The first comprehensive survey of habitat suitability and population size for the endangered Grande Comoro Scops Owl (Otus pauliani)*: implications for its conservation*

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Journal of Ornithology

ISSN 2193-7192
Volume 160
Number 4

J Ornithol (2019) 160:1121-1132
DOI 10.1007/s10336-019-01689-0

Journal of Ornithology (2019) 160:1121–1132
https://doi.org/10.1007/s10336-019-01689-0

ORIGINAL ARTICLE

The first comprehensive survey of habitat suitability and population size for the endangered Grande Comoro Scops Owl (*Otus pauliani*): implications for its conservation

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Received: 19 October 2018 / Revised: 6 June 2019 / Accepted: 15 July 2019 / Published online: 24 July 2019

Abstract

The Grande Comoro Scops Owl (*Otus pauliani*) is an endangered, rare and elusive owl species restricted to the Karthala forest, Grande Comore. This scops owl species is listed among the most threatened animals of the Comoro archipelago. The species is subjected to strong anthropogenic pressures causing a high rate of habitat loss. Little is known about the species' population size, habitat suitability and geographic distribution, making the establishment of relevant conservation strategies difficult. In this study we assessed the population density and abundance of the species using the distance sampling approach through (1) the conventional distance sampling method (CDS), and (2) density surface modeling (DSM). Based on DSM, we applied a species distribution modeling method to investigate habitat suitability and geographic distribution of the species to close this knowledge gap. Average population density was estimated to be ca. 27 individuals km^{-2}. We estimated a global population size of 3452 individuals. Our DSM suggested that the Grande Comoro Scops Owl has a very limited distribution (133 km^2), restricted to high elevations in Grande Comore's remaining natural forests (between 800 and 2000 m altitude). However, the currently high level of habitat disturbance and conversion of natural forest into agricultural land could render the species vulnerable to extinction. To ensure the viability of the species and the biodiversity of the Karthala forest, we suggest (1) restoring forest and securing corridors in the Karthala remnant forest; (2) avoiding the conversion of secondary forest into agricultural land, and using existing agroforestry for plantation development; (3) involving a broad community of local individuals and entities in their conservation and management.

Keywords Comoro Islands · Density surface modeling · Habitat loss · Karthala forest · Population size · Species distribution modeling

Zusammenfassung

Habitat-Eignung und Populationsgröße: erste umfassende Untersuchung bei der bedrohten Komoren-Zwergohreule (*Otus pauliani*) und Schlussfolgerungen für ihren Schutz.

Die Komoren-Zwergohreule (*Otus pauliani*) ist eine seltene, bedrohte und schwer aufzuspürende Vogelart, die nur in den Wäldern an den Hängen des Karthala auf den Komoren vorkommt. Sie wird als eine der am meisten bedrohten Tierarten der Komoren-Inselgruppe geführt. Die Art ist einer immensen anthropogenen Belastung ausgesetzt, die mit einem schnellen Verlust an Lebensraum einhergeht. Das Aufsetzen wirksamer Strategien zu ihrem Schutz wird dadurch erschwert, dass

Communicated by T. Gottschalk.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10336-019-01689-0) contains supplementary material, which is available to authorized users.

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nur wenig über die Populationsgrößen, die geographische Verteilung und die Kriterien für geeignete Habitate für diese Art bekannt ist. In unserer Untersuchung bewerteten wir die Populationsdichte und das Vorkommen der Art anhand von Stichprobenverfahren auf Distanz: (1) der konventionellen distance sampling Methode (CDS) und (2) dem density surface modelling (DSM). Auf der Basis der DSM wandten wir ein Spezies-Verbreitungs-Modell (SDM) an, um mit dessen Hilfe die Eignung eines Habitats sowie die geographische Verbreitung der Art zu untersuchen. Die mittlere Populationsdichte schätzten wir auf etwa 27 Individuen pro Quadratmeter, die gesamte Population auf 3452 Tiere. Unser DSM legte nahe, dass die Verbreitung der Komoren-Zwergohreule auf 133 Quadratkilometer außerordentlich klein und auf die Hochlagen (zwischen 800 und 2.000 m Höhe) der Urwälder auf der Komoren-Hauptinsel begrenzt ist. Aber das in letzter Zeit starke Ausmaß an Störungen im Habitat sowie die Konversion von natürlichen Wäldern in landwirtschaftlich genutzte Flächen könnte die Art einer Ausrottung nahebringen. Zum ihrem Erhalt und dem der Biodiversität des Karthala-Forstes schlagen wir folgende Maßnahmen vor: (1) Aufforsten der Wälder und Anlegen sicherer Korridore im Karthala-Forst; (2) keine weitere Umwandlung der Sekundärwälder in landwirtschaftlich genutzte Flächen sowie die Anwendung von Methoden der früheren Agroforstwirtschaft bei der Entwicklung der Plantagen; (3) Einbeziehung möglichst vieler Menschen und Einrichtungen in den Kommunen, wenn Naturschutz-Aktionen durchgeführt werden sollen.

Introduction

Human-induced habitat changes such as habitat degradation, fragmentation and habitat loss are considered some of the principal threats to biodiversity and wildlife survival (Ripple et al. 2016). These different types of habitat change have been identified as the main drivers of biodiversity extinction (Brook et al. 2008).

