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Density and ecological drivers of free-ranging cat abundance and activity in Madeira Island, Macaronesia

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Abstract

Mammalian predators introduced to oceanic islands pose a significant threat to biodiversity and have led to numerous extinctions. Free-ranging cats are particularly problematic due to their predatory habits and negative impact on conservation. However, there is limited information on the ecology and population status of free-ranging cats in insular ecosystems, where they often represent the apex terrestrial predator. Using a peri-urban protected area in the subtropical island of Madeira as a case study, we employed camera traps to assess the density of free-ranging cats and investigate the ecological drivers influencing their abundance and activity in nonurban insular habitats. Based on 582 trapping-nights, we identified 25 individual cats from 156 cat detections. Spatially explicit capture–recapture models revealed a density of 1.4 cats per km^2. Cat activity was positively affected by both the proportion of rocky areas in the landscape and the distance to human resource subsidies, whereas no significant driver was found for abundance. Our results indicate that cats are highly abundant throughout the protected area and suggest that their core home ranges are associated with rocky terrain, away from the most humanized sections of the park. Free-ranging cats do not appear to heavily rely on anthropogenic food sources, signaling that they may rely mostly on wild prey to fulfill their dietary needs. Their preference for rocky areas could be explained by the increased availability of shelter and prey, such as the Madeira wall lizard (*Teira dugesii*). Notably, cat abundance and activity were particularly high in the vicinity of the only known breeding colony of the locally threatened Manx shearwater (*Puffinus puffinus*) on Madeira Island. Our findings suggest that cats pose a significant threat to the native vertebrate fauna of the protected area and thus their management, particularly during the breeding season of the Manx shearwater, should be considered.

KEYWORDS
camera traps, domestic species, Ecological Park of Funchal, *Felis catus*, feral cats, invasive predators, island conservation, *Puffinus puffinus*

Ana Filipa Palmeirim and Ricardo Rocha contributed equally to this study.

1 | INTRODUCTION

Invasive species are one of the greatest threats to biodiversity (Bellard, Cassey, & Blackburn, 2016; Bellard, Genovesi, & Jeschke, 2016; Spatz et al., 2017). Mammalian alien predators are a particularly damaging group, having been implicated in the extinction of at least 87 birds, 45 mammals, and 10 reptile species worldwide (Doherty et al., 2016). As a result of evolutionary isolation, islands have a disproportionate share of global terrestrial biodiversity (Russell & Kueffer, 2019), with species often exhibiting "ecological naïveté"—that is, loss of defensive traits and behaviors needed to deal with novel predators (Carthey & Banks, 2014; Wallach et al., 2022)—making them particularly vulnerable to predation (Azumi et al., 2021; Courchamp et al., 2003; McCreless et al., 2016; Nogales et al., 2006). Although predation is often the most visible impact, invasive mammalian predators can also impact native biodiversity by competition, disease transmission, and through a wide range of cascading ecological impacts (Bourgeois et al., 2004; Carrete et al., 2022; Nogales et al., 1996; Rando et al., 2020).

The domestic cat (*Felis catus*) results from the domestication of the African wildcat (*Felis silvestris lybica*) some 9000 years ago (Driscoll et al., 2007) and is now among the most harmful and widely distributed mammalian predators worldwide (Doherty et al., 2016). Throughout their area of occurrence, they tend to be ubiquitous and to reach high densities, especially in the proximity of human populations (Crowley et al., 2020). Cats have established free-ranging populations on most oceanic islands, where they often sit at the top of the terrestrial food webs (Medina et al., 2014) and have contributed to the populational decline and extinction of numerous native insular species worldwide (Doherty et al., 2016; Medina et al., 2014; Medina et al., 2011; Nogales et al., 2013). Although the true magnitude of their impacts is still poorly understood (see e.g., Alho et al., 2022), free-ranging cats are currently associated with 33 (14%) of the modern birds, mammals, and reptile insular extinctions (Loss et al., 2013). Their impacts on island ecosystems are far-reaching and cross multiple taxonomic groups (e.g., Pérez-Méndez et al., 2016) but due to their long-life spans and low fecundity rates, island-breeding seabirds are particularly vulnerable to cat impact (Dias et al., 2019; Ratcliffe et al., 2010).

Unowned and owned free-ranging cats are widespread and often sympatric in all inhabited Macaronesian islands, a biogeographic region that encompasses the archipelagos of Madeira, Azores, the Canaries, and Cabo Verde (Silva et al., 2008). In the former, free-ranging cats prey on multiple endangered taxa, including seabirds, such as the IUCN Endangered Zino's Petrel (*Pterodroma madeira*) (Zino et al., 2001) and bats, as the IUCN Vulnerable *Pipistrellus maderensis* (Rocha, 2015). They also prey on endemic reptiles as the IUCN Critically Endangered Tenerife speckled lizard (*Gallotia intermedia*) and the Madeiran wall lizard (*Teira duguesii*) (Medina et al., 2010; Ravelo & Reyes, 2021), as well as on non-native mammals such as rodents (*Mus musculus* and *Rattus* spp.) and rabbits (*Oryctolagus cuniculus*) (Cook & Yalden, 1980; Medina et al., 2010). Yet, throughout Macaronesia, reliable estimates of free-ranging cat density are lacking and information about free-ranging cat ecology is mostly anecdotal and limited to a few islands (but see e.g., Medina et al., 2011; Oppel et al., 2012).

Human-associated food subsidies and environmental features such as vegetation type are usually an important factor modulating the abundance, activity (i.e., intensity of habitat use), and habitat selection of free-ranging cats. In urban areas, where food provisioning tends to be more common, free-ranging cat densities are often higher than in areas where cats rely solely on hunting, leading to smaller cat home ranges, usually below 1 km^2 (Bengsen et al., 2016; Hall et al., 2016; Kays et al., 2020). In natural, typically resource-deprived areas, human food subsidies can also enable the persistence of large cat populations (Crowley et al., 2020; Maeda et al., 2019; Sims et al., 2008) and potentially lead to "hyper-predation" events (Maeda et al., 2019). Vegetation type can influence the predation success of cats, with some studies indicating that cats prefer structurally complex habitats over simpler ones (e.g., Hohnen et al., 2016), while others suggest that cats are more successful hunters in areas with sparse vegetation (e.g., McGregor et al., 2015).

