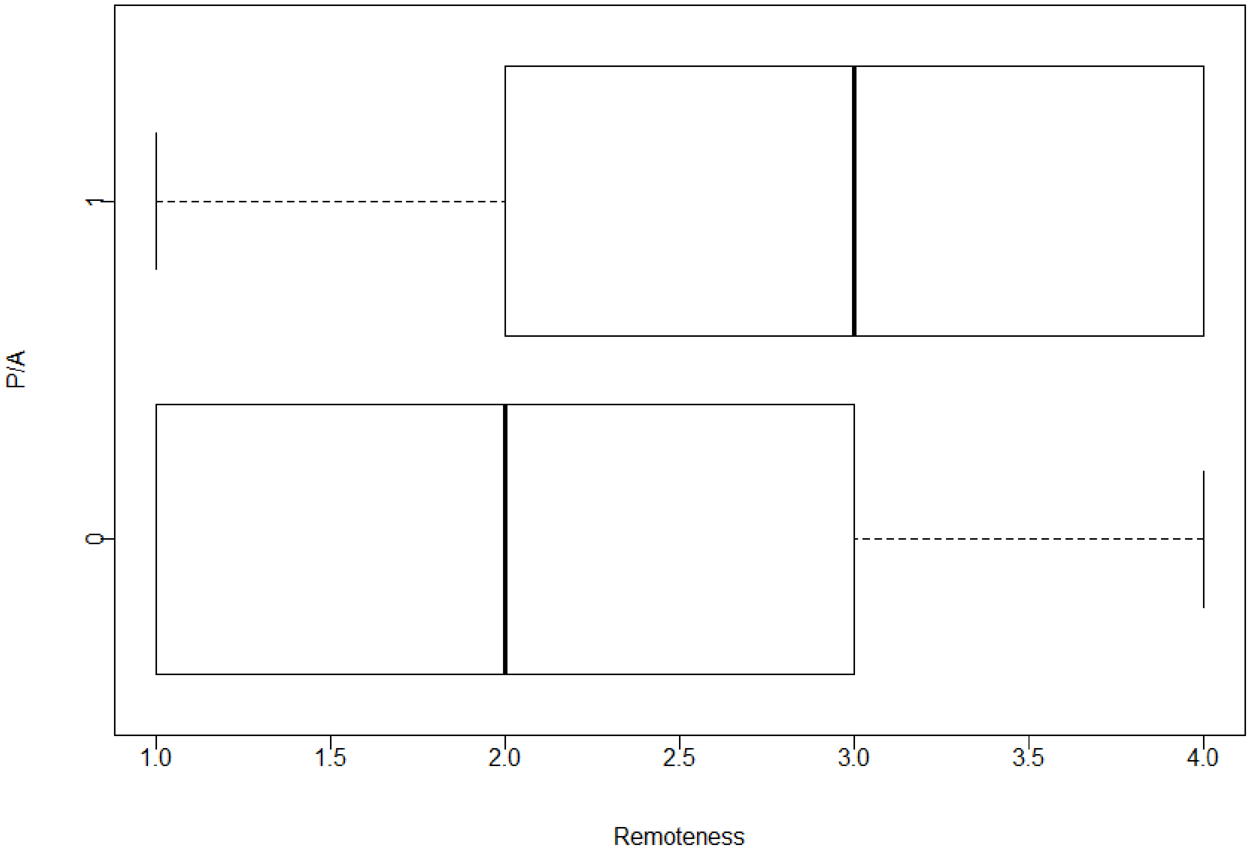

Figure S6 - Variation of the presence of the Príncipe thrush with remoteness in native forest. *Boxplot representing the variation of the presence of the species with remoteness. Absence (0); Presence (1). Low remoteness category (1) to the highest remoteness (4).*