Insular animals are among the fauna most threatened by human-induced habitat change in the short-term (Brooks et al. 1997, 2002). Insular fauna are characterized by lower species richness and endemic species and often have small populations, making them more susceptible to demographic stochasticity and an increased risk of extinction (Donlan and Wilcox 2008). Moreover, their ability to disperse in response to habitat degradation is severely limited because of their geographic isolation (Paulay 1994). As a consequence, many species have gone extinct on islands worldwide, especially on oceanic islands (Gaston et al. 2003).

Understanding the suitability of habitats and the ecological requirements of insular species, especially those living in changing habitats, are essential to gaining insight into how these species respond to habitat fragmentation. This information is of paramount importance to establishing reliable conservation plans for these species (Ibouroi et al. 2018b).

The Comoro archipelago is a biodiversity hotspot due to its high level of endemism (Myers et al. 2000). However, this archipelago is also one of the poorest nations in the world (Bourgoin et al. 2017), and about 72% of the population directly depends on forest resources for their subsistence (Bourgoin et al. 2017; Fisher and Christopher 2007). Because of this natural resource dependence, natural habitats on these islands have undergone dramatic change, and the islands are facing one of the highest rates of habitat loss worldwide {9.3% year^{-1} [Food and Agriculture Organization of the United Nations (FAO) 2010]}. According to Fisher and Christopher (2007), 60% of Comorians live below the poverty line and 49% are undernourished. Moreover, the island population is fast growing, which increases the need for more agricultural land and wood for construction (Elvidge et al. 2009). This intensive land use is the direct cause of the high rate of natural habitat loss recently observed in the archipelago (Ibouroi 2017; Ibouroi et al., unpublished data). In the Comoro Islands, all endemic forest-dwelling animals are mostly threatened by rapid habitat loss and are classified as either critically endangered or endangered by the International Union for Conservation of Nature (IUCN) due to their small population sizes and limited distributions (Daniel et al. 2016; Ibouroi et al. 2018a; b).

The Grande Comoro Scops Owl (*Otus Pauliani*) is one of the islands' endemic species most threatened by rapid habitat loss (Louette et al. 2004). This nocturnal raptor is confined to the mountainous and high elevation forest of Karthala, Grande Comore (Herremans et al. 1991). Grande Comoro Scops Owl has a very small range and occurs in only one forest on Grande Comore, where forest clearance for agriculture is increasing drastically (FAO 2010; Herremans et al. 1991). Yet, despite the fact that the Grande Comoro Scops Owl is of conservation concern (BirdLife International 2017a), little is known about its population size, habitat requirements or geographic distribution. The last population size and geographic distribution surveys of the species were reported 28 years ago, when the population was small [about 2000 individuals (Herremans et al. 1991)]. Because none of this species' habitat is officially protected (Ibouroi et al. 2018b), and a quickly increasing human population on the island is increasing anthropogenic pressure on it, there is a need to update our knowledge of its current population size and geographic distribution to establish relevant conservation plans.

This study represents the first comprehensive field survey of the Grande Comoro Scops Owl in over 28 years. We aimed to:

1. Estimate the average density of this species using a distance sampling method based on conventional distance sampling (CDS).
2. Estimate the global population size by using a density surface modeling (DSM) approach, which combines the detection function from (1) and a spatial model of the species' abundance to provide a spatially explicit population estimate.
3. Investigate the drivers of habitat suitability and the geographic distribution of the species using DSM.
4. Identify the pressures on the Grande Comoro Scops Owl based on our findings and recommend specific measures for its conservation.

Materials and methods

Study area

The four archipelagic Comoro islands (Grande Comore, Mohéli, Anjouan and Mayotte) are located in the Indian Ocean, midway between Madagascar and the eastern coast of Africa (11°20′S–12°25′S, 43°11′E–44°32′E). These islands have a volcanic origin, considerable topographic variation and have never been connected to the continental mainland or to each other (Goodman et al. 2010).

Grande Comore (the youngest island of the Comoro archipelago; Fig. 1) is located at the western extremity of the archipelago. It is dominated by large areas of basaltic lava flows from recent volcanic eruptions and has a massive, active volcano at its center (Michon 2016). It is characterized by its mountainous area, with the Karthala Massif (2361 m high) the highest point of the archipelago (Maugé et al. 1982; Michon 2016). The Karthala Massif harbors one of the largest remaining rainforests of the Comoro Islands (Michon 2016). The lower limit of the Karthala forest (600 m high in the southwest and up to 1000 m in the north and east) includes some degraded vegetation, under-planted forests and exotic thickets from abandoned cultivation. Above the lower limit (1000–2000 m), the Karthala Massif harbors intact, native mixed mountain forest with dense and humid vegetation (Hawlitschek et al. 2011).

Sampling site selection

The fieldwork took place from March to May 2018 and from February to March 2019 (wet season) in the Karthala forest. The selection of sampling sites was based on published data (Herremans et al. 1991; Louette et al. 2004). According to Herremans et al. (1991), the Grande Comoro Scops Owl is located on the northern, western and southern flanks of the Karthala forest (Herremans et al. 1991). These three locations were targeted for data collection. In addition, we selected the northeastern flank to achieve a representative sampling structure of the Karthala forest (Fig. 2). In these four locations, we sampled sites where a wide variety of habitats was available, from lowlands with degraded vegetation and under-planted forests (600 m high) to high-elevation forest (2000 m altitude). This range of habitats is necessary when sampling occurrence data to compare sites in which a species is present with sites from which it is absent.