Here, we investigate the ecology of free-ranging cats in the Ecological Park of Funchal, a protected area located in the periphery of the main urban area of the subtropical Madeira Island, in the eastern Atlantic Ocean. To accomplish this, we employed camera-trap surveys and spatial explicit capture–recapture (SECR) models that account for animal movement and detection to estimate cat density. Additionally, we used Generalized Linear Mixed Models (GLMMs) to identify the environmental drivers that influence the abundance and activity of free-ranging cats. We hypothesized that cat abundance and activity are likely to be greater in areas near human-provided resources, as these areas offer greater access to shelter and anthropogenic food, and in the proximity of urban areas where owned cats are anticipated to be more common. Furthermore, we predict that cats will be more associated with rocky areas and areas with complex vegetation structure, as these are likely to harbor higher prey density and allow for increased hunting success.

2 | METHODS

2.1 | Study area

Fieldwork was conducted in the Ecological Park of Funchal on Madeira Island, Portugal (Figure 1). Madeira (737 km^2) is situated about 900 km from mainland Portugal and 600 km from Morocco, in the eastern Atlantic Ocean. It is the largest island of the Archipelago of Madeira and has a population of over 250,000 people (2021), most (55%) inhabiting the island's capital, Funchal (DREM, 2021).

The Ecological Park of Funchal is a protected area of 7.5 km^2, managed by Funchal City Council, located north of Funchal, at elevations between 470 and 1818 m. Half of its area (3.6 km^2) is included in the Natura 2000 Network and the park, and its immediate surroundings, are a popular leisure destination, featuring multiple picnic areas, restaurants, and rental houses. It is traversed by two main water courses that strongly influence its topography: Ribeira de Santa Luzia on the west side of the park and Ribeira das Cales running through its center (Figure S1). The park's vegetation is diverse, with large portions of it affected by forest fires in 2010 and 2016. These fires favored fire-prone invasive species, which currently occupy considerable sections of the park's grassland and shrubland habitats. The southern sections of the park, located at lower altitudes, are dominated by non-native and invasive tree species (*Acacia* and *Eucalyptus* spp.), being replaced at higher altitudes by the invasive shrubs *Cytisus scoparius* and *Ulex europaeus*. These invasive species compete with native species that require more time to establish—for example, tree heath (*Erica arborea*) and besom heath (*Erica platycodon maderincola*), pride-of-Madeira (*Echium candicans*) or the Madeira broom (*Genista tenera*). Very few hectares of native vegetation were not affected by fires, and these are located mainly in the steep hillside along the Valley of Ribeira de Santa Luzia. Considerable areas of the park are occupied by exotic species that are not considered invasive—for example, oaks (*Quercus ilex*), walnuts (*Juglans regia*), and European chestnuts (*Castanea sativa*) (Nunes et al., 2010).

The park is home to numerous native vertebrates, including endemisms at the species and subspecies level such as the Madeira wall lizard (*Teira dugesii*), the trocaz pigeon (*Columba trocaz*), the Madeiran firecrest (*Regulus madeirensis*), and the Madeira lesser noctule (*Nyctalus leisleri verrucosus*). Other than free-ranging cats it also hosts a diverse suite of invasive mammals, including black and Norway rats (*Rattus rattus* and *R. norvegicus*, respectively), house mice (*Mus musculus*), and European rabbits (*Oryctolagus cuniculus*). Furthermore, the park is home to one of the southernmost breeding colonies of Manx shearwater (*Puffinus puffinus*), a locally threatened seabird, whose population size and ecology throughout Macaronesia is scarcely known (Rodríguez et al., 2020). Currently, the only known breeding colony of Manx shearwater identified in the Archipelago of Madeira is located in the valley of Ribeira de Santa Luzia, within the Ecological Park of Funchal (Nunes et al., 2010).

2.2 | Camera-trap surveys

We conducted camera trap surveys at the Ecological Park of Funchal between 23rd of August (Summer) and 30th of November (Autumn) 2021. In order to maximize the number of individuals recorded we divided the park into a 1 × 1 km grid, based on the home range of cats in similar conditions (0.005–0.2 km^2, with most of the tracked cats not venturing >800 m from their homes, Hervías et al., 2014). A cluster of three cameras were set in each grid cell, at a minimum distance of 300 m apart (Table S1). Each camera (3 × Browning 2020 Patriot; 8 × Browning dark OPS HD; 3 × Bushnell core; and 1 × Victure HC 400) was fixed to the trunk of a tree or, in the absence of trees, to wooden stakes, at approximately 50 cm above the ground, facing animal trails or rarely used pedestrian paths which have been recorded to be highly used by free-ranging cats (Meek et al., 2012; Read et al., 2015).