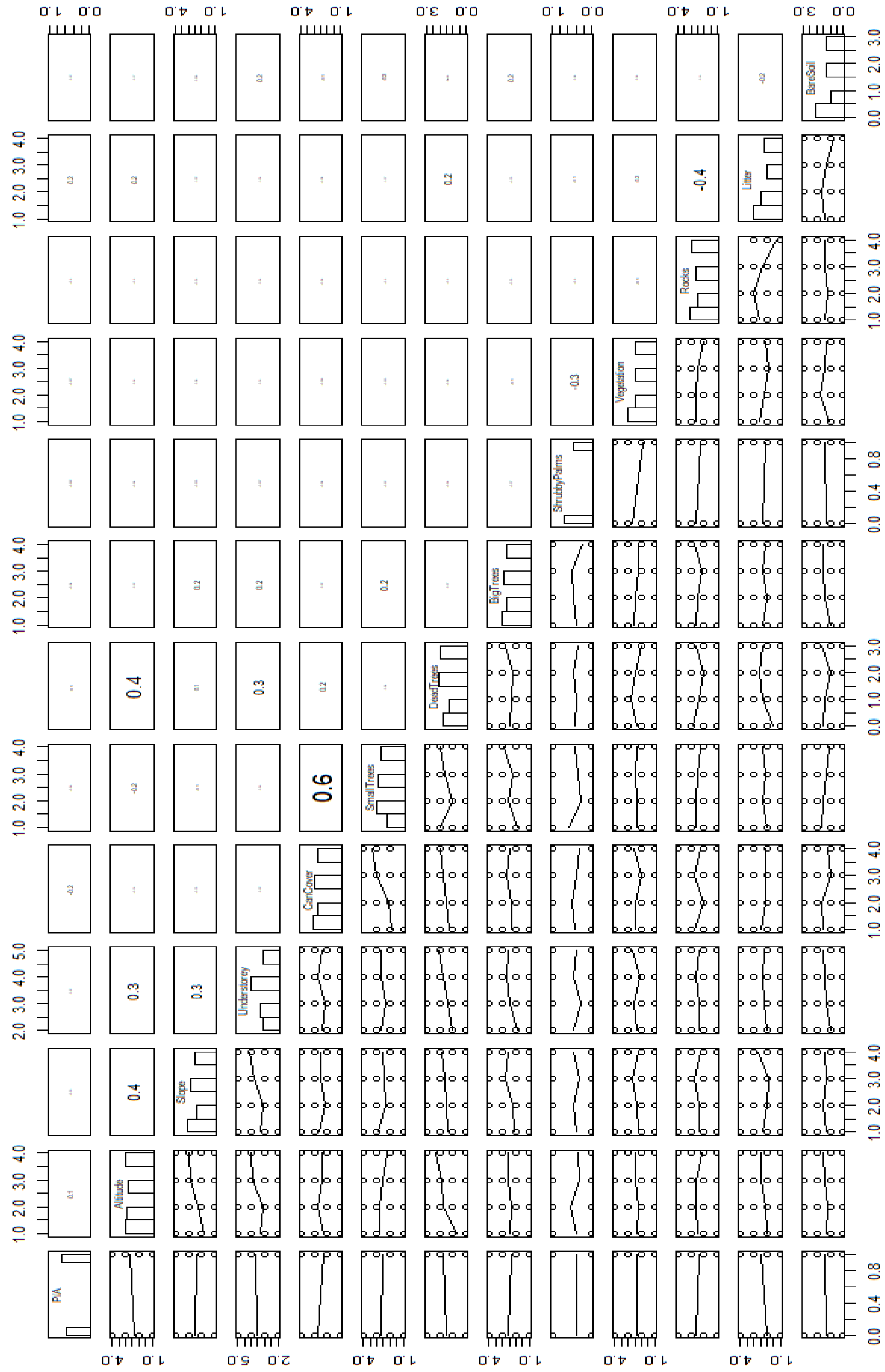

Figure S7 - Spearman rank correlation coefficient panel. Between local environmental variables and presence and absence of the Príncipe thrush.

Table S3 - Best models for the Príncipe thrush local environmental associations. *Models are ranked based on the Akaike Information Criterion corrected for small sample sizes (AICc). Each line represents a model. Altitude (1); % of bare soil (2); Number of large trees (3); Canopy cover (4); Number of dead trees (5); % of soil covered by forest litter (6); % of soil covered in rock (7); Number of shrubby palms (8); Slope (9); Understorey density (10); % of soil covered with vegetation (11). Weight is the number of trials when the response is the proportion of successes.*

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Df**	**Bootstrapped Weights**
0.2917			-0.3351								3	**0.08**
0.3322			-0.3532					-0.1169			4	**0.03**
			-0.3486								2	**0.03**
0.2874			-0.3308		0.0977						4	**0.02**
0.2833			-0.3347			-0.0586					4	**0.02**
0.3073											2	**0.02**
0.2924	-0.0899		-0.3455								4	**0.02**
			-0.3772	0.1810							3	**0.02**
0.2947			-0.3287				0.1458				4	**0.02**
0.2887		0.0574	-0.3390								4	**0.02**
0.2844			-0.3344						0.0329		4	**0.02**

