



How vulnerable are the nesting sites of loggerhead turtles in Cabo Verde?

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Abstract

Marine turtles' nesting grounds face imminent threats from urbanisation, climate change, and pollution. In this study, we estimated the vulnerability of loggerhead turtles (*Caretta caretta*) nesting beaches in Cabo Verde, one of the largest rookeries globally. We surveyed 61 sandy beach segments (~100 m) with a drone and modelled nest density by incorporating topographical and oceanographic variables. Then, we digitised all beaches across the islands, divided them into smaller sections (digitised segments), and projected the model onto this layer. Each digitised beach segment was evaluated considering their exposure to five risk factors: (a) marine litter density, (b) inundation trends, (c) land surface temperature trends, (d) light pollution trends, and (e) tourism pressure. Our analysis revealed that 48% of digitised segments are exposed to at least one threat. São Vicente, Santiago, and Sal are the most affected islands, mainly from marine debris and light pollution, while Santo Antão and Maio are the least impacted. Sal showed the highest overlap between vulnerable areas and high-density sites, highlighting its priority for conservation, though less affected islands should also be protected. We found that marine debris correlates positively with nest density, while light pollution negatively affects it. Our study emphasises the need for conservation efforts to ensure the sustainability of nesting sites amid escalating global changes.

Keywords Atlantic islands · *Caretta caretta* · Climate change · Coastal squeeze · Environmental changes · Remote sensing

Introduction

Sandy beaches constitute over one-third of the coastlines on Earth. Situated at the land–ocean interface, these ecosystems are vulnerable due to their low-elevation and unconsolidated materials, making them highly susceptible to erosion (Defeo et al. 2009; Nicholls and Cazenave 2010). By 2050, it is estimated that one-third of all low-elevation coastal zones will face significant erosion (Vousdoukas et al. 2020). This is exacerbated by increasing urbanisation, natural resource exploitation, and climate change—a phenomenon known as coastal squeeze (Defeo et al. 2009; Defeo and Elliott 2021; Fanini et al. 2020).

The shrinking of sandy beaches threatens critical habitats for coastal nesters, such as marine turtles (Mazaris et al. 2009; Fuentes et al. 2010; Biddiscombe et al. 2020). Female sea turtles have philopatric behaviour, returning to their natal

beaches to lay their eggs. The choice of the nesting site is crucial for the survival of embryos, as the microhabitat conditions determine their successful development (Ackerman 1997). This site selection can sometimes be unsuccessful due to multiple threat factors, particularly among young females (Pfaller et al. 2009; Martins et al. 2022). For instance, nests can be inundated due to poor site selection, natural events (storms), and sea-level rise, risking nests being washed away or flooded (Pike et al. 2015). Another significant threat is the warming of sand on nesting beaches, often linked to broader climatic trends, as sea turtles have temperature-dependent sex determination (Fuentes et al. 2011; Howard et al. 2014; Laloë et al. 2014). Higher sand temperatures can skew sex ratios toward females (reducing genetic diversity and their resilience to environmental changes in the long term) or cause embryonic mortality (Howard et al. 2014; Lockley and Eizaguirre 2021; Laloë and Hays 2023). Moreover, marine litter accumulation on beaches, particularly plastics, poses further threats. It can modify the nesting behaviour of females (Fujisaki and Lamont 2016); change sediment permeability (Carson et al. 2011); alter sand temperature

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(Lavers et al. 2021; Fuentes et al. 2023); chemically contaminate the sand (Sousa-Guedes et al. 2023a); and act as physical barriers, disrupting hatchling emergence synchrony or hampering their arrival at the sea (Aguilera et al. 2018; Sousa-Guedes et al. 2023b). Indeed, sandy beaches are increasingly becoming sinks for marine litter (Lavers and Bond 2017; Sousa-Guedes et al. 2024). Additionally, urbanisation growth has globally increased artificial light pollution, affecting multiple species (Falchi and Bará 2023). For sea turtles, nocturnal artificial lighting can disorient females and hatchlings, leading them away from the ocean, and reducing their survival chances (Witherington 1992; Lorne and Salmon 2007). It can also cause females to avoid bright beaches or delay nesting, resulting in unsuccessful nesting attempts (Silva et al. 2017). Furthermore, recreational and tourist activities are overwhelmingly concentrated on sandy beaches. Large tourist developments attract a lot of people, leading to increased light pollution, trampling of nests, and accelerated beach erosion due to the destruction of dunes (Costa et al. 2023).

The insular archipelago of Cabo Verde, off the west coast of Africa, hosts one of the largest nesting populations of loggerhead turtles (*Caretta caretta*) worldwide, and the only stable reproductive population of the Eastern Atlantic (Marco et al. 2011, 2012; Casale and Marco 2015; Patino-Martinez et al. 2022). The discovery of these islands in 1456 was quickly followed by the official record of sea turtles nesting there, described as occurring ‘in abundance’ (Taxonera et al. 2022). The archipelago hosts a large and growing nesting population, with an increasing annual number of nests (Laloë et al. 2020). This phenomenon is still not fully understood, partially attributed to successful conservation efforts or environmental changes at the sea or on land. Despite this, the loggerhead turtle population in Cabo Verde remains classified as endangered by the IUCN (Casale and Marco 2015).

Considering all the threats to sea turtle rookeries, our study aims to assess the vulnerability of loggerhead nesting sites across seven islands of Cabo Verde, focusing on the loss of suitable nesting areas by (1) marine litter pollution, which affects incubation, hatchlings’ emergence, and females behaviour; (2) increasing nest inundation risk, resulting in egg mortality or displacement; (3) warming sands, leading to female-biased hatchlings or increased mortality; (4) increasing light pollution, which disorients nesting females and hatchlings; and (5) tourism pressure on beaches, increasing direct disturbances. We integrated aerial drone surveys, predictive modelling, satellite remote sensing data, and trend analysis to identify the threats at each site. Additionally, we predicted nests’ density across beaches to determine whether they overlap with the most vulnerable areas. By identifying resilient beaches and those losing habitat quality, we seek to inform conservation efforts

and provide insights into immediate threats to their nesting beaches (Fuentes et al. 2011; Patrício et al. 2021).