Two of the three camera locations per grid were chosen based on cat signs recorded on previous visits to the area, or in locations with particularly distinctive vegetation (e.g., areas of native vegetation unaffected by the 2010 and 2016 fires), and the third was randomly selected using QGIS research tool. Each cluster of three cameras remained active for 24 h, during eight nights, and was then moved to the next grid. Each grid was surveyed twice, leading to a total of 16 trap-nights per camera, with one to four grids sampled at any given time. Due to bad weather conditions, which prevented the installation or removal of the cameras in some scheduled fieldwork days, the period of 16 night-traps planned was not always achieved. From the 33 camera-sites, two recorded less than 16 trap-nights (10 and 15 trap-nights), and 26 presented more than 16 nights recorded, resulting in a mean of 18.24 trap-nights per camera-site (±3.4 SD) (for information on the sampling effort at each camera-site see Table S1 and Figure S3). Cameras were baited with meat (chorizo), which was replaced after 4 days. We programmed cameras to shoot three consecutive images each time the sensor was triggered, with a minimal interval between images in a set, and 30 s between sets. To avoid false triggers, the vegetation in areas where the

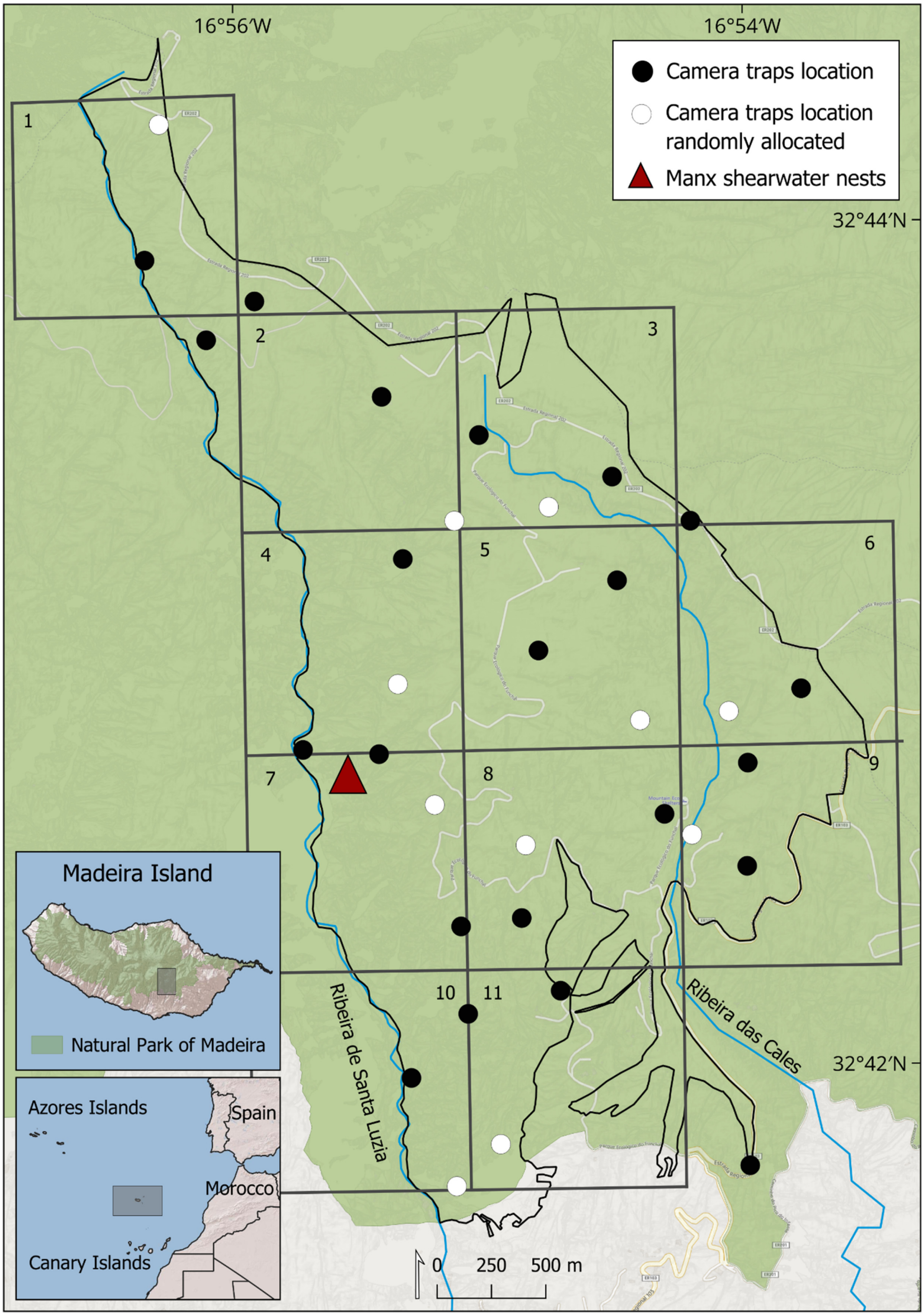

FIGURE 1 Location of the Ecological Park of Funchal in Madeira Island, Portugal. The map displays the camera-sites in a 1 × 1 km grid, marked by dots. The randomly selected camera-sites are indicated by a white dot. Each grid is numbered in the upper corner. The coordinates for each camera-site can be found in Table S1.

cameras were deployed was removed as much as possible and, to reduce the risk of theft, cameras were locked with steel cables and padlocks, with a note explaining the study purpose.

2.3 | Cat identification and classification

Photos were retrieved after each camera-trapping period and processed using Timelapse Image Analysis software

(Greenberg, 2022; Greenberg & Godin, 2015). Detections were considered distinct when the interval between them was >30 min, or when different individuals were recorded (Wearn & Glover-Kapfer, 2017). Every detection was tagged according to the photographed species, and the data was recorded in a Microsoft Excel™ (version, 2022) spreadsheet with columns for data of GridID/CameraID/location/day/hour/species.

Individual cats were identified based on pelage, morphology, and other diagnostic features (e.g., notched ears, wounds; Figure 2). Photos that did not allow for the identification of the individual cat were not included in the analysis regarding cat population size. These instances were mostly due to poor photo quality caused by poor weather conditions such as rain or fog or the speed and angle of the cats. Cats have been traditionally classified in four groups, based on the degree of human restrictions to their movement, feeding, and reproduction: indoor or house cats, indoor-outdoor cats, free-ranging cats, and feral cats (Crowley et al., 2020). In this study, due to the difficulty of distinguishing between owned and semi-owned cats with outdoor access, we refer to "free-ranging cats" as those categorized by Crowley et al. (2020) as "indoor-outdoor," "free-ranging cats," and "feral cats" (Figure S2).