Line transect surveys

Distance sampling data were recorded along line transects. Two to three parallel line transects of 800–2000 m in length were established by our team in each of the four selected locations (Fig. 2). In each location, transects were approximately 500–1000 m apart. The starting point of a transect was randomly selected and the transect followed the altitudinal gradient (Fig. 2).

Each transect was visited at least three times in total from 6:30 to 10:30 p.m. by two to three observers (Ibouroi et al. 2013; Meyler et al. 2012). In each forest, two to three teams worked simultaneously along the different transects during the surveys. In each survey, observers of each team walked slowly (0.5–1 km h^{-1}) with head lamps along each line transect (Ibouroi et al. 2013; Salmona et al. 2014). In between line transect surveys, at least one team member of each group changed team and transect (Buckland et al. 2004). During the surveys, when a scops owl was observed or heard at a distance of between 0 and 150 m from the center of the line transect, the estimated perpendicular distance and time of sighting were recorded. To ensure the consistency of the estimated perpendicular distance, all observers estimated this distance by ear or by direct observation. As we could not determine the exact perpendicular distances, all observations were categorized into predefined intervals (e.g. 0–10, 10–20, 20–30, …, 90–100 m) and the considered perpendicular distance was the midpoint of the interval. In the first 5–15 min after a presence had been recorded (visual or acoustic), we paid special attention to avoid double counting the same individual. We used the records of the Grande Comoro Scops Owl as presence points in the modeling process. Some random points were also recorded. For example, when owls were seen/heard after a recording along a transect had finished, and was a minimum of 1 km from any transect, occurrence data were also collected. These observations were considered to be independent of those along the transect. We recorded absence data of the species across the whole island (Fig. 1). These absence data were from different field surveys performed at night by different field teams who collected presence and absence data of the Comoro Islands's biodiversity including bats, birds and mammals from 2014 to 2019 (see Ibouroi et al. 2018b). During our

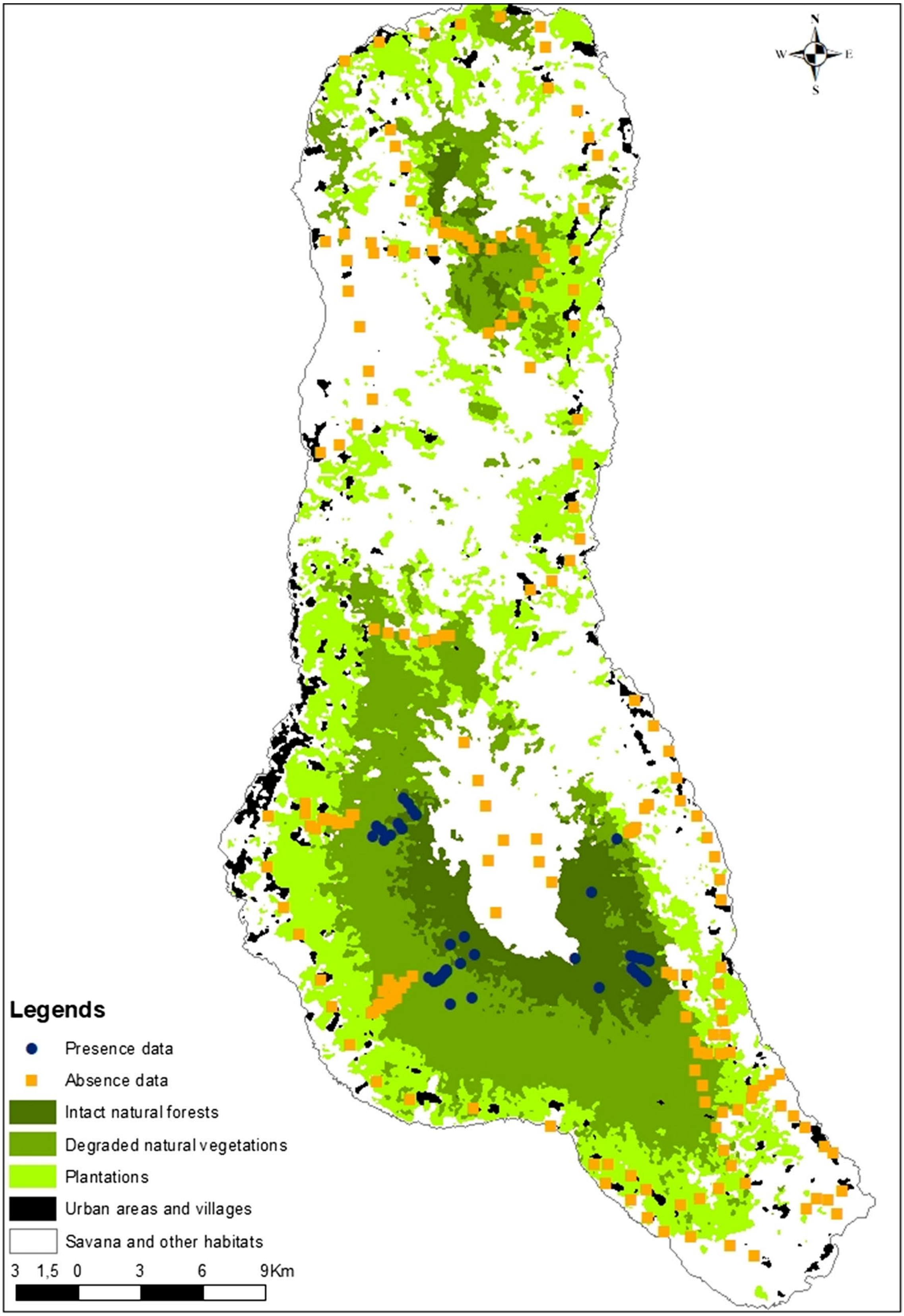

Fig. 1 Map showing the presence-absence data and the different types of habitat on Grande Comore