Materials and methods

Study area

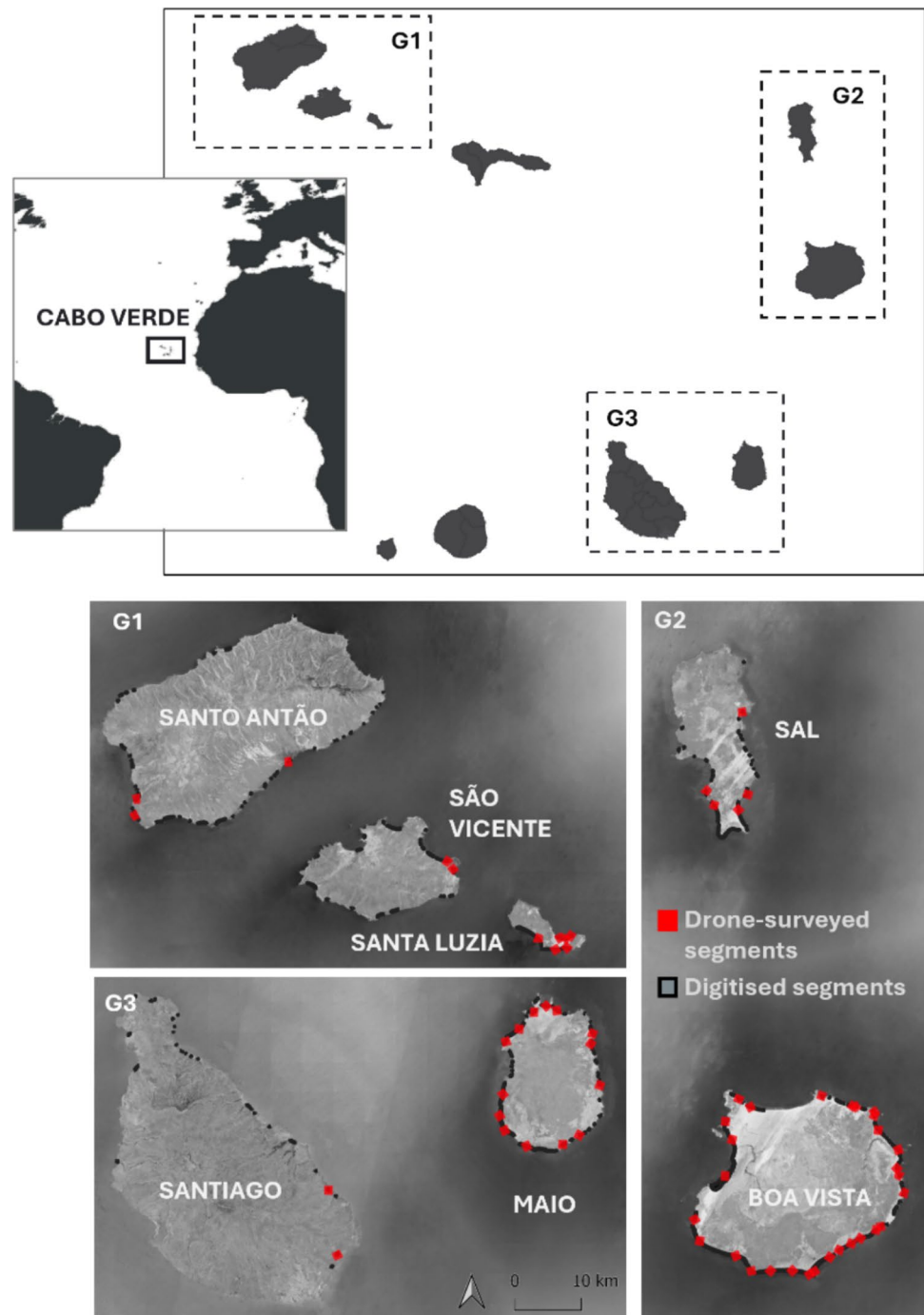
The Cabo Verde archipelago is located in the northeast Atlantic Ocean, off the west coast of Africa. All ten islands are of volcanic origin and characterised by a dry, windy, and subtropical climate. Tourism is the fastest-growing economic sector in the country (Akkemik et al. 2024), contributing to over one-third of the country’s GDP in 2019 (Sarmiento and Monteiro 2023). Despite that, Cabo Verde faces economic vulnerability and limited natural resources.

Our study focused on seven islands: Santo Antão, São Vicente, Santa Luzia, Sal, Boa Vista, Maio, and Santiago (Fig. 1). We excluded the islands of São Nicolau, Fogo, and Brava due to their minimal sandy beaches and low nesting activity (Marco et al. 2011).

To assess loggerhead nest density and marine litter pollution, we conducted aerial surveys on 61 sandy beach segments (~100 m each) across the seven islands. Surveys were conducted in September and October 2021 (Boa Vista), October 2022 (Santo Antão, São Vicente, and Santa Luzia), October 2023 (Sal), and December 2023 (Maio and Santiago). We used the DJI Mavic Air 2 unmanned aerial vehicle (UAV or drone), at an altitude of 15 m and 80% image overlap (forward and lateral), following the methodology by Sousa-Guedes et al. (2024). Each surveyed segment represents an independent sampling unit, selected to characterise the diversity of beaches in terms of morphology, environmental conditions, and exposure to risk factors, covering ~100 m along the waterline and the entire beach width. Each segment corresponded to a different beach: there were no continuous segments, with the closest segments being separated by ~600 m. The resulting spatial resolution was ~5 mm. We processed the images into orthophotos using Agisoft Photoscan (Metashape Professional v2).

To complement the surveyed data, we created a layer of all sandy beaches in the archipelago, delineated using Google satellite imagery within QGIS 3.32.2. For comparability, we divided this digitised layer into segments ranging from 100 to 1000 m in length, depending on the total beach extension. Longer beaches were subdivided into multiple segments (e.g. a 5000-m beach was divided into five 1000-m segments) to capture variability in risk exposure along their extent. Shorter beaches (< 1000 m) were retained as single segments, while very small beaches (< 100 m) were excluded. This segmentation allowed for standardisation across beaches of varying lengths while avoiding the overrepresentation of

Fig. 1 Study area across seven islands in Cabo Verde. Drone-surveyed segments are represented in red (61 segments, each ~100 m in length) and digitised segments are outlined in black (306 segments manually digitised, 100–1000 m in length). Segments' widths are exaggerated for representation



smaller beaches. By allowing lengths to vary between 100 and 1000 m, we captured variability where needed without unnecessary fragmentation. This facilitated model extrapolation, resulting in a total of 306 segments.

Thus, we obtained two distinct layers of nesting beaches (Fig. 1): (i) a layer comprising 61 segments (~100 m) independently surveyed using drones, hereafter called drone-surveyed layer; and (ii) a layer comprising 306 digitised segments of sandy beaches both surveyed and

non-surveyed (from 100 to 1000 m), hereafter called digitised layer.

Nest density modelling

To predict the density of nests, we counted the number of loggerhead turtle nests within the drone-surveyed layer from two sources: (i) photointerpretation of orthophotos (nests with freshly visible tracks to ensure they were

recently laid; only 1 day of data from the drone surveys in September/October 2021, 2022, or 2023), and (ii) data from local NGOs (ten randomly selected monitoring days between August and September 2020, 2021, and 2022). NGOs that provided data are Biosfera, Project Biodiversity, BIOS.CV, Cabo Verde Natura 2000, and Maio Biodiversity Foundation. Main nesting beaches are monitored daily during the nesting season by NGOs; however, due to data restrictions, we included data from only ten random days across the seasons in each beach. Moreover, not all beaches are monitored by NGOs.

We calculated a nest density index as the number of nests per 100 m per day, which can be expressed as

$$\frac{\text{Total number of nests in drone-surveyed segment}}{\text{Segment length(m)} \times \text{Number of surveyed days}} \times 100.$$

We used predictive modelling to assess the spatial distribution of nest density index across beaches, by assigning to each segment (both drone-surveyed and digitised) a set of environmental variables: topographical data derived from the digital elevation model (DEM) of the Shuttle Radar Topography Mission (SRTM v3; Farr et al. 2007), with a spatial resolution of ~30 m; and oceanographic data from Bio-ORACLE v3 (Assis et al. 2024) for present-day conditions (2010–2020), with a resolution of ~5.5 km. We selected the environmental variables based on their importance for nest site selection (Wood and Bjørndal 2000; Putman et al. 2010; Christiaanse et al. 2024). Topographical variables included slope (the ratio of the elevation difference to the horizontal distance between two points, in percentage); and northness and eastness (respectively calculated as $\cos(\text{aspect})$ and $\sin(\text{aspect})$, ranging from 1 to -1, from full north/east to full south/west; Guisan et al. 1999; Sillero et al. 2021). Oceanographic variables included minimum, maximum, and median values of ocean temperature (°C); seawater velocity (ms^{-1}); northward seawater direction ($\cos(\text{seawater direction})$, from 1 to -1); and southward seawater direction ($\sin(\text{seawater direction})$, from 1 to -1). For each segment of both drone-surveyed and digitised layers, we extracted the median values of topographical variables and the closest pixel value of oceanographic variables. Additionally, we treated island as a categorical variable (with seven levels corresponding to the seven islands) to account for the philopatric behaviour of sea turtles (~77% of nesting females lay their eggs within 15 km of their previous nests; Patino-Martinez et al. 2022). This resulted in three topographical variables (median slope, northness, and eastness), 12 oceanographic variables (minimum, maximum, and median ocean temperature, seawater velocity, northward seawater, and southward seawater), and one categorical variable (island). We excluded highly correlated variables using the variance inflation factor ($\text{VIF} > 2$) (Sillero et al. 2021).

We modelled the nest density index within the drone-surveyed layer using the algorithm Gradient Boosting

Machine (GBM), with nest density index as the response variable, and five explanatory variables with correlation below the VIF threshold: median slope, median eastness, minimum northward seawater, maximum seawater velocity, and island. We used tenfold cross-validation to assess model performance and determined the optimal hyperparameters based on the lowest Root Mean Squared Error (RMSE). We fitted the final GBM model using the 'gbm' function in R (R Core Team 2020) with Gaussian distribution and projected onto the digitised layer. To evaluate the model's predictive performance, we fitted a linear regression to compare the actual versus predicted values.

Risk factors

The five risk factors were selected based on their impact on sea turtle nesting (Vousdoukas et al. 2020; Simantiris 2024) and data availability. Risk layers were derived using predictive modelling (marine debris density), trend analyses (inundation, warming, and light pollution), and the identification of tourism pressure. The final output indicates the presence or absence of each risk in every digitised segment.

Marine debris density model

We identified large marine debris (> 25 mm; fragments, fishing materials, containers/packaging, processed wood, clothing, and others) through photointerpretation of orthophotos at the drone-surveyed layer (Sousa-Guedes et al. 2024). We quantified marine debris density in each segment as the number of items per 100 m of beach length, log-transformed and standardised (between 0 and 1) for analysis.

To predict the spatial distribution of marine debris densities, we used GBM modelling with Gaussian distribution, and four explanatory variables (calculated as in the 'Nest density modelling' section): median eastness, median northness, minimum northward seawater, and maximum seawater velocity. We selected the variables based on their role in marine debris accumulation (Cardoso and Caldeira 2021; Sousa-Guedes et al. 2024). We trained the model on the drone-surveyed layer and projected it onto the digitised layer using the same procedure as the nest density model in R.

Inundation, warming, and light pollution trends

To assess temporal changes in water inundation, warming, and light pollution, we obtained data from different satellite imagery sources. All satellite imagery processing and trend analyses were conducted in the cloud-based platform Google Earth Engine (GEE; Gorelick et al. 2017). We detected water inundation over time for all islands with the Modified Normalised Difference Water Index (MNDWI; Xu 2006),

using Landsat 8 images (USGS, L2/C2/T1) from 2013 to 2023, during nesting season (June–October) at the original resolution of ~ 30 m. The MNDWI uses the green and shortwave infrared bands (*Green*—*SWIR1*/*Green* + *SWIR1*), identifying open water while suppressing noise from built-up, vegetation, and soil. Similar techniques have been used to estimate flooding on beaches (Makris et al. 2023). We removed pixels with clouds and cloud shadows with bitwise operations (QA_PIXEL).

For warming trends, we generated land surface temperature (LST) data from 2000 to 2023, during the nesting season (June–October), from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor (8-day L3; Wan et al. 2021). LST captures the thermal behaviour of the land surface across large areas and periods (Reiners et al. 2023). We computed the nighttime LST at their original spatial resolution of ~ 1 km, scaled the values from Kelvin to Celsius, and implemented a cloud masking function (QC_Night). We focused on nighttime LSTs rather than daytime, which have shown stronger trends in recent years (Almeida et al. 2023).

Similarly, to assess light pollution, we calculated the nighttime light using the VIIRS/DNB satellite (monthly Stray Light Corrected Nighttime Day/Night Band Composites v1), at a spatial resolution of ~ 500 m (Mander et al. 2023; Hu et al. 2018; Attum and Nagy 2024). We calculated the annual maximum light during the nesting season (June–October) for 2014–2019, excluding post-2020 data due to temporary reductions in tourism and light pollution from COVID-19 lockdowns, which have since returned to pre-pandemic levels (Sarmiento and Monteiro 2023; Attum and Nagy 2024; Akkemik et al. 2024; Sillero et al. 2024).

Then, we assessed temporal trends in inundation, nighttime LST, and light pollution using the Mann–Kendall test (Kendall 1990). This non-parametric test identifies monotonic trends in time series data, distinguishing between downward (negative) or upward (positive) slopes over time. We conducted trend analyses at a 95% confidence level and exported the pixels with significant positive trends ($p < 0.05$). By focusing on trends rather than stationary values, we assume that increasing inundation, temperatures, and light pollution will persist due to climate change, urbanisation, and population growth (Nicholls and Cazenave 2010; IPCC 2021).

We obtained three trend layers (inundation, warming, and light pollution) covering the whole area of the islands. To extract trends within the digitised beach segments, we clipped the inundation and LST layers to match the segment boundaries. For inundation trends, we applied an additional filtering step to ensure that segments are not wrongly classified as inundated due to isolated, artificial significant pixels. Thus, segments were only considered inundated if they contained at least three significantly positive pixels (~ 90 m, equivalent to three times the Landsat pixel size).

Light pollution trends were assessed differently, as light sources are located outside the beach. For this, we calculated the visibility from the centroid of each digitised segment (306 points) to the nearest light source (i.e. centroids of pixels with significant positive Mann–Kendall slope in light pollution, at the 75th percentile) using the ‘intervisibility network’ function in QGIS. This function uses the DEM of the islands to determine visibility between an observer and a target point, both set at a ground-level height, within a 5000-m radius.

Tourism pressure

A tourism pressure layer was calculated by identifying the location of major tourist resorts using Google Maps within QGIS.

Vulnerability index

We classified each risk factor as present or absent based on the 75th percentile threshold, identifying 25% of the most vulnerable segments (except for tourism pressure). This conservative threshold prioritises conservation efforts and resources to areas most in need. We created binary layers, assigning a value of 1 to digitised segments exceeding the defined threshold in each risk factor. For tourism pressure, a value of 1 was assigned to digitised segments with such infrastructures. We then computed a vulnerability index for each digitised segment, ranging from 0 to 5 (considering marine debris density; inundation, warming, and light pollution trends; and tourism pressure), by summing the binary risk factors (presence = 1, absence = 0). We also calculated and normalised the percentage of segments with each risk factor and vulnerability index class by island.

Additionally, to assess whether high nest density index co-occurs with each risk factor, we performed a linear regression using the modelled predicted nest density index as the response variable and the risk factors as explanatory variables, in R.

Results

Nest density modelling

The 61 drone-surveyed segments exhibited a nest density index ranging from 0 to 13.3 nests per 100 m of beach length per surveyed day, totalling 5991 nests, with the highest index value observed in eastern Boa Vista (Fig. S1, Supplementary Materials).

The performance of the GBM nest density model indicated a good fit ($R^2 = 0.85$). The linear regression presented a strong positive correlation between the predicted and the

actual values (estimate = 1.109, SE = 0.059, $p < 0.001$). The most influential variable in the model was seawater velocity (26.3%), followed by island (20.0%), eastness (19.1%), slope (18.6%), and northward seawater (16.0%). When projecting the model to all islands, Boa Vista showed the highest predicted nest density index (65.5% of all nests; Table 1), with a total of 22 digitised segments between 8.1 and 11.5 nests/100 m/day (high season), on the eastern side of the island. The second island with the highest proportion of predicted nests is Sal (14.5%), followed by Maio (6.9%), São Vicente (6.2%), Santa Luzia (5.5%), Santo Antão (0.9%), and Santiago (0.4%).

Risk factors

All drone-surveyed segments had at least one item of marine debris, ranging from 1 (in Santo Antão) and 5038 items/100 m (Santa Luzia) (Fig. S1 and Table S1, Supplementary Materials). The performance of the GBM model for marine debris density indicated a reasonably good fit ($R^2 = 0.56$). The linear regression showed a strong positive correlation between the predicted and actual values (estimate = 1.088, SE = 0.125, $p < 0.001$). The most influential variable in the model was northness (40.0%), followed by northward seawater (24.0%), eastness (18.9%), and seawater velocity (17.1%). A total of 78 digitised beach segments were above the threshold of predicted values (75th percentile of log-transformed and standardised marine debris density = 0.618), with the most affected island being Santiago

(66.7% of its segments) and in absolute numbers Boa Vista (23 segments) (Table 2). Santo Antão had only one digitised segment accumulating large volumes of marine litter. Segments oriented to the north and east had a higher probability of accumulating a large number of marine debris across most islands (Fig. 2).

We identified significant positive inundation trends (75th percentile of significant positive slopes = 0.007) on 24 digitised segments from five islands (Table 2), with the most affected islands being São Vicente (16.7% of its segments) and Boa Vista (10 segments). Santiago and Santa Luzia showed no significant increase in inundation trends. Nighttime LST revealed significant positive trends (75th percentile of significant positive slopes = 0.075 °C/year) on 28 segments from six islands, with Santa Luzia being the most affected (31.3% of its segments) and São Vicente by absolute numbers (seven segments). Santiago exhibited no warming trends. We found increased light pollution levels (75th percentile of significant positive slopes = 0.320 nW/cm²/sr/year) in 54 segments from six islands, with São Vicente being the most affected (58.3%, totalling 14 segments). Santa Luzia showed no increase in light pollution. We observed tourism pressure on 13 segments from four islands, with Sal being the most developed (14.0%, totalling seven segments). Santo Antão, Santa Luzia, and Maio showed no evidence of tourism pressure.

Marine litter is the most widespread risk, affecting 78 segments (25.5%), followed by increasing light pollution (54 segments, 17.6%), increasing nighttime LST (28 segments,

Table 1 Predicted number (n) and percentage (%) of nests per day as estimated with the GBM model, and total length of digitised segments per island

	Santo Antão	São Vicente	Santa Luzia	Sal	Boa Vista	Maio	Santiago	Total
Predicted nests/day (n)	34.7	230.2	203.8	536.0	2420.8	256.3	13.5	3695.2
Predicted nests/day (%)	0.9	6.2	5.5	14.5	65.5	6.9	0.4	100
Total length	15.2 km	11.8 km	10.7 km	18.8 km	67.0 km	33.7 km	6.5 km	163.8 km

Table 2 Number (n) and percentage (%) of digitised segments with each risk factor in each island (> 75th percentile). In bold, the highest value for each factor

Risk factor	Santo Antão		São Vicente		Santa Luzia		Sal		Boa Vista		Maio		Santiago		Total segments	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%
Marine debris	1	2.3	10	41.7	3	18.8	17	34.0	23	25.6	10	16.4	14	66.7	78	25.5
Inundation	1	2.3	4	16.7	0	0	3	6.0	10	11.1	6	9.8	0	0	24	7.8
Land surface temperature	1	2.3	7	29.2	5	31.3	5	10.0	6	6.7	4	6.6	0	0	28	9.2
Light pollution	5	11.4	14	58.3	0	0	12	24.0	13	14.4	5	8.2	5	23.8	54	17.6
Tourism pressure	0	0	1	4.2	0	0	7	14.0	4	4.4	0	0	1	4.8	13	4.2
Total segments	44		24		16		50		90		61		21		306	

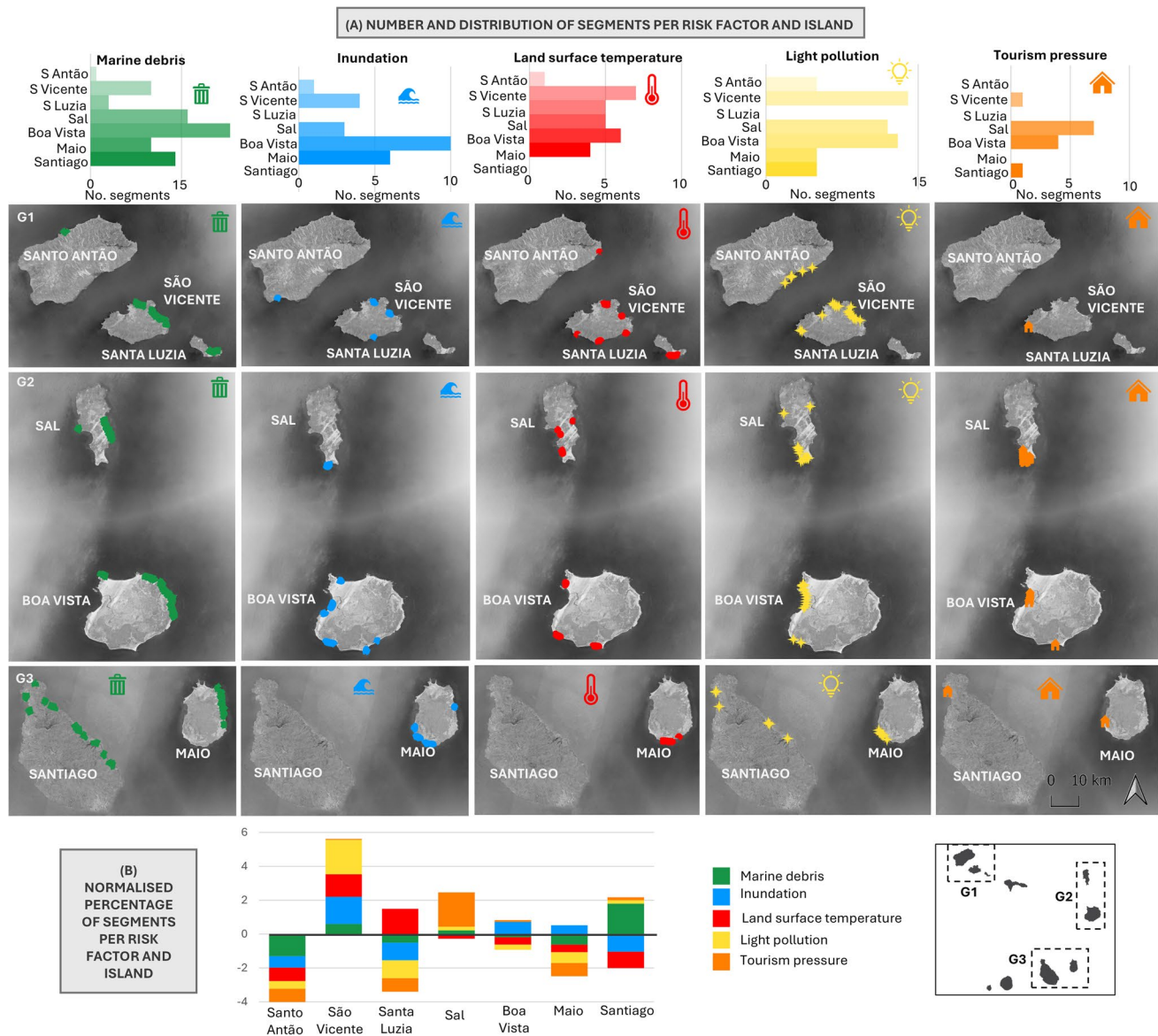


Fig. 2 (A) Number and distribution of digitised beach segments at risk per risk factor and island; (B) normalised percentage of segments per risk factor and island, where negative and positive values indicate a lower and higher percentage of segments compared to the average, respectively

9.2%), increasing inundation (24 segments, 7.8%), and tourism pressure (13 segments, 4.2%; Table 2). São Vicente is at higher risk across all factors, while Santo Antão has the lowest risk (Fig. 2B).

Relationship between risk factors and nest density

The linear regression model of the relationship between nest density index and risk factors showed weak performance (adjusted $R^2 = 0.08$). The model indicated that marine debris density and light pollution were significantly related to nest density index, with marine debris having a positive effect (estimate = 1.727, SE = 0.349,

$p < 0.001$) and light pollution having a negative effect (estimate = -1.198, SE = 0.425, $p = 0.005$). The remaining risk factors were not significantly related to the predicted nest density index.

Vulnerable areas

We identified 158 non-vulnerable digitised segments (vulnerability index of 0), with the safest island being Santo Antão (81.8% are safe) and Boa Vista in absolute numbers (45 are safe). São Vicente and Santiago have 83.3% and 66.7% of segments with some risk, respectively (Table 3). Additionally, 112 segments had one risk factor (all islands),

Table 3 Number (*n*) and percentage (%) of digitised segments corresponding to each vulnerability index class in each island. In bold, the highest value for each index class

Vulnerability index	Santo Antão		São Vicente		Santa Luzia		Sal		Boa Vista		Maio		Santiago		Total segments	
	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%
0	36	81.8	4	16.7	8	50.0	19	38.0	45	50.0	39	63.9	7	33.3	158	51.6
1	8	18.2	9	37.5	8	50.0	22	44.0	37	41.1	19	31.1	9	42.9	112	36.6
2	0	0	7	29.2	0	0	6	12.0	6	6.7	3	4.9	4	19.0	26	8.5
3	0	0	3	12.5	0	0	3	6.0	2	2.2	0	0	1	4.8	9	2.9
4	0	0	1	4.2	0	0	0	0	0	0	0	0	0	0	1	0.3
Segments at risk	8	18.2	20	83.3	8	50.0	31	62.0	45	50.0	22	36.1	14	66.7	148	48.4

26 had two risk factors (all islands except Santo Antão and Santa Luzia), nine had three risk factors (São Vicente, Sal, and Boa Vista), and only one had four risk factors (São Vicente). No segment had all five risk factors.

There is no substantial spatial overlap between high predicted nest density index and vulnerable areas in Santo Antão, Santa Luzia, Maio, and Santiago (Fig. 3). In São Vicente, multiple segments with high nest density index face one to three risk factors (Fig. 3D). Sal also showed some overlap between high nest density index overlaps and vulnerability, while Boa Vista primarily has segments with either no risks or just one risk factor.

Discussion

Our study revealed that 48% of the sandy beaches in Cabo Verde are exposed to some threat, with vulnerability levels varying across islands. Marine debris is the most widespread risk, affecting 26% of the beach segments, including high-density loggerhead nesting areas. Most marine debris is fisheries-related plastics, posing risks of entrapment and toxicity (Aguilera et al. 2018; Weidlich and Lenz 2022; Sousa-Guedes et al. 2023a, 2023b, 2024). Of the 61 *drone-surveyed* segments, 47 exceeded the recommended European threshold of 20 macro-litter items/100 m (Van Loon et al. 2020). In fact, five segments exceeded the threshold by over two orders of magnitude: Achados (three segments with up to 5038 items/100 m; Santa Luzia; Sousa-Guedes et al. 2024), Ponta de Roque and Figura (5010 and 2727 items/100 m, respectively; Boa Vista); and 12 segments in Santo Antão, Boa Vista, and Maio surpassed the threshold by over 20 times (Table S1, Supplementary Materials). The absence of data on clean-up frequency (which occurs at least once a year on some of the main nesting beaches) may have skewed results, underestimating pollution levels in some areas. Furthermore, while a single drone survey per beach might overlook seasonal variations (Frias et al. 2018), our marine debris model aligns with previous studies indicating

higher accumulation on north and east-facing beaches, driven by ocean currents (Cardoso and Caldeira 2021; Weidlich and Lenz 2022; Sousa-Guedes et al. 2024). Northern islands, particularly Santa Luzia and Boa Vista, are more affected because they may act as barriers against the North Atlantic Gyre, with strong clockwise currents. We also found a significant co-occurrence of marine debris and high nest density index, which could negatively impact incubation and hatchling emergence (Aguilera et al. 2018; Fuentes et al. 2023; Sousa-Guedes et al. 2023a, 2023b). As females seem to avoid nesting in heavily polluted beaches (Fujisaki and Lamont 2016), future studies should explore correlations between marine debris and nesting failure or clustering.

Rising light pollution, affecting 18% of segments, was concentrated near urban centres. A significant negative relationship between light pollution and nest density index suggests potential avoidance of brightly lit beaches by females (Hu et al. 2018). However, this pattern might instead reflect the spatial separation between main urban centres (west coast) and loggerhead nesting preferences (east coast), rather than active avoidance of illuminated beaches. Artificial lighting is known to reduce nesting success and hatchling survival due to disorientation (Lorne and Salmon 2007; Silva et al. 2017). In Cabo Verde, many isolated areas remain unaffected by artificial light, providing important nesting refuges. Although hatchlings can be influenced by artificial ambient light from sources several kilometres away, with effects intensifying nearer the source (Kamrowski et al. 2015; Weishampel et al. 2016), this impact is minimal in Cabo Verde, due to the small size and poor illumination of urban settlements. Additionally, artificial lighting on beaches can delay hatchlings' ocean dispersal, keeping them nearshore 23% longer than under ambient light, increasing predation risk (Thums et al. 2016).

Nesting in Cabo Verde currently occurs during the warmest time of the year. Rising temperatures affect 9% of beach segments, with Santa Luzia and São Vicente being the most affected. Wider beaches with less vegetation seem more vulnerable to warming, with an average width of 23 m versus

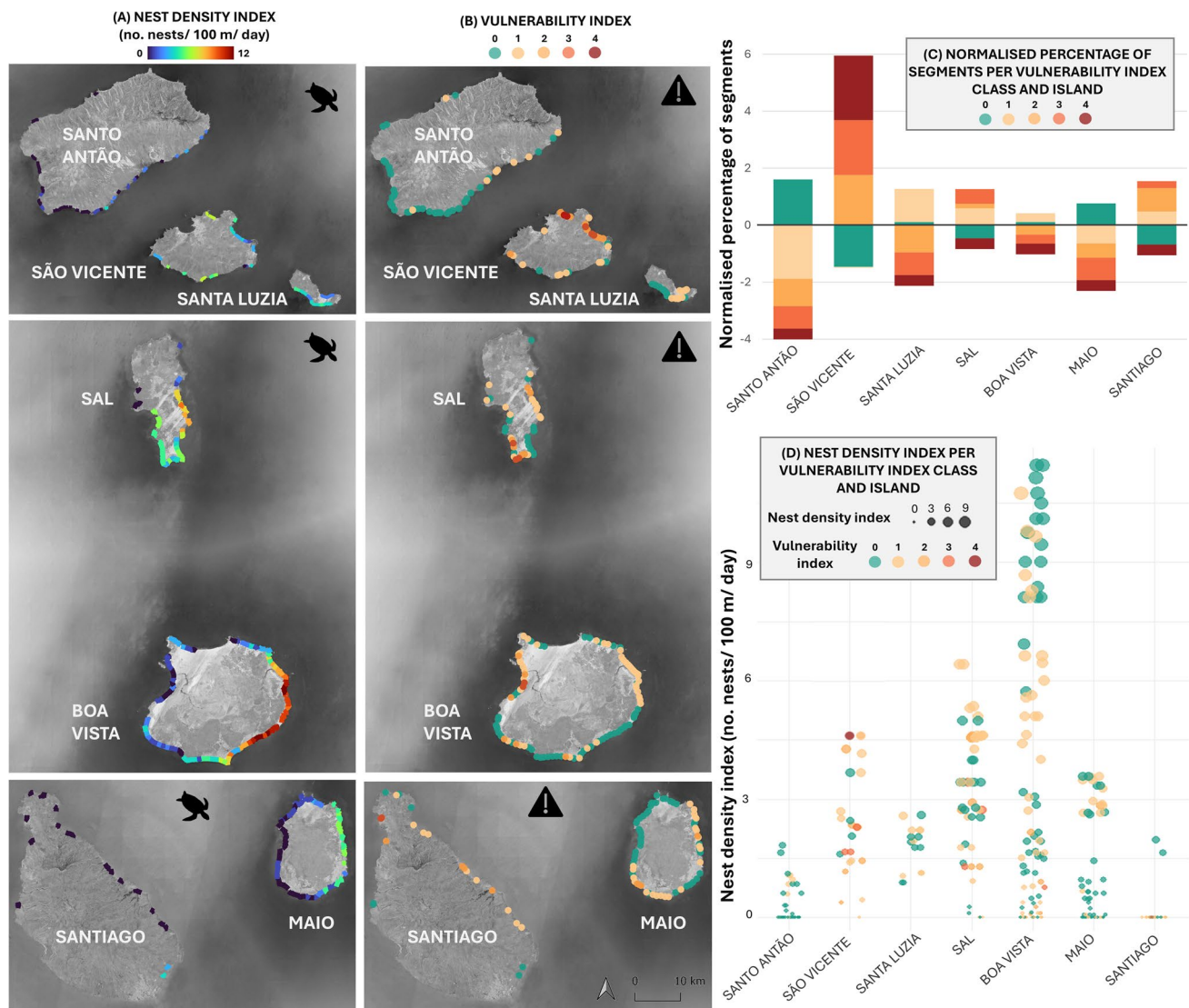


Fig. 3 (A) Predicted nest density index across digitised beach segments; (B) vulnerability index across segments; (C) normalised percentage of beaches per vulnerability index class and island, where negative and positive values indicate a lower and higher percentage

of segments compared to the average, respectively; (D) predicted nest density index per vulnerability index class and island, with circle sizes increasing with nest density index

15 m for non-warming segments (Mann–Whitney U test, $p=0.005$). Other factors, such as exposure to winds, may also contribute. In Sal, nesting occurs mostly on the coolest beaches (Albert Taxonera, personal observation), whereas in Boa Vista, it is mainly concentrated on its warmest beaches (Abella-Perez et al. 2016; Tanner et al. 2019). Despite many beaches in Boa Vista producing nearly all-females hatchlings, the island is considered relatively resilient, with a few cooler beaches producing a significant number of male hatchlings (e.g. Boa Esperança, Lacacão and Varandinha; Tanner et al. 2019). Among these, Lacacão, located in the south, has shown significant warming trends in the present study (Fig. 2). Cooler beaches may be more sensitive

to rising temperatures, while warmer beaches may have reached a point where further warming is limited. Under a low-emission scenario (1.8 °C increase), primary sex ratios in Cabo Verde are projected to exceed 99% female hatchlings by 2100 (Tanner et al. 2019). If temperatures continue to rise, hatching success could be compromised (Abella-Perez et al. 2016; Laloë et al. 2017; Tanner et al. 2019). Conserving cooler beaches should be prioritised to secure the production of male offspring. While ongoing warming can drive temporal or spatial shifts in nesting, these are unlikely to offset the predicted effects of rising temperatures (Laloë and Hays 2023; Fuentes et al. 2024).

We observed an increasing inundation trend on 8% of beach segments, with higher proportions in São Vicente, Boa Vista, and Maio, particularly on southern shores. Boa Vista and Maio, along with Sal, are the geologically oldest islands and the most eroded ones, which may increase their flooding risks (Gomes et al. 2019; Samrock et al. 2022). Sea-level rise and more frequent storms are expected to further intensify inundations (Nicholls et al. 2011; Young et al. 2011; Lee et al. 2017), but these impacts will not occur uniformly across the globe (Nicholls and Cazenave 2010; Romine et al. 2013). In Boa Vista, future sea-level rise is predicted to have the greatest impact in Sal Rei (northwest coast; Gomes et al. 2019), which often inundates during winter, potentially due to reduced beach management and deteriorated dunes. Our study, conducted during summer, coincides with winter in the southern hemisphere, a period of frequent storms, potentially exacerbating inundations on southern beaches. Climate change affects erosion-accretion dynamics (Feagin et al. 2005; Romine et al. 2013), amplified by coastal development, that restricts the natural landward migration of beaches, ultimately reducing the area available for nesting (Armstrong and Lazarus 2019; Patrício et al. 2019). While Boa Vista remains moderately impacted due to its undeveloped coastline and dune systems (Abella-Perez et al. 2016), globally, one-quarter of sea turtle nesting coastlines are bordered by anthropogenic structures (Biddiscombe et al. 2020).

Tourism pressure, affecting only 4% of segments, is heavily concentrated in Sal (14% of its segments) and Boa Vista (4%), the two most important nesting islands. Loggerhead nesting activity has been reduced in areas with tourist developments in Sal (Taylor and Cozens 2010). Given the growth of the tourism industry, with overnight stays more than doubling since 2010 (~5 million in 2023, more than half occurring in Sal; INE 2023), the impact on nesting activity is likely even greater today. Large all-inclusive resorts occupy most southern beaches in Sal and some of the northwest coast in Boa Vista, which are also suitable for turtle nesting. Boa Vista has its most important nesting areas protected under the Sea Turtle Natural Reserve. In non-protected areas, a legally established 80-m coastal buffer zone for infrastructure construction is frequently ignored. Furthermore, tourism activities focused on turtle-watching, especially in Boa Vista and Sal, can have minimal impact on the nesting if conducted responsibly (Marco et al. 2021), but tourism development could exacerbate risks. Current and future planned developments in Sal, Boa Vista, and Maio (outlined in instruments like ZDTIs—Integral Touristic Development Zone) could further threaten nesting habitats through increased light pollution and beach degradation.

Overall, São Vicente, Santiago, and Sal are the most threatened islands (83%, 67%, and 62% of their beach segments at risk, respectively), with marine debris and light

pollution affecting the greatest number of segments. These three islands are also the most densely populated (INE 2023), and their urbanisation results in strong illumination reaching multiple beaches. Conversely, Santo Antão and Maio are the safest islands (18% and 36% at risk, respectively). Their relative isolation, lower urbanisation, and limited tourist activity contribute to the reduced risk levels. Furthermore, Santa Luzia and Boa Vista have half of their beach segments at risk, largely due to the accumulation of marine debris. Santa Luzia is a special case as an uninhabited island: even without human settlements, its beaches have some type of risks. Overall, over half of the beach segments in the archipelago remain free from any identified risks, with 158 segments classified as safe.

Our nest density model indicated that seawater velocity significantly influences beach selection. Favourable ocean currents can influence hatchling dispersal by facilitating rapid escape to open waters and providing suitable foraging areas for adult females (Putman et al. 2010). Overall, our model predicted that east-facing beaches have a higher probability of hosting more nests, supported by multiple studies on the islands (Marco et al. 2011, 2012; Laloë et al. 2020; Patino-Martinez et al. 2022, 2023). Our model (Fig. 3A) underestimated nest densities on western Sal (Laloë et al. 2020), likely due to better calibration and a larger dataset for Boa Vista. Additionally, the lack of local habitat variables (e.g. sand type), may have caused unsuitable locations to be misclassified as suitable. Among islands with high nest densities (Boa Vista, Sal, and Maio), Sal presents the greatest overlap between vulnerable areas and high-density beaches, making it a conservation priority.

While this study considers cumulative risks, their relative impacts on nesting grounds are not uniform. The interactions between threats can amplify these impacts, as global changes rarely act in isolation (Harley et al. 2006; Brooks et al. 2009). For example, rising sea levels could transport marine debris to higher beach strata, increasing the overlap with nests and intensifying density-dependent issues (Tiwari et al. 2006). The development of tourism infrastructure on beaches affects erosion-accretion dynamics and exacerbates beach loss and inundations (Miles et al. 2001). Warmer sands, combined with plastic pollution, may increase sand temperatures even further or amplify the leakage of harmful plastic additives (Lavers et al. 2021; Fuentes et al. 2023; Sousa-Guedes et al. 2023a).

The resilience of sea turtle populations to environmental changes will depend on the persistence of suitable nesting sites and their adaptive capacity (Patrício et al. 2021). Exposed and highly dynamic sandy beaches, reshaped by wind and waves, support this adaptability. Females may lay multiple clutches over weeks and locations, reducing the risk of losing all nests in an adverse event (Hirth 1980). In Cabo Verde, around 20% of nests are over 15 km from a female's previous nest, suggesting room for colonisation of new areas

(Patino-Martinez et al. 2022). Hopefully, sea turtles might adapt to these upcoming climate changes, as they did in the past—which were similar in magnitude but not at the current rate (Fuentes et al. 2011; Quintero and Wiens 2013; Patrício et al. 2021). Protecting beaches with a high density of nests is a priority, but neglecting other beaches might overlook future suitable sites, and there is no reason to expect that the distribution of nests will remain the same in the future.

Our assessment aims to inform local stakeholders of immediate threats to nesting beaches. A multifaceted approach is needed, including waste management, lighting regulations, and sustainable tourism. Zoning strategies are important for managing spatial gradients of human impact, with site-specific actions based on feasibility, risk, cost, and success probability (Pressey and Bottrill 2009). For instance, relocating nests to cooler areas may work in some cases but is impractical for remote sites like Santa Luzia. Thus, conservation efforts should be adapted to local risks, and future evaluations should incorporate population sensitivity and adaptive capacity for comprehensive vulnerability analyses of nesting sites (Butt et al. 2022; Lettrich et al. 2020).

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Data availability The data used in this study will be made available upon reasonable request.

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