2.4 | Explanatory variables

A set of human influence and habitat variables hypothesized to affect cat abundance and activity was measured with the QGIS software (Version 3.18—Zurich, QGIS.org, 2022) (Table 1). Human influence was quantified by calculating the proximity from each sampling site to urban areas and to locations of potential human resource food subsidies, based on orthophotos from 2018/2019 (Infraestrutura Regional de Informação Geográfica da Madeira, 2018). Locations considered as human resource food subsidies were any infrastructure that frequently provides anthropogenic food to wild animals. These included 11 picnic areas, 2 rental accommodations (5 buildings in total), 1 astronomy observatory, 12 rubbish containers, and 3 restaurants. The distance between the location of each camera and the closest main water course (Ribeira de Santa Luzia or Ribeira das Cales) was also measured. The percentage cover of open areas

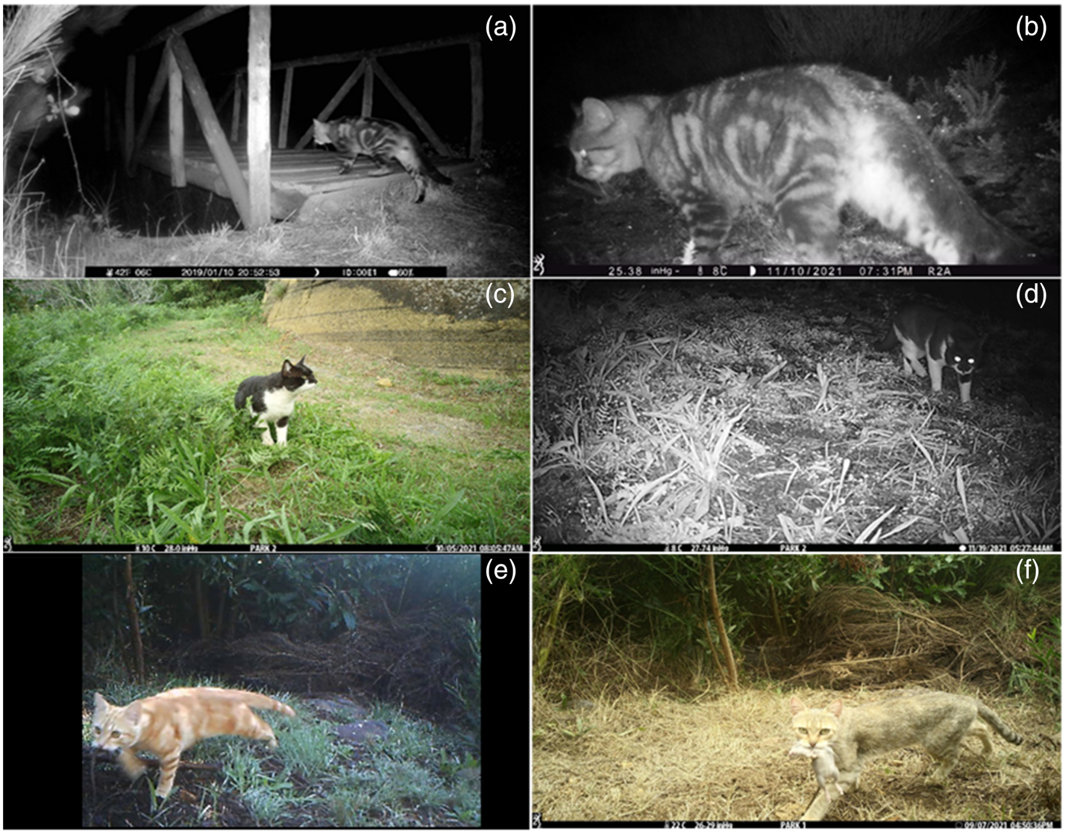

FIGURE 2 Examples of cats with different fur patterns photographed at the Ecological Park of Funchal, Madeira Island, Portugal. Photos (a) and (b) represent one individual, while (c) and (d) depict another. Photos (e) and (f) show cats carrying the endemic Madeira wall lizard and a rodent, respectively.

TABLE 1 Description of the explanatory variables used to investigate the abundance and activity of free-ranging cats in the Ecological Park of Funchal, Madeira, Portugal.

Explanatory variables	Type	Unit	Min	Max	Mean ± SD
Human influence					
Distance to urban area (DTU)	Continuous	m	550	5589	2829.9 ± 1234.5
Distance to human resources subsides (DTHR)	Continuous	m	35	903	398.8 ± 232.7
Geographic setting					
Distance to closest water course (DTW)	Continuous	m	2	725	309.4 ± 211.3
Slope	Continuous	(°)	0	26	5.9 ± 4.9
Altitude	Continuous	m	588	1738	1274.8 ± 271.2
Habitat structure (buffer of 150 m)					
Invasive trees	Nominal	%	0	95	20.2 ± 31.7
Noninvasive trees	Nominal	%	0	30	9.5 ± 8.8
Invasive shrubland	Nominal	%	5	70	35.5 ± 19.8
Noninvasive shrubland	Nominal	%	0	60	15.8 ± 15.4
Open area	Nominal	%	0	85	29.7 ± 21.2
Rocky area	Nominal	%	5	65	25.0 ± 15.4

Note: For each variable, we indicate mean, standard deviation (SD), minimum, and maximum values.

(comprising non-rocky areas with no vegetation, or grassland), rocky surface (exposed rock-covered surfaces, or stone walls with little or no vegetation), invasive trees, noninvasive trees, invasive shrubland, and noninvasive shrubland was also measured within a 150 m-buffer. A digital terrain model with a 10 m resolution was used to obtain altitude and slope (Infraestrutura Regional de Informação Geográfica da Madeira, 2018).