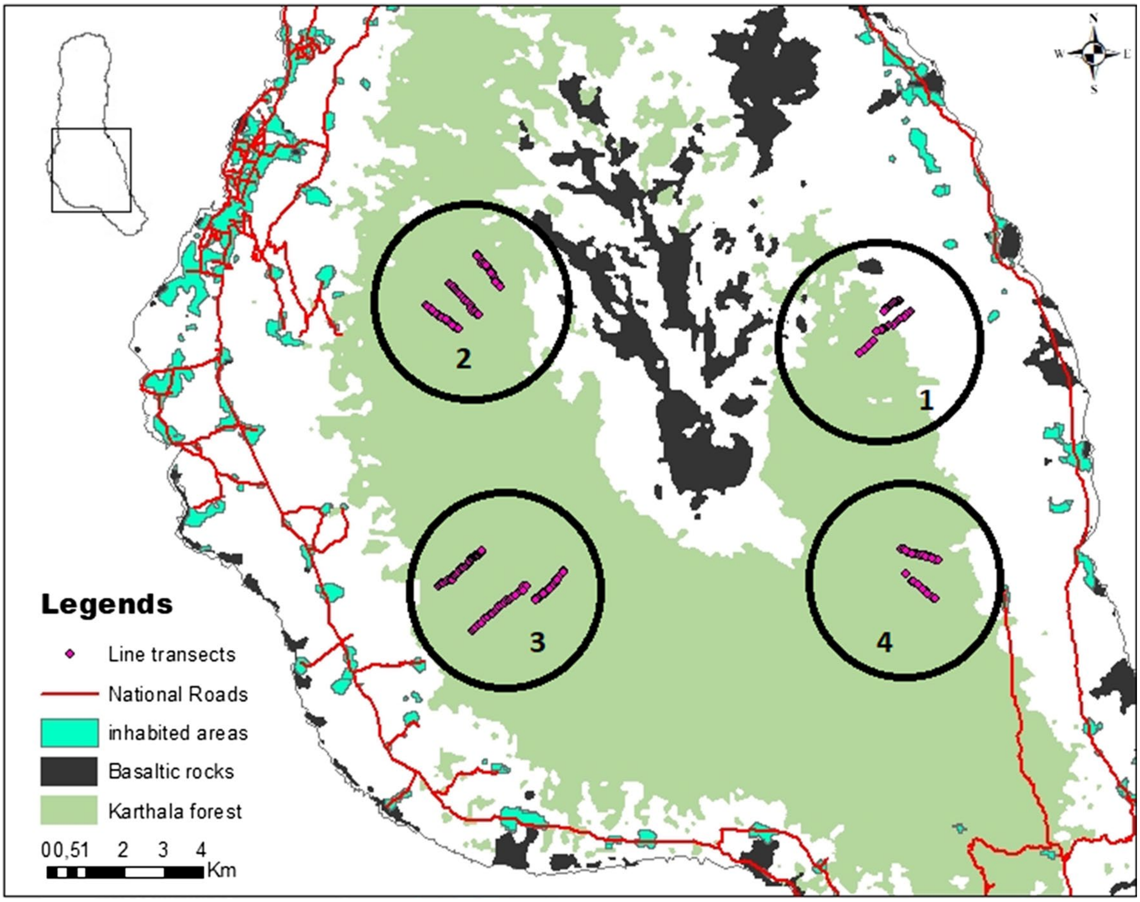

Fig. 2 Study areas; the Karthala forest includes both intact and degraded natural forest. *1* Idjinkoundzi, *2* Mvouni, *3* Gnoumbadjou, *4* Ntsinimoipanga

fieldwork, sampling was carried out on 1 night in the lowlands to collect absence data of the species. At high elevation, sampling (presence and absence data collection) was carried out at least three times because the targeted species is usually found in these areas. Presence and absence data were used in the modeling process.

Ecological predictors of habitat suitability and DSM

To perform species distribution modeling and DSM, we used habitat category predictors and elevation. To obtain percentage cover for four habitat/vegetation categories (intact natural forest, degraded natural vegetation, cultivated areas, urban areas), we extracted raw data as polygons from a georeferenced general layer map developed by Hawlitschek et al. (2011). We then calculated the percentage cover of each habitat/vegetation category in a 300-m radius around the center of each pixel of a 200-m resolution raster using Environmental R 3.3.2 (R Development Core Team 2016) and the package raster (Hawlitschek et al. 2011; Hijmans et al. 2019). Elevation was extracted from 220-m resolution digital elevation model data from the NASA Shuttle Topographic Mission (US Geological Survey 2004), and resampled to 200-m pixel resolution.