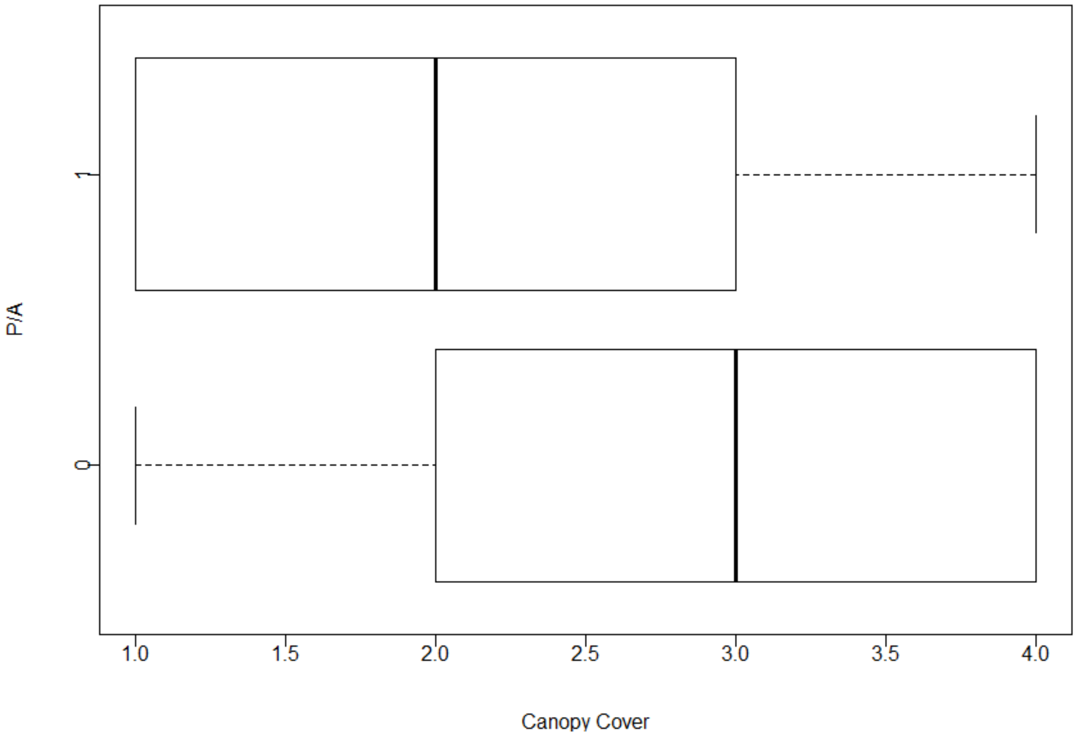

Figure S8 - Variation of the presence of the Príncipe thrush with canopy cover. *Boxplot representing the variation of the presence of the species with canopy cover. Absence (0); Presence (1). Low canopy cover category (1) to the highest canopy cover (4).*

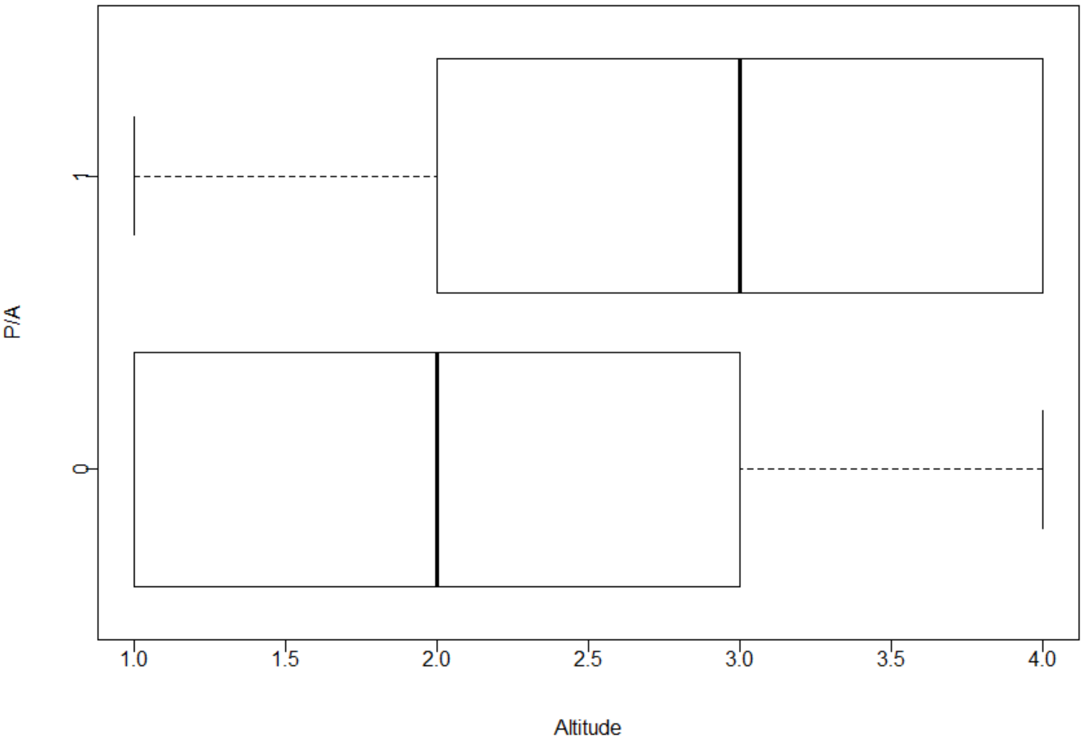

Figure S9 - Variation of the presence of the Príncipe thrush with altitude. *Boxplot representing the variation of the presence of the species with altitude. Absence (0); Presence (1). Lower altitude category (1) to the highest altitude (4).*

Figure S10 - Spearman rank correlation coefficient panel. Between environmental variables and presence and absence of the Obô Giant Snail for the entire Príncipe island.

__Table S4 - Top models for the Obô Giant Snail landscape associations at island scale.__ Models are ranked based on the Akaike Information Criterion for the bootstrapped weights corrected for small sample sizes (AICc). Each line represents a model. Weight is the number of trials when the response is the proportion of successes.