2.5 | Data analysis

First, we calculated the trapping effort (in trap-nights) for each camera accounting for the number of trap-nights during which the camera was active over the study period. We calculated capture efficiency (in number of capture events/100 trap-nights) by dividing the number of cat detections for all cameras by the total trapping effort and then multiplying by 100 (Juhasz et al., 2022).

2.6 | Cat density estimate

We used SECR models to estimate the density of adult free-ranging cats per km^2 which then allowed us to infer about the cat population size for our study area. SECR models incorporate auxiliary data from camera trap locations to explicitly account for animal movement and detection probability in density estimates and are fitted by maximizing the likelihood (Efford, 2011). Prior to analysis we prepared a capture history matrix for the identified individuals at each camera location and, as camera-traps were not simultaneously active at all locations, we made an effort history matrix to account for periods when cameras were active at each location. SECR models were fitted in R 4.1.3 (RStudio Team, 2022) using the package 'SECR' version 4.5.7 (Efford, 2022). We used the 'count' detector function and assumed that cat home ranges were distributed following a homogeneous spatial Poisson process throughout the trapping period (Borchers & Efford 2008; Efford et al., 2009). Half normal with a log link was selected as the best detection function for our data (see Figure S3 and Table S2). To estimate density, SECR models construct a habitat mask around the detectors to represent potential occupancy area of the species of interest. This mask is generated by forming a grid that extends 'buffer' meters to the South, East, and West of the detectors and dropping centroids that are more than 'buffer' meters away from the nearest detector (Efford, 2022). Using the buffer function in SECR we selected a 1200 m-buffer around each camera trap, resulting in a habitat mask area of 26.04 km^2.

2.7 | Ecological drivers of cat abundance and activity

For each camera-site, we quantified free-ranging cat abundance as the number of individual cats detected and cat activity as the number of detections. Cat abundance and activity was investigated using GLMMs fitted with a Poisson distribution. The initial set of 11 predictor variables were considered: altitude, slope, distance to main water courses (DTW), distance to urban areas (DTU), distance to human resources subsides (DTHR) and percentage coverage of non-invasive shrubland, invasive shrubland, non-invasive trees, invasive trees, open areas, and rocky surface (Table 1). Inter-variable correlation was analyzed using Pearson's correlation coefficient, whereby we considered variables with $r > 0.7$ to be highly correlated, justifying the exclusion for the analysis. A set of four non-correlated variables was kept for subsequent analysis (DTU, DTHR, DTW, and Rocky area). Prior to analysis variables were standardized to a mean of zero and standard deviation of one. Models included grid ID as a random factor, to account for the nested sampling design. To account for any potential bias caused by the use of different camera trap models (Palencia et al., 2022; Taggart et al., 2019), we included the camera model as a random factor. Additionally, we tested if the different effort in each camera site, resulting from different number of trap-nights cameras in some sites, affected our models by adding the total number of trap-nights in each camera site as an offset in the GLMMs. Neither the inclusion of the camera models as a random factor nor the offset accounting for the number of camera trap-nights provided any additional explanatory power (Table S2) and therefore we decided not to include