Statistical analysis

Conventional distance sampling

The population density of the Grande Comoro Scops Owl was estimated using Distance 7.1 software (Buckland et al. 2004). The average density (D) is computed as a simple function of the effective strip width (ESW), the total number of observations (N_t), and the total length of the transects (L_t) as follows:

$$D = \frac{N_t}{2 \times \mathrm{ESW} \times L_t}$$

We then applied CDS to our data to estimate the average population density (Buckland et al. 2004; Kun-Rodrigues et al. 2014).

This method explicitly fits detection functions and models the decreasing probability of observing an animal as its distance from the transect increases; it also corrects for undetected animals as well as for failed identifications at a greater distance from the line transect (Buckland et al. 2004).

We fit three key functions (e.g. half-normal, hazard rate, and uniform) with selected series adjustments (e.g., cosine, simple polynomial, and Hermite polynomial) to estimate ESW (Buckland et al. 2004). We did not include the negative-exponential key function based on the recommendations of Buckland et al. (2001). We then compared models using Akaike's information criteria (AIC) (Akaike 1973), and their respective performance using goodness-of-fit (GOF) tests. The model with the lowest AIC was considered the best detection function, and when ΔAIC $\leq$ 2 between models, the highest GOF was used to choose how to model the detection function. We did not apply truncation because some sites had less than the minimum number of 40 observations (Table S1) required for adequate density estimation via line transect (Buckland et al. 2004). To calculate the average population density, we used ESW estimated from our best model (Buckland et al. 2001; Thomas et al. 2010). For locations where the number of recorded owls was less than 40 individuals, we used a generic ESW of the entire dataset as we assumed that the four study locations were similar ecologically and thus had a similar detection probability for the owls (Table 1).

Density surface modeling

Population size of the Grande Comoro Scops Owl was assessed using DSM (Buckland et al. 2004). This method is designed to provide population estimation from distance sampling data which are not collected following a systematic sampling scheme and allowed us to (1) assess the population size of the species as a function of distances to the transects and spatially referenced ecological variables, and (2) generate predictions about how the estimated Grande Comoro Scops Owl abundance is distributed in space. As it was the case for the CDS method, DSM also fits detection functions by considering a perfect detection along the transect, which allows estimation of the number of individuals present in the studied areas (Buckland et al. 2004). Abundance is then estimated according to the counts and the suitability of the estimated habitat with a generalized additive model (Hastie and Tibshirani 1990). Surveyed transects and trails (for presence and absence data collection) were firstly split into segments where each segment corresponded to one pixel of the study grid (see Environmental variables), resulting in 260 segments. We then considered presence and absence data from entire study areas of Grande Comoro Island and our five eco-variables (see above) to fit our model. Each occurrence data point was associated with the nearest segment. Only one observation per 200 m pixels (the one with the highest cluster size if there was more than one individual per observation) was included in the DSM analysis to avoid overestimating local abundances. All absence data collected in 300 m around an occurrence data point were discarded from the analysis resulting in 65 occurrences and 189 absences. We performed model selection by adding covariates from a simple model and the selected model based on the explained deviance (Table 2; Hedley et al. 2004). All analyses were performed with package dsm (Miller et al. 2019).

Global population size estimate and habitat suitability

The global population size of Grande Comoro Scops Owl in the study area was estimated as the sum of the estimated abundances in each of the 200-m pixel grid cells (see above). We calculated the suitable range of the species by excluding all near-zero abundance cells from the Extent of occurrence [according to Gaston (1991), the 100% abundance map represents the full range containing all cells with abundance > 0]. For this, only the "area of occupancy" according to the IUCN definition was considered by excluding all cells containing less than 2.5% abundance [i.e., 0.1 individuals per 200-m pixel grid cell; Fig. 4a; see Gaston (1991)].

Table 1 Average density estimates and key function comparisons

Key function	Adjust-Serie	AIC	GOF χ^2 p	Effort (km)	$N_{obs.}$	ESW (m)	Density (ind./km^2)		
							D	95% CI	95% CI
Hazard rate key	Cosine	916.23[a]	0.58[a]	40.59[a]	111[a]	50.54[a]	27.04[a]	16.93[a]	47.21[a]
Half-normal key	Simple polynomial	919.16	0.52	40.59	111	44.18	30.94	15.07	55.64
Uniform key	Cosine	922.24	0.50	40.59	111	43.20	31.64	16.37	56.67

N Population size, *obs.* observations, *ind.* individuals, *D* average density, *CI* confidence interval

[a]Selected detection function and associated Akaike's information criteria (AIC), goodness of fit (*GOF*), effective strip width (*ESW*) and density

Table 2 Density surface model selected for the Grande Comoro Scops Owl

Models	Covariables	ED (%)	Population size (*N*)
FI	s(FORINT)	17.04	4853
FI.ALT	s(FORINT)+s(ALTITUDE)	40.40	3574
M	s(ALTITUDE)+s(FORDEG)+s(FORINT)	48.70[a]	3452[a]
MM	s(ALTITUDE)+s(FORDEG)+s(FORINT)+s(PLANT)	48.50	3518

FORINT Intact natural forests, *ALTITUDE* elevation, *FORDEG* degraded natural vegetation, *PLANT* plantations

[a]Selected model, associated explained deviance (*ED*) and population size

Results

Population density estimated by CDS

In total, 40.5 km of transects were surveyed during our nocturnal surveys, during which 111 Grande Comoro Scops Owls were recorded. Amongst the four surveyed locations, the highest number of owls was recorded in Nyoumbadjou followed by Ntsinimoipanga and Mvouni (Table s1). The model hazard rate was selected as the best detection function for the ESW estimate. The population density was estimated at 27.04 (16.93–47.21) individuals (ind.)/km^2 when using the entire dataset (Table 1). The highest population density estimate was for Ntsinimoipanga ($D = 41.71$ ind./km^2) followed by Gnoumbadjou ($D = 38.92$ ind./km^2; Tables 1, S1).