Altitude	Land-use	Ruggedness	TPI	Df	Bootstrapped Weights
0.5486	+	0.2310	+	10	0.35
0. 5118	+			5	0.28
0.6014	+		+	9	0.24
0.4769	+	0.1316		6	0.12

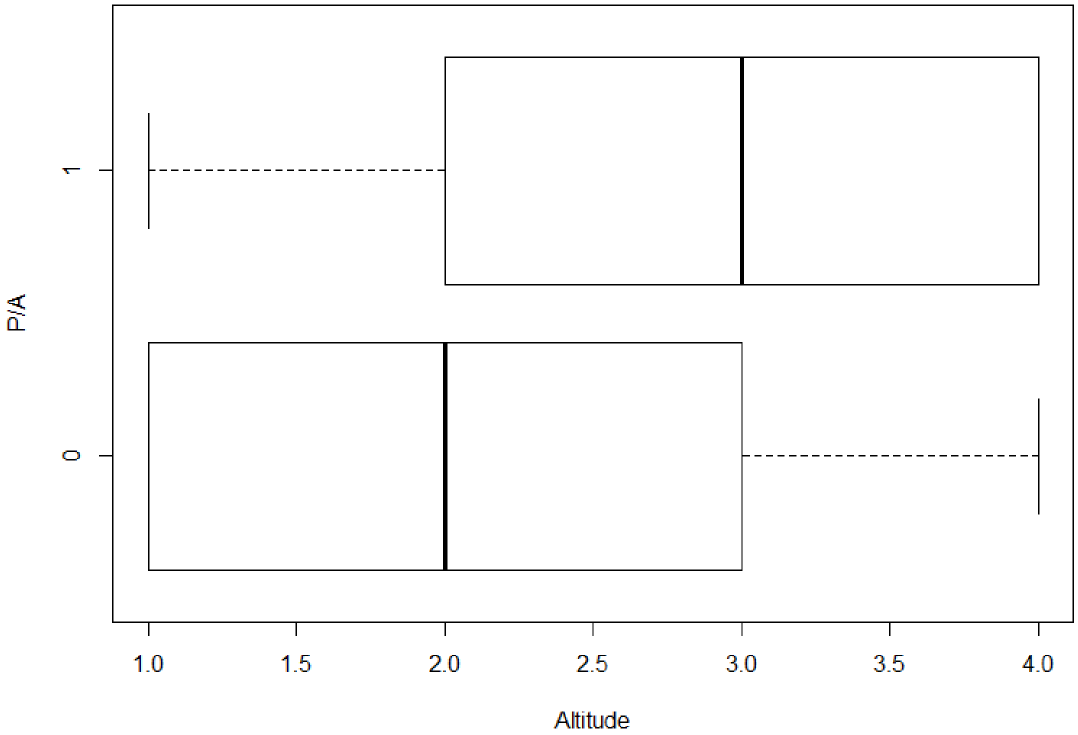

__Figure S11 -Variation of the presence of the Obô giant snail with altitude.__ Boxplot representing the variation of the presence of the species with altitude. Absence (0); Presence (1). Lower altitude category (1) to the highest altitude (4).

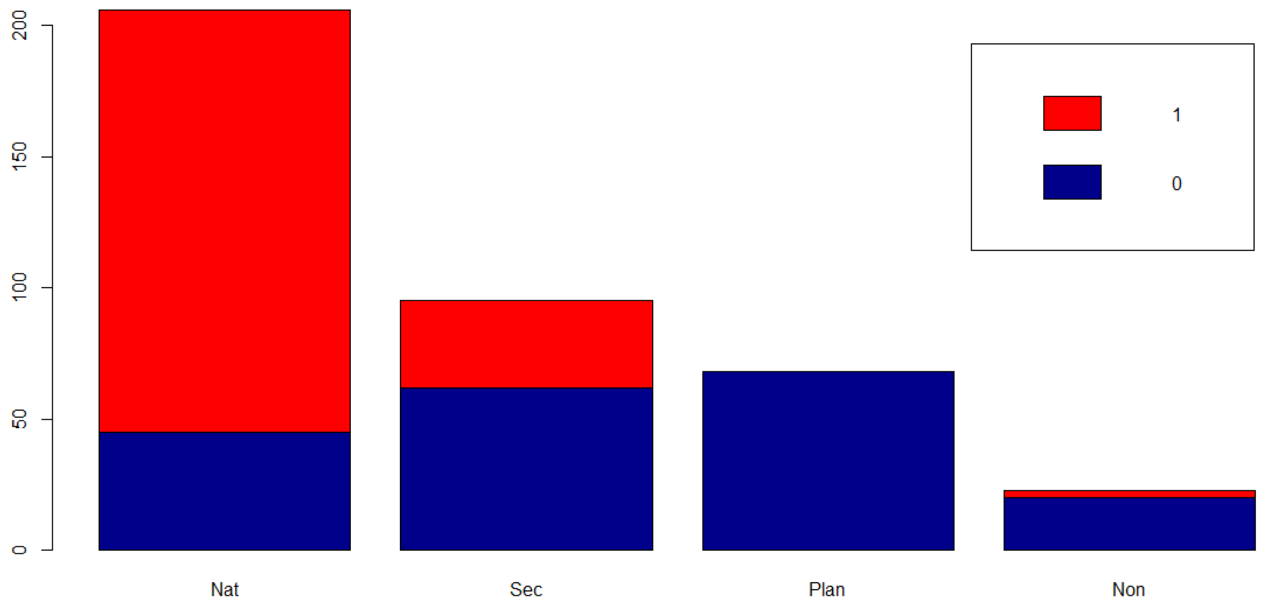

Figure S12 - Variation of the presence of the Obô giant snail with land-use. *Stacked plots representing the variation of the presence of the species with land-use. Absence (0); Presence (1). Native forest (Nat); Secondary forest (Sec); Shade plantation (Plan); Non forested (Non).*

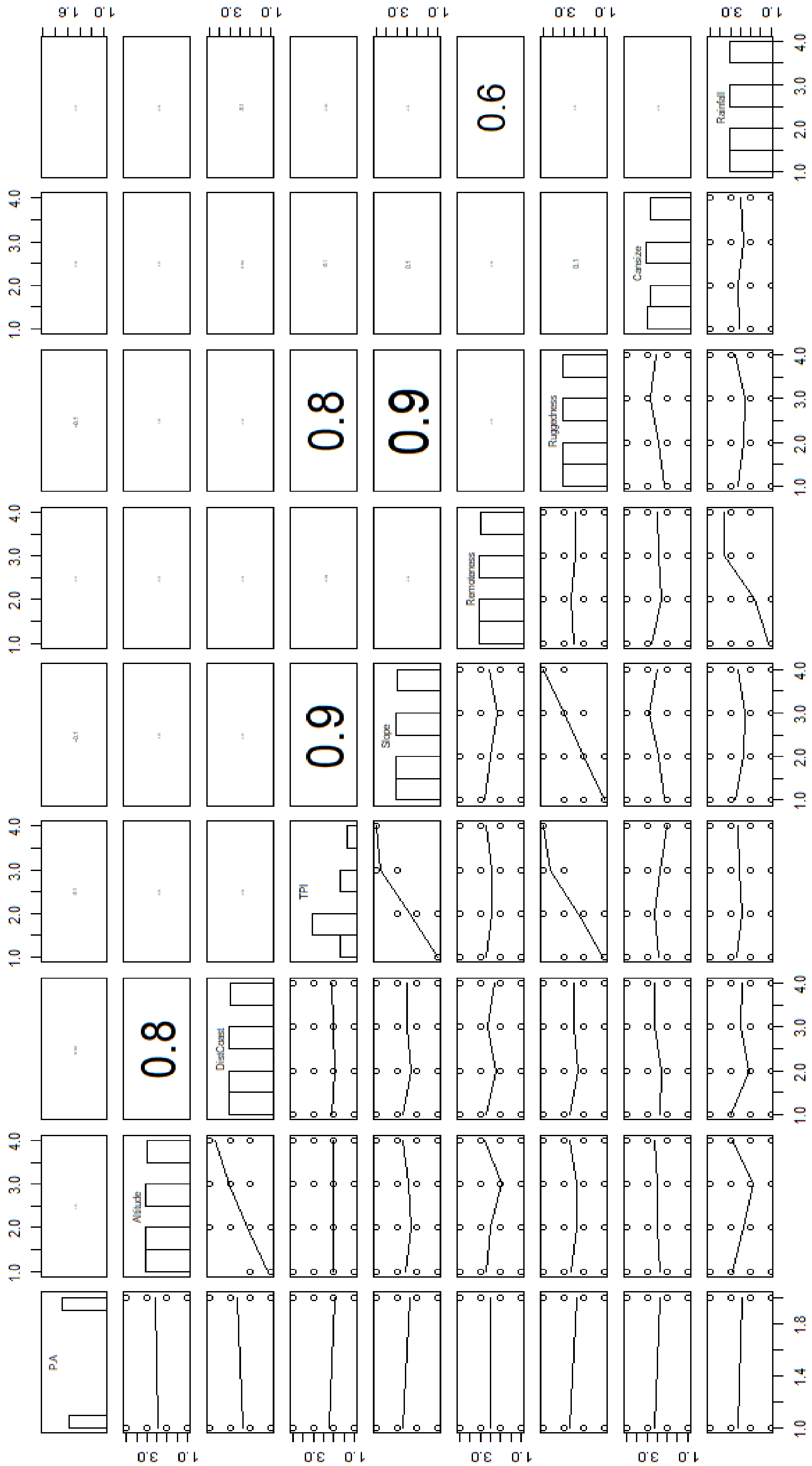

Figure S13 - Spearman rank correlation coefficient panel. Between environmental variables and presence and absence of the Obô Giant Snail for the native forest of the Príncipe island.

__Table S5 - Top models for the Obô Giant Snail landscape associations in the native forest.__ Models are ranked based on the Akaike Information Criterion for the bootstrapped weights corrected for small sample sizes (AICc). Each line represents a model. Weight is the number of trials when the response is the proportion of successes.

Proportion of large canopies	Distance to coast	Rainfall	TPI	Df	Bootstrapped Weights
-0.1955	0.2015		+	6	0.30
	0.1847		+	5	0.16
-0.1781			+	5	0.12
			+	4	0.09
-0.1970	0.1925	-0.07199	+	7	0.09
-0.1812		-0.9579	+	6	0.07
		-0.08978	+	5	0.04
	0.1761	-0.06790	+	6	0.04
-0.1563	0.1835			3	0.02
-0.1385				2	0.02

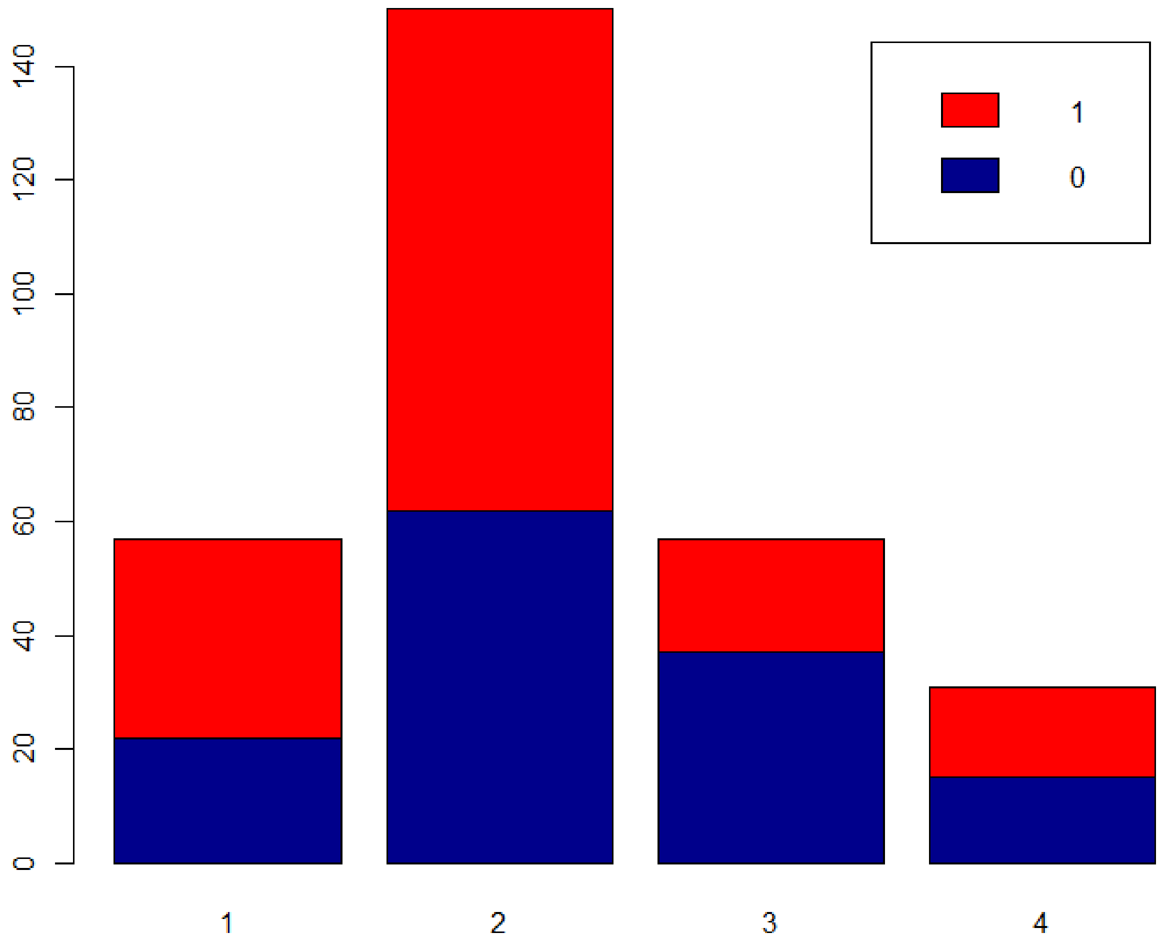

__Figure S14 - Variation of the presence of the Obô giant snail with TPI in native forest.__ Stacked plots representing the variation of the presence of the species with TPI. Absence (0); Presence (1). Flat plain areas and valleys (1); Middle slope (2); Upper slope (3); Ridges (4).

Section II: R scripts

This is an exemplificative R script, which was used to model the distribution of the Príncipe thrush and to assess habitat preferences, in this case, for native forest. All similar analysis were based on an equivalent script.