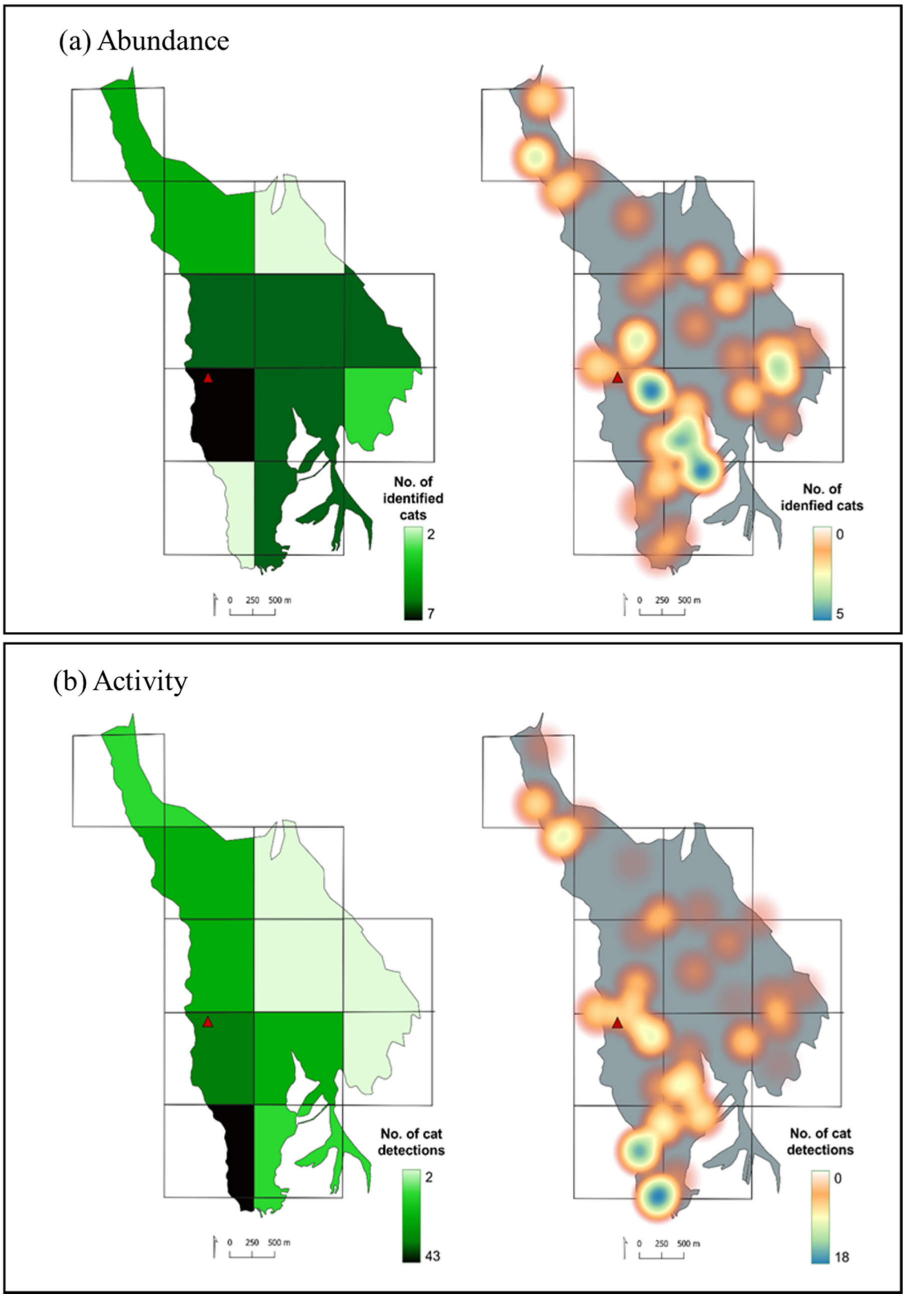

FIGURE 3 Patterns of free-ranging cat (a) abundance and (b) activity in the Ecological Park of Funchal at the 1 × 1 km grid- (left panels) and site-level (right panels). Cat abundance is given by the number of different cats detected and activity by the total number of detections. The red triangle represents the location of the only known colony of Manx shearwaters in the Archipelago of Madeira.

them in further analysis. We investigated all possible combinations of fixed factors using the 'MuMIn' R Package (Bartón, 2022) and the most parsimonious model set was ranked based on their maximum likelihood through the Akaike's Information Criterion corrected for small sample size (AICc) (Grueber et al., 2011; Symonds & Moussalli, 2011). Model uncertainty was accounted for by performing model-averaging of the most parsimonious model set (i.e., $0 < \Delta\text{AICc} > 2$, $\Delta\text{AIC} = \text{AIC}_i - \text{AIC}_{\text{min}}$ in which $i = i^{\text{th}}$ model). Model goodness-of-fit was assessed as the conditional R^2 (Nakagawa & Schielzeth, 2013). GLMMs were run using the 'lmer4' R package.

Unless otherwise specified, all analyses were conducted in R 4.1.3 (RStudio Team, 2022).

3 | RESULTS

From a total of 102,935 photos, we obtained 946 animal detections during 582 trap-nights. The most frequently detected vertebrates were rats (400 detections; 42.3% of the total) and cats (156 detections; 16.7% of the total). Cat capture efficiency was 26.8 detections per 100-night traps. Passerines, mice, rabbits, and non-passerine birds (e.g., common buzzards *Buteo buteo harterti* or Macaronesian kestrels *Falco tinnunculus canariensis*), represented respectively 13.1%, 12.8%, 9.4%, and 5.8% of the total photos of vertebrates. From the cat photos we could identify at least one pregnant female and three instances of trophic interaction (Figure 2e,f).

Twenty-five individual cats were recognized from 144 photos (92.3% of total cat detections). Photographed cats could not be identified in 12 of the cat photos. Grid no. 10 (see Figure 1 for grid number) had the highest number of cat detections, from two different cats (Figure 3). One of which was the most recorded in the survey (45 different detections, in two cameras of grid no. 10). The second cat recorded in grid no. 10 was also photographed in grids no. 3, 4, 5, 6, 8, 10, and 11 and displayed the longest distance covered between different detections: 2338 m. Grid no. 3 had the lowest number of cat detections (two detections corresponding to two individuals; Figure 3).

The number of cat detections per camera varied between 0 and 18 (mean = 4.7; ±4.4 SD). Yet, cats were detected in every sampling grid (between 2 and 43 detections per grid; mean = 14.2; ±11.2 SD), with an activity

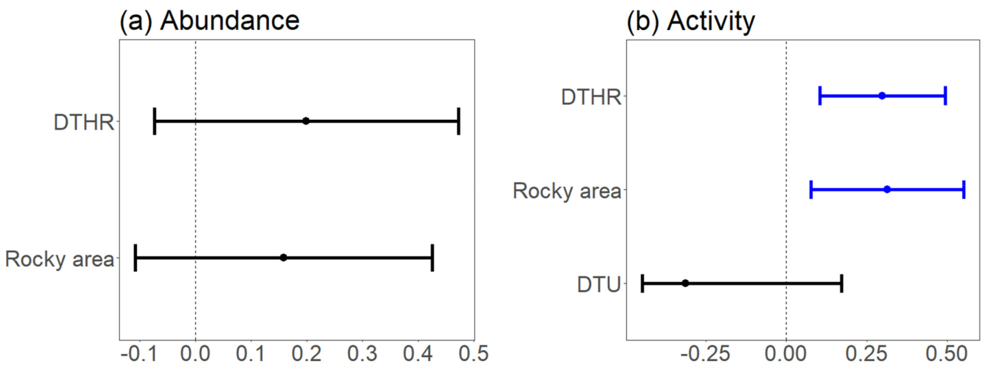

FIGURE 4 Estimates of averaged models and their 95% confidence intervals for predictors of (a) abundance (number of individuals) and (b) cat activity (number of detections) in the Ecological Park of Funchal, Madeira Island, Portugal. Positive significant coefficients are displayed in blue, while nonsignificance are displayed in black. DTU, distance to urban areas; DTHR, distance to human resources subsides.