Habitat suitability and global population size estimate

When comparing different DSMs, the model including elevation, degredated forest and intact forest cover (model M) showed the highest explained deviance (Table 2). According to the DSM response curves, optimal habitats for the Grande Comoro Scops Owl are degraded vegetation and intact natural forest at 800–2000 m a.s.l. (Fig. 3). The abundance and habitat suitability maps for the Grande Comoro Scops Owl according to the best-fit DSM (model M) are given in Fig. 4a, b. The most suitable habitat predicted for the Grande Comoro Scops Owl was restricted to the main Karthala forest, i.e., primary, mountainous forest and some degraded natural forest, with a total range estimated at 133 km^2. This area includes all the remaining primary forest, and some degraded forest on the northern to southeastern flank, and from the southwestern to the western flank of the Karthala forest. A few small areas of high suitability were predicted in the northern part of the island, notably in Lagrille forest, in which the Grande Comoro Scops Owl has never been reported. High abundances were predicted at high elevation within the intact natural forest of Karthala. The total population size was estimated to be 3452 Grande Comoro Scops Owls.

Discussion

Estimated population of the Grande Comoro Scops Owl

The total population of the species, estimated for the first time for Grande Comoro Island using robust and statistical analyses, was 3452 individuals. In the same area and using a direct count method in the dry season of 1989, Herremans et al. (1991) estimated a total population of more than 2000 individuals (1000 pairs). According to Birdlife International (2017a), in September 2005, the species was more abundant on the southeastern flank of Karthala forest than previously estimated by Herremans et al. (1991). These findings are in line with our results. The difference in the estimated population size between our study and Herremans et al.'s (1991) study is probably due to the different methods used, as we accounted for erroneous detection. Finally, although our survey was carried out almost 28 years after that of Herremans et al. (1991) we do not consider that there has been a major change in population size, which is a good result for this species. We are confident that the area of this owl species' distribution remains stable [10,000 ha according to Herremans et al. (1991), 13,300 ha in the present study], although the intact forest has been degraded more by human activity at higher elevation than described in the former study.

Our surveys were carried out during the wet season. As highlighted by many studies on tropical scops owl population sizes, seasonal fluctuations in population size can generate different counts (Alba-Zúñiga et al. 2009; Green et al. 2015; Pilla et al. 2018). Scops owl calling activity changes according to precipitation and environmental conditions, and decreases during the dry season (Alba-Zúñiga et al. 2009; Pilla et al. 2018). Lloyd (2010) suggested a population size of about 5900 individuals for the Anjouan Scops Owl (*Otus capnodes*) on Anjouan Island (Comoro archipelago). In the same area, Green et al. (2015) estimated a population size of the same species ranging from 3450 in the dry season to 5450 in the wet season. Further studies need to be carried out on the population size of

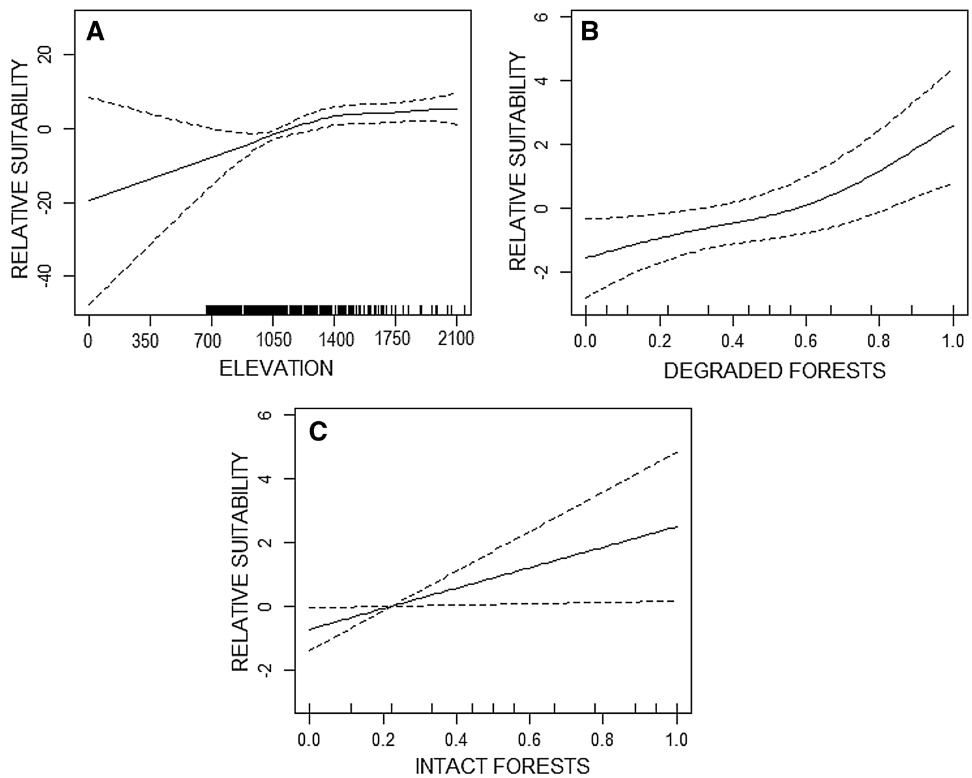

Fig. 3 Plots of the effect of elevation (**a**), degraded natural vegetation (**b**) and intact natural forest (**c**) used in the final Grande Comoro Scops Owl density surface model. *Dotted lines* show ~95% confidence interval for the smoothed terms