1) Exploratory analysis

```
# Import data
Tordos <- read.csv(file="C:/Users/guigu/Desktop/Tordo-do-príncipe/Work/Species distribution
model/With Bootstrap/Native forest/Data/import.r.csv", header = TRUE, sep = ";", dec = ",", fill =
TRUE)
names(tordos)

# Import packages
library(vegan)
library(caTools)
library(Amelia)

# Define environmental variables
ID <- tordos$ï..Folha
Envvar <- tordos[,5:13]

# Define categorical variables
envvar$TPI <- as.factor(envvar$TPI)
tordos$P.A <- as.factor(tordos$P.A)

# Evaluate outliers with Cleveland dotplot, only for continuous variables
dotchart(envvar$Altitude, main = "Altitude", group = NULL)
dotchart(envvar$DistCoast, main = "Distance to coast", group = NULL)
dotchart(envvar$Slope, main = "Slope", group = NULL)
dotchart(envvar$Remoteness, main = "Remoteness", group = NULL)
dotchart(envvar$Ruggedness, main = "Ruggedness", group = NULL)
dotchart(envvar$CanSizeGaus, main = " Proportion of large canopies ", group = NULL)

# Analyse outliers with boxplot, only for continuous variables
boxplot(envvar$Altitude, data = envvar, main = "Altitude")
boxplot(envvar$DistCoast, data = envvar, main = "DistCoast")
boxplot(envvar$Slope, data = envvar, main = "Slope")
boxplot(envvar$Remoteness, data = envvar, main = "Remoteness")
boxplot(envvar$Ruggedness, data = envvar, main = "Ruggedness")
boxplot(envvar$CanSizeGaus, data = envvar, main = " Proportion of large canopies ")
# Evaluate multicollinearity with Spearman’s rank correlation coefficient

Z <- cbind(tordos$P.A ,tordos$Altitude ,tordos$DistCoast ,tordos$TPI250m2
,tordos$Slope,tordos$Remoteness,tordos$Ruggedness,tordos$CanSize,tordos$CanSizeGaus,tordos$C
anSize33)
```

```
colnames(z)<-c("P.A","Altitude","DistCoast","TPI","Slope","Remoteness","Ruggedness",
"Cansize","CansizeGaus","Cansize33")
panel.smooth2<-function (x, y, col = par("col"), bg = NA, pch = par("pch"),
                        cex = 1, col.smooth = "red", span = 2/3, iter = 3, ...)
{
  points(x, y, pch = pch, col = col, bg = bg, cex = cex)
  ok <- is.finite(x) & is.finite(y)
  if (any(ok))
    lines(stats::lowess(x[ok], y[ok], f = span, iter = iter),
          col = 1, ...)
}
panel.cor<-function(x, y, digits=1, prefix="", cex.cor)
{
  usr <- par("usr"); on.exit(par(usr))
  par(usr = c(0, 1, 0, 1))
  r1=cor(x,y,use="pairwise.complete.obs")
  r <- abs(cor(x, y,use="pairwise.complete.obs"))
  txt <- format(c(r1, 0.123456789), digits=digits)[1]
  txt <- paste(prefix, txt, sep="")
  if(missing(cex.cor)) cex <- 0.9/strwidth(txt)
  text(0.5, 0.5, txt, cex = cex * r*3)
}
panel.hist<-function(x, ...)
{
  usr <- par("usr"); on.exit(par(usr))
  par(usr = c(usr[1:2], 0, 1.5) )
  h <- hist(x, plot = FALSE)
  breaks <- h$breaks; nB <- length(breaks)
  y <- h$counts; y <- y/max(y)
  rect(breaks[-nB], 0, breaks[-1], y, col="white", ...)
}
pairs(z,lower.panel=panel.smooth2,upper.panel=panel.cor,diag.panel=panel.hist)
```

 # Evaluate which variables have NA values

```
missmap(envvar, main = "Missing values vs observed")
```

 # Mantel test

```
points.dists <- dist(cbind(tordos$Longitude, tordos$Latitude))
PA.dists <- dist(cbind(tordos$P.A))
as.matrix(points.dists)[1:5, 1:5]
as.matrix(PA.dists)[1:5, 1:5]
library(ade4)
mantel.rtest(points.dists, PA.dists, nrepet = 9999)
```

2) Generalized linear model with binomial distribution and model validation

 # Import data

```
Tordos <- read.csv(file="C:/Users/guigu/Desktop/Tordo-do-príncipe/Work/Species distribution model/With Bootstrap/Native forest/Data/import.r.csv", header = TRUE, sep = ";", dec = ",", fill = TRUE)
names(tordos)

# Import packages
library(MASS)
library(AER)
library(VGAM)
library(MuMIn)
library(tidyverse)
library(caret)
library(car)
library(pscl)
library(ROCR)
library(InformationValue)
library(raster)

# Define categorical variables
tordos$TPI <- as.factor(tordos$TPI)
tordos$P.A <- as.factor(tordos$P.A)

# Build a logistic model
options(na.action = "na.fail")
set.seed(101)
fm<- glm ( P.A ~ Altitude  + CanSizeGaus + TPI + Slope + Remoteness , family = "binomial", data = tordos)

# Select best model
fml <- lapply(dredge(fm, eval = FALSE), eval)
am <- model.avg(fml)
Weights(am) <- bootWeights(am, data = tordos, R = 1000)
summary(am)

#RVI and VIF
sw(am)
vif(fm)

#Best model
modtordo <- glm ( P.A ~ Altitude + Remoteness + Slope , family = "binomial", data = tordos)

#Goodness of fit Pseudo R^2 – McFadden's Index
library(pscl)
pR2(modtordo)

#ROC curve and AUC
predTurxan <- predict(modtordo, newdata = tordos, type = "response")
ROCRpredTurxan <- prediction(predTurxan, modtordo $P.A)
```

```
ROCRperfTurxan <- performance(ROCRpredTurxan, 'tpr','fpr')
plot(ROCRperfTurxan, colorize = TRUE, text.adj = c(-0.2,1.7))
auc <- performance(ROCRpredTurxan,measure = "auc")
auc <- auc@y.values[[1]]
auc
```