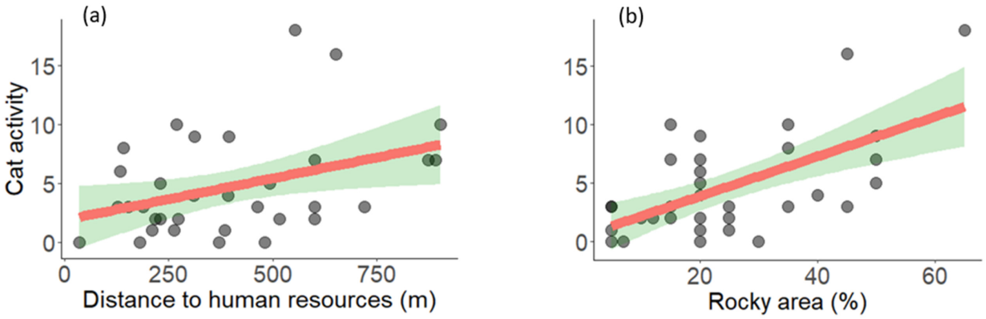

FIGURE 5 Relationship between cat activity (number of detections) and (a) distance to human resources subsides and (b) rocky area. Red lines represent the model adjusted for the strongest relationships ($p < .05$), and green shaded areas represent the 95% confidence intervals.

considerably higher on the western section of the park (mean of 21.2 detections in the western vs. 8.3 detections in the eastern grids; Figure 3b).

3.1 | Cat density

The results of the SECR models revealed a maximum detection probability at each camera trap (g0) of 0.17 (95% CI [0.13; 0.24]) and a spatial scale of movement (σ) of 387 m (95% CI [342.23; 439.14]). The estimated population density of free-ranging cats was 1.4 cats/km^2 (95% CI [0.94; 2.1]). The estimated population size for the surveyed area is 36 cats (with a 95% confidence interval of [25; 55]).

3.1.1 | Ecological drivers

According to the GLMMs, free-ranging cat abundance was not affected by any of the variables considered. However, cat activity was positively influenced by the proportion of rocky areas (95% CI [30.07; 0.55]) and the distance from human resource subsidies (95% CI [0.10; 0.59]) (Figures 4 and 5; Tables S3 and S4).

4 | DISCUSSION

Free-ranging cats have substantial negative impacts in insular wildlife, but rigorous assessments of cat density and habitat associations in island ecosystems are rare (Loss et al., 2022; Medina et al., 2011). Here, we quantified cat density and investigated the drivers of abundance and activity of free-ranging cats in the peri-urban Ecological Park of Funchal in the subtropical Macaronesian island of Madeira. Our results indicate that, during our surveys, the Ecological Park of Funchal was likely to be used by 36 adult cats, which were particularly associated with rocky terrains and away from the most humanized sections of the park.

4.1 | Free-ranging cat density in Madeira and other islands

Free-ranging cats were the second most detected species during the camera-trap surveys, with an estimated density of 1.4 cats/km^2. Studies from other oceanic islands (sensu Fernández-Palacios et al. (2021)—i.e., islands that emerged as volcanoes from the seabed and remain disconnected from any continent) have reported cat densities ranging from 0.25 in Reunion Island to 73.4 cats/km^2 in Corvo Island (Azores Archipelago) (Table 2). Our results show a high number of cats compared to previous research in natural (i.e., non-urban/rural) areas, only surpassed by densities reported by Lavery et al. (2020) in Valevahalo, an abandoned mountain village in the Solomon Islands. Here, authors suggested that differences in cat densities were probably due to higher prey abundances or increased carrying capacity due to previous human influence (Lavery et al., 2020). Notably, densities reported in Corvo Island are much higher when compared to other

TABLE 2 Summary of existing cat density studies using camera-trap surveys in oceanic islands, indicating the surveyed area, the method used to infer the density from camera trap data (SECR: spatially explicit capture–recapture; SCR: spatially capture–recapture), the trapping effort (number of trap-nights cameras recorded in total), number of cat detections, identified cats, and the estimated density.

Region and surface (km^2)	Surveyed area (km^2)	Area	Method	Trapping effort	No. cat detections	No. identified cats	Density (cats/km^2, 95% CI)	Source
Madeira Island (801)	26.0	Natural/ peri-urban	SECR	582	156	25	1.4 (0.9–2.1)	Present study
Réunion Island (2512)	–	Natural	SECR	1082	60	10	0.25 (0.1–0.5)	Juhasz et al. (2022)
Guadalcanal-Kovi, Solomon Islands (5302)	–	Natural	SCR	2672	–	9	0.31 (0.2–0.5)	Lavery et al. (2020)
Guadalcanal-Valevahalo, Solomon Islands (5302)	–	Natural	SCR	2369	–	12	2.65 (1.3–4.0)	Lavery et al. (2020)
Kolombangar, Solomon Islands (687)	–	Natural	SCR	1178	–	5	0.65 (0.2–1.4)	Lavery et al. (2020)
Corvo, Azores Islands (17.2)	11.4	Natural/ peri-urban	SECR	–	104	30	3.6 (2.5–5.4)	Oppel et al. (2012)
Corvo, Azores Islands (17.2)	1.39	Urban	SECR	–	395	74	73.4 (58.1–92.7)	Oppel et al. (2012)

studies, which may be due to the particular small size of the island/sampling area (Oppel et al., 2012).

The number of cat detections in this study is notably high when compared to other camera trap studies focused on free-ranging cats on islands (Table 2; but see results for the Island of Corvo, Azores; Oppel et al., 2012). Cove et al. (2018) suggested that differences in cat densities between urban and natural areas were likely due to contrasting levels of habitat modification and human densities. This is supported by other studies that reported high densities of unowned cats in non-insular urban and suburban areas, such as 35.9 cats/km^2 in New York (Kays & DeWan, 2004) and between 132 and 1580 cats/km^2 in the UK (Sims et al., 2008). Free-ranging cats in urban and suburban areas, often have more access to shelter sites and human-associated food resources (e.g., food waste) that can sustain a higher number of rodents, which in turn, can sustain higher populations of cats (Oppel et al., 2012). Indeed, cat densities in urban and suburban areas seem to be more reflective of human densities than of the density of their prey (Bengsen et al., 2016; Sims et al., 2008; Turner & Bateson, 2000).