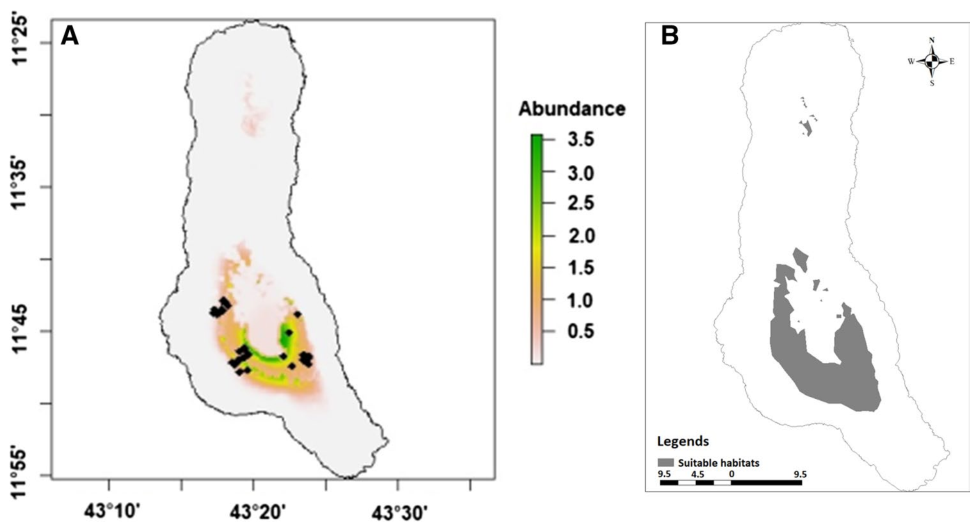

Fig. 4 Distribution of the Grande Comoro Scops Owl in the Karthala forest, Grande Comoro Island, according to density surface modeling. **a** Abundance (no. individuals per 200-m pixel), **b** suitable habitat. *Black points* indicate Grande Comoro presence

the Grande Comoro Scops Owl during the dry season for comparison with the current results.

Habitat suitability and species distribution

The Grande Comoro Scops Owl is a forest-dwelling species restricted to the remaining high-altitude forests of Karthala on Grande Comoro (Herremans et al. 1991; Louette et al. 2004). Some other scops owl species are also found in forest and agroecosystems. For example, in Madagascar, the Malagasy Scops Owl (*Otus rutilus*) inhabits a variety of habitats ranging from primary and secondary moist forest and dry forest to urban parks (BirdLife International 2016a). On the Comoro Islands, Green et al. (2015) suggested that the Anjouan Scops Owl (*O. capnodes*) lives in undisturbed forest, areas of agroforestry and forest with significant levels of disturbance. On Mohéli Island (Comoro archipelago), the Mohéli Scops Owl (*Otus moheliensis*) is common in undisturbed forest, but some populations were recently recorded in forest under-planted for agriculture (Birdlife International 2017b).

Our results based on DSM (Figs. 3, 4a, b) indicate that there is a strong relationship between the Grande Comoro Scops Owl (*O. pauliani*) and higher elevation (800–2000 m a.s.l.) forest including intact forests, and some types of degraded natural vegetation. The area suitable for the Grande Comoro Scops Owl in Karthala forest was estimated to be 133 km^2 (12.97% of the total surface area of Grande Comoro). This estimated area consists largely of the remaining natural forest here, both intact and degraded. This is considered a very small range for the distribution of Grande Comoro Scops Owl compared to other Asian, African and Indian Ocean scops owl ranges [20,000 km^2 for the Sangihe Scops Owl *Otus collari* from Indonesia; 220 km^2 for the Morden's Scops Owl *Otus ireneae* from Kenya and Tanzania, and 20,000 km^2 for the Malagasy Scops Owl *Otus rutilus* from Madagascar (Birdlife International 2016a, b, c)]. Therefore, our results suggest that the Grande Comoro Scops Owl, which largely relies on preserved forest, a habitat which is currently undergoing dramatic change, is currently at a high risk of extinction (FAO 2010; Sewall et al. 2007).

We propose two hypotheses to explain why this species is restricted to high elevations and undisturbed forests: because these provide suitable habitat and resource availability, and allow the species to avoid more disturbed areas (Green et al. 2015). Firstly, dense vegetation in old forest with large trees may benefit the owls by providing nesting cavities and is probably also a habitat for their prey, which live in humid and undisturbed forest (Herremans et al. 1991; Green et al. 2015; Virani et al. 2010). Secondly, according to our abundance and habitat suitability maps, the species may avoid urban areas and plantations (Figs. 1, 4a, b). The correlation between the Grande Comoro Scops Owl and high elevation could also be a consequence of lower anthropogenic disturbance in these areas and the fact that intact natural forests are usually found at higher altitudes at greater distances from urban areas and are also inaccessible to humans for wood harvesting and agriculture (Ibouroi et al. 2018b). A finer scale study, including an investigation of the food resources of this species, may help to disentangle collinearity between the different drivers of the Grande Comoro Scops Owl distribution.

Implications for conservation management

It appears that the Grande Comoro Scops Owl will be highly threatened in the near future because of its low population size (ca. 3452 individuals), its small distribution range (133 km^2), and the high rate of its habitat loss in the Comoro archipelago [9.3% year^{-1} (FAO 2010)]. Due to the species' strong dependence on forests and undisturbed vegetation, our results suggest that it will become increasingly vulnerable to extinction in the coming years if conservation measures are not rapidly implemented to ensure its long-term viability.

Many researchers have proposed actions to conserve Comorian biodiversity (Daniel et al. 2016; Granek 2002; Ibouroi et al. 2018a, b; Sewall et al. 2007, 2011; Trewhella et al. 1998, 2001, 2004). Some of these measures have been developed in collaboration with local, national, and international organizations such as Action Comores, Action Comores International and Dahari, a non-governmental organization (NGO). Despite the crucial efforts of researchers and NGOs to ensure the long-term conservation of biodiversity here, the unsustainable use of natural resources continues. Other intensive efforts, especially those of the Comoros government, are needed because the efforts of NGOs alone are insufficient to ensure the conservation of this highly threatened species. However, a bigger problem is that Comorians are constrained by poverty, and thus rely heavily on forests and their exploitation (Ibouroi et al. 2018b, unpublished data). Reducing poverty and improving the subsistence conditions of the rural population are of prime importance to the successful implementation of long-term conservation strategies to protect the species' habitat (Ibouroi 2017, unpublished data). In the Comoros, the most effective conservation management plan would be to adopt programs that tackle poverty in communities that live near forests (Ibouroi et al., unpublished data). This strategy could begin by not only addressing the needs of local people but also ensuring that they are less dependent on forest resources. For instance, it will be necessary to propose a locally acceptable and sustainable plan to both protect intact forest and restore degraded ones, as well as offsetting the costs of this to local impoverished farmers.

Agreements are currently being signed between Comoros National Parks (Parcs Nationaux des Comores) and the Ministry of Forestry-Comoros to create a national system of protected areas to ensure the long-term conservation of biodiversity within the intact and degraded natural forests here [Stratégie et Plan d'Action Nationale sur la Biodiversité (SPANB 2016)]. The Karthala forest is included in this network, with the protected status of a national park [Karthala National Park, SPANB (2016)].

We identified suitable areas for the endangered Grande Comoro Scops Owl by creating high-resolution maps depicting its spatial abundance and limits of its distribution in the Grande Comoro forests, information critical for in situ conservation efforts for this species. Both the habitat suitability and abundance maps could help decision-makers determine the best means of protecting this species' habitat, and can be used as references to reduce or prevent habitat loss and degradation of the Grande Comoro forests. We suggest that all suitable habitat or "areas of occupancy" of the Grande Comoro Scops Owl according to our DSM (Fig. 4b) should be considered as priority conservation areas for Karthala

National Park. This should help to ensure the protection of the Grande Comoro Scops Owl and its associated endemic biodiversity. More specifically, we recommend reinforcing efforts to conserve intact and high-elevation forests (1500–2000 m high), which are highly suitable habitats for this species and where its abundance is highest. Special attention must be paid to Mvouni (Fig. 2, site 2) where the species is still abundant but is facing a high rate of habitat destruction. Habitat fragmentation in particular in this area will likely contribute to a decrease in the Grande Comoro Scops Owl population (Ibouroi, personal observation). Surveys should be carried out in the Lagrille forest to confirm the presence of the species here. If the Grande Comoro Scops Owl does occur in this forest, it may be highly threatened because of the high rate of habitat degradation.

Key strategies to ensure the preservation of the Karthala forest and the Grande Comoro Scops Owl are: (1) investigate the plant species used by this species for roosting, nesting/breeding, and its breeding ecology; (2) better understand the ecological and socioeconomic determinants of land use change in the Karthala forest; (3) restore forest and secure corridors in the Karthala remnant forest; (4) avoid the conversion of secondary forests into agricultural land and use existing agroforestry for plantations; (5) involve a broad community of local individuals, NGOs and other entities in the conservation of this area.

Acknowledgments We would like to thank Comoros National Direction of the Environment and Forests for permission to conduct our fieldwork. The fieldwork was funded by the Réseau National d'Aires Protégées (RNAP), Parcs Nationaux des Comores, and the Rufford Foundation (grant no. 26731-2 to M. T. I.) through a research support grant. We are grateful to our local assistants and eco-guards for their contribution and assistance during the field surveys. Special thanks go to Ali Soidik, Ibrahim Msahazi, Fahami Abderemane, our drivers, Abdoulfatah and Abdérémane, and the whole RNAP team. The absence data used in this study were obtained from different Comoros institutions, including the University of Comoros, the Géothermie Project and Comoros National Parks. Finally, we are grateful to the two anonymous reviewers who provided extensive and critical corrections that improved the improvement.

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