 # Reclassification of the rasters to match to 4 categories created

```
Altitude = raster("C:/Users/guigu/Desktop/Tordo-do-príncipe/Work/Species distribution model/With Bootstrap/Native forest/Cut rasters/Altitude.tif")
plot(Altitude)
a<- c(0, 153, 1,153,268,2,268,448,3,448,9999,4)
reclassalt<- matrix(a, ncol=3, byrow=TRUE)
reclassalt
rca<-reclassify(Altitude, reclassalt, include.lowest=TRUE)
plot(rca)
writeRaster(rca,"Altitude.tif")

Remoteness = raster("C:/Users/guigu/Desktop/Tordo-do-príncipe/Work/Species distribution model/With Bootstrap/Native forest/Cut rasters/Remoteness.tif")
plot(Remoteness)
r<- c(0, 2.51556, 1, 2.51556, 2.77763, 2, 2.77763, 2.92627, 3, 2.92627, 999999, 4)
reclassrem<- matrix(r, ncol=3, byrow=TRUE)
reclassrem
rce<-reclassify(Remoteness,reclassrem, include.lowest=TRUE)
plot(rce)
writeRaster(rce,"Remoteness.tif")

Slope = raster("C:/Users/guigu/Desktop/Tordo-do-príncipe/Work/Species distribution model/With Bootstrap/Native forest/Cut rasters/Slope.tif")
plot(Slope)
r<- c(0, 8.54924, 1, 8.54924, 13.44751, 2, 13.44751, 17.05057, 3, 17.05057, 999999, 4)
reclassrem<- matrix(r, ncol=3, byrow=TRUE)
reclassrem
rce<-reclassify(Slope,reclassrem, include.lowest=TRUE)
plot(rce)
writeRaster(rce,"Slope.tif")
```

#Import rasters

```
Altitude = raster("C:/Users/guigu/Desktop/Tordo-do-príncipe/Work/Species distribution model/With Bootstrap/Native forest/Rasters/Altitude.tif")
par(mfrow=c(1,1),mar=c(2,4,2,4))
plot(Altitude)
Remoteness = raster("C:/Users/guigu/Desktop/Tordo-do-príncipe/Work/Species distribution model/With Bootstrap/Native forest/Rasters/Remoteness.tif")
plot(Remoteness)
Slope = raster("C:/Users/guigu/Desktop/Tordo-do-príncipe/Work/Species distribution model/With Bootstrap/Native forest/Rasters/Slope.tif")
plot(Slope)
```

```
# Stack rasters
rasters <- stack(Altitude,Remoteness,Slope,  bands=NULL)
names(rasters)
plot(rasters)

# Create potential distribution map
ptordo <- predict(rasters, modtordo, type="response")
plot(ptordo, xaxt='n', yaxt='n', main = "Turdus xanthorynchos")
writeRaster(ptordo, 'ptordoNF.tif', overwrite=TRUE)

# Find optimal cutoff
trainpred <- predict(modtordo, tordos, type = "response")
traincutt <- optimalCutoff(actuals=tordos$P.A , predictedScores=trainpred, optimiseFor="Both",
returnDiagnostics=TRUE)# Accuracy = (TP+TN)/(TP+TN+FP+FN)
traincutt

# Reclassification of the map into a binary map
r<- c(0, 0.57145, 0, 0.57145,100, 1)
reclassrem<- matrix(r, ncol=3, byrow=TRUE)
reclassrem
rce<-reclassify(ptordo,reclassrem, include.lowest=TRUE)
plot(rce)
writeRaster(rce,"bintordo.tif")
```

3) *Output figures*

```
# Figure S2
boxplot(Altitude~P.A, horizontal=TRUE,xlab = "Altitude",
        ylab = "P/A", data = tordos)
# Figure S3
lu<- read.csv(file = "C:/Users/guigu/Desktop/lufig1.csv", header = TRUE, sep = ";", dec = ",", fill =
TRUE)
names(lu)
lu$Landuse1 <- factor(lu$Landuse, levels = c("Nat", "Sec", "Plan", "Non"))
lu$Landuse1
counts <- table(lu$ï..PA, lu$Landuse1)
counts
barplot(counts,col=c("darkblue","red"),
        legend = rownames(counts))
# Figures S5 and S6
boxplot(Altitude~P.A, horizontal=TRUE,xlab = "Altitude",
        ylab = "P/A", data = tordos)
boxplot(Remoteness~P.A, horizontal=TRUE,xlab = "Remoteness",
        ylab = "P/A", data = tordos)

# Figures S8 and S9
boxplot(CanCover~PA,horizontal=TRUE,xlab = "Canopy Cover",
```

```
        ylab = "P/A", data = tordos)
boxplot(Altitude~PA,horizontal=TRUE,xlab = "Altitude",
        ylab = "P/A", data = tordos)
```