4.2 | Free-ranging cat abundance and activity in the Ecological Park of Funchal

Some of our sampling sites were close enough to human settlements (<600 m) to be within the typical home-range described for free-ranging cats (usually <1 km^2; Kays et al., 2020). We anticipated greater cat abundance and activity closer to urban areas, where the number of owned cats is likely to be greater. However, our results did not show any correlation between abundance or activity and proximity to human settlements. Indeed, none of the considered ecological drivers seems to influence free-ranging cat abundance, which may indicate that cats are evenly distributed throughout the park or that an important variable was not taken into consideration in our analysis. Another possibility is that, although the study area presents a high variability in many of the analyzed variables, it may not be large enough to reflect the potential factors that may influence the distribution of cat distribution.

Cat activity was higher in areas with a greater coverage of rocks and further away from human resources subsidies. These results suggest free-ranging cats in our study area do not rely on anthropogenic food resources and may avoid human interaction. Instead, free-ranging cats may rely mostly on hunting to meet their dietary needs, as evidenced by multiple cats photographed carrying prey (Figure 2e,f). The diet of free-ranging cats in mountainous areas of Madeira is primarily composed of invasive mammals (rodents and rabbits) and, to a lesser extent, native birds, and reptiles (Medina et al., 2010). Studies (e.g., Hervías et al., 2014; Plein et al., 2022) have shown that the presence of non-native alternative prey does not equate to reduced cat predation on native wildlife on oceanic islands and instead may indeed boost cat populations, leading to hyper-predation of native prey (Courchamp et al., 2000; Donlan & Wilcox, 2008; Dumont et al., 2010; Medina et al., 2011; Ravelo & Reyes, 2021).

The association between cat activity and more rocky areas is likely related to prey availability. Lizards, which are a common prey of cats in Madeira (Medina et al., 2010; Figure 2e), are often found in rocky habitats (Pacheco, 2008; Penado et al., 2015). Indeed, cat feces and regurgitations collected during this study revealed abundant remains of Madeira wall lizards (one regurgitation had >8 adult lizards and one mouse). Madeira wall lizards are key arthropod predators, seed dispersers (Sadek, 1981), pollinators (Esposito et al., 2021), and prey of a wide array of native predators (Jesus et al., 2005; Rocha et al., 2010). Declines in lizard abundance can have considerable negative cascading effects to native animal and plant populations in oceanic islands (e.g., Pérez-Méndez et al., 2016) and thus the potential impact of free-ranging cats in Madeira can be magnified by predation-induced downstream effects on ecosystem dynamics. On the other hand, the association of cat activity and rocky areas may also be due to greater shelter availability, especially if prey is evenly distributed throughout the park (Calhoon & Haspel, 1989).

4.3 | Potential impacts of free-ranging cats on the Madeiran population of Manx shearwater

Free-ranging insular cat populations are especially detrimental for seabirds (Dias et al., 2019; Medina et al., 2011; Nagata et al., 2022; Oliveira et al., 2022). A recent study by Rodríguez et al. (2022) found that predation by cats and rats has shaped the current breeding distribution of petrel colonies in the Canary Islands, relegating them to isolated predator-free areas. Similar findings have been reported in numerous other studies (e.g., Hervías et al., 2014), and likely explain the restricted breeding range of Manx shearwater in Madeira. Notwithstanding that multiple additional factors (e.g., habitat loss due to fires and light pollution; Dias et al., 2019) are likely impacting seabirds in Madeira, evidence from the Canary Islands, where cats are suspected to have contributed to the post-European arrival extinction of the Lava shearwater *Puffinus olsoni* (McMinn et al., 1990; Rando & Alcover, 2008), and from Cape Verde, where they were implicated in the island-level extirpation of Boyd's shearwater *Puffinus lherminieri boydi* from Santa Luzia (Alho et al., 2022), suggests that if left unchecked the free-ranging cats—currently particularly abundant/active near the breeding grounds of the Ecological Park of Funchal colony of Manx shearwater (Figure 3)—might compromise the long-term persistence of the species in Madeira.

5 | CONCLUSIONS

Our results reveal that the mountainous areas in the periphery of Madeira's capital are home to a substantial population of free-ranging cats. Free-ranging cats are a non-native species with pronounced impacts on the conservation of multiple species protected under national and international laws (Carrete et al., 2022; Trouwborst et al., 2020; Calver et al., 2023) as well as on human health and local economies (e.g., Legge et al., 2020; Neves et al., 2020; Szentivanyi et al., in press). They are particularly dangerous to island biodiversity (Medina et al., 2011) and in the recently approved Montreal Biodiversity Framework, Portugal and other nations agreed to "(…) eradicate or control invasive alien species on islands and other priority sites" (Convention of Biological Diversity, 2022) by 2030. To meet this target there is an urgent need to adopt science-driven, evidence-based management strategies that incentivize responsible pet ownership and safeguard native species and the ecosystem services and ecological processes they support.

AUTHOR CONTRIBUTIONS

Conceptualization: Ricardo Rocha, Elena J. Soto, João Nunes, and Ana Filipa Palmeirim. *Methodology*: Ricardo Rocha, Elena J. Soto, João Nunes, Eduardo Nóbrega, and Ana Filipa Palmeirim. *Writing original draft preparation*: Elena J. Soto and Ricardo Rocha. *Writing review and editing*: Ricardo Rocha, Elena J. Soto, João Nunes, Eduardo Nóbrega, and Ana Filipa Palmeirim; *Project administration*: Ricardo Rocha, Elena J. Soto, Eduardo Nóbrega, and João Nunes, *Funding acquisition*: Ricardo Rocha, Elena J. Soto, João Nunes, and Ana Filipa Palmeirim. All authors have approved the submitted version of this manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest

DATA AVAILABILITY STATEMENT

Data available within the article or its Supporting Information.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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