ECOLOGICAL NICHE HABITAT SUITABILITY MODELING OF SOOTY FALCON IN SAUDI ARABIA'S ISLAND

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Paper Overview: This paper explores how the use of ecological modeling techniques, which integrate long term data and machine learning algorithms into the spatial distribution of nesting habitats of Sooty Falcon.

ABSTRACT

Sooty Falcon (*Falco concolor*), categorized by the IUCN Red List as globally vulnerable globally and regionally endangered, is a species of High Conservation Priority (HCP) in the Kingdom of Saudi Arabia. Its population is estimated around 2,800-4,000 globally. The Red Sea islands are critical breeding grounds for this migratory bird with estimated population of 300 in KSA. Globally, habitat loss due to development activities has led to a population decline. Red Sea Global (RSG) operates in areas inhabited by Sooty Falcon, making it essential for RSG to integrate habitat conservation into project master planning and design. There is limited data on the Sooty Falcon's nesting habitats and microhabitat environmental variables, which are crucial for habitat suitability assessments. This study involved three years of ecological surveys during the breeding seasons, to document the species' abundance and nesting locations on one of the island. Using drone surveys, a Digital Terrain and Surface Models was developed and the MaxEnt model was applied to identify key environmental variables (such as roughness, distance to shoreline, slope, aspect, habitat types, Heat Load Index (HLI), and nesting space) that influence habitat suitability. The study's results, validated by three-year field survey findings, provided spatial distribution data on nesting habitat and critical environmental variables. Modelling helped identify that 70% of the Island area, predominantly in the South, is highly suitable for nesting. The findings from the study will help design targeted protection measures and long-term conservation planning for the Sooty Falcon on the island.

Introduction

The Red Sea coast of the Kingdom of Saudi Arabia (KSA) is home to a variety of breeding avifauna, many of these have globally recognized conservation status. Also, Saudi Arabia's coastline is important for breeding terns and gulls and major migratory flyways exist (Figure 1). The first systematic seabird survey in this region was conducted by the International Union for Conservation of Nature (IUCN) and the Marine Environmental Protection Authority (MEPA) during the summers of 1982 and 1983. This survey highlighted the importance of Saudi Arabia's coastline for breeding terns and gulls (Shobrak, 2013). However, studies on some of the coastal avifauna species of the Red Sea remain limited.

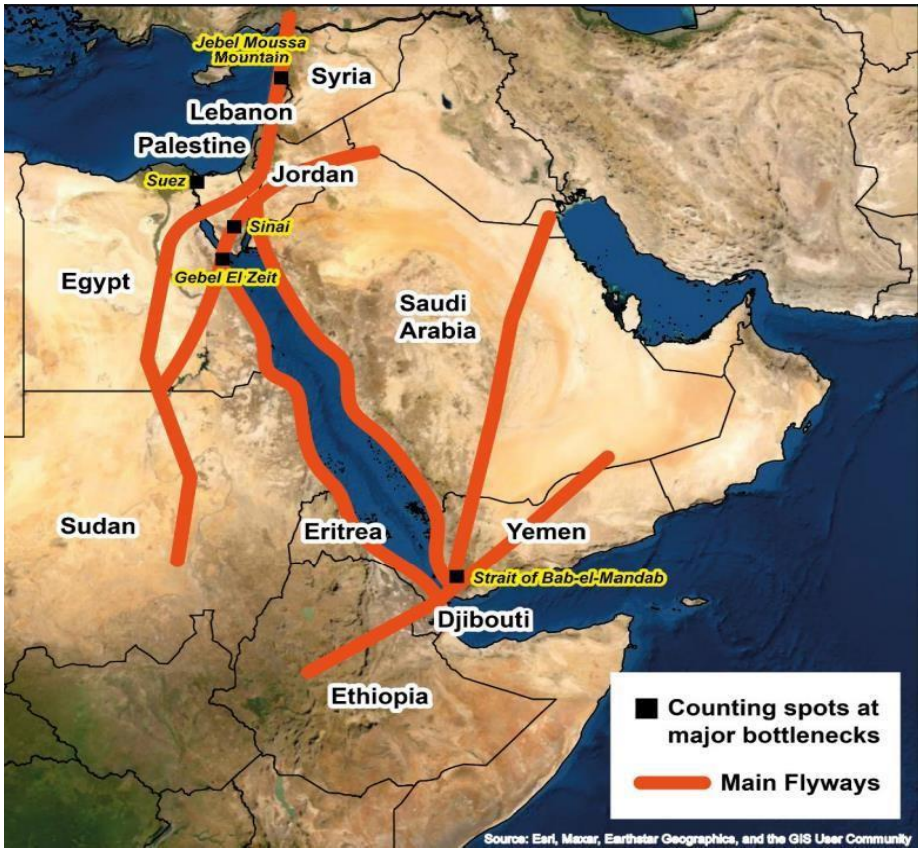

Figure 1 Migratory Bird Routes within Red Sea (Birdlife International)

One such coastal species is the Sooty Falcon (*Falco concolor*) (Figure 2), which is listed as globally Vulnerable and regionally endangered on the IUCN Red List, with both global and regional populations are in decline (Boland & Al Suhaibani, 2020). The Sooty Falcon is known to breed in arid, hot environments, typically on inland and coastal cliffs, small rocky islands, and rugged desert mountains and found in Saudi Coastline (Boland & Al Suhaibani, 2020). Their nests are typically found in shallow depressions within rock niches or shaded by natural overhangs, and the species exhibits high site fidelity for nesting. Breeding occurs from April to November, when the Sooty Falcons migrate from Madagascar and southeastern Africa to the Red Sea coast and the Arabian Gulf islands, returning to Madagascar after the breeding season (Boland & Al Suhaibani, 2020).

Figure 2 Sooty Falcon Juvenile in the island

Given the limited information available on this species and the habitat it needs to breed in the Red Sea coastal island, Red Sea Global (RSG) took steps to further investigate its nesting habitat. No available data has been found of previous attempts to study Sooty Falcon nesting habitat. RSG selected Species Distribution Modeling (SDM) to model the Sooty Falcon's breeding habitat. SDM, also known as ecological niche modeling, is widely used method in ecology and conservation biology to predict the potential distribution of a species based on environmental variables. This approach utilizes statistical and mathematical techniques to correlate known occurrences of a species with environmental factors such as climate, topography, and land cover. The resulting models allow for the prediction of a species' potential distribution across larger areas, making SDMs a robust tool in conservation planning, invasive species management, and other ecological applications.

Species Distribution Model

MaxEnt, also referred to as Presence-only -prediction, is an open-source software for modelling species niches and distributions based on maximum entropy, a machine learning technique. The tool was developed by the Center for Biodiversity and Conservation at the American Museum of Natural History in partnership with AT&T-Research (History, 2025). It uses known occurrence points, and explanatory variables in the form of fields, rasters, or distance features to provide an estimate of presence across a study area. The output is a heat map which shows the varying probability of occurrence across the subject location (Figure 3).

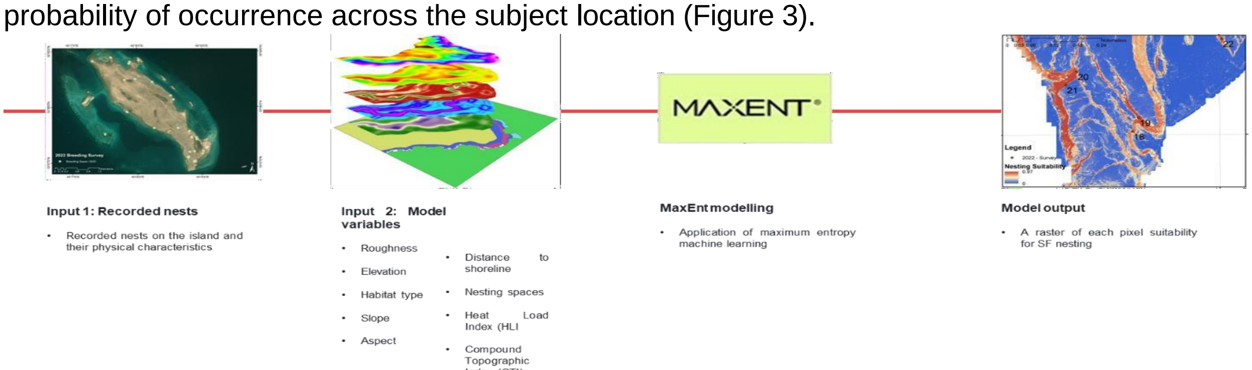

Figure 3: Maxent - inputs and outputs (ESRI, 2025)

It models the presence of a phenomenon given known presence locations and explanatory variables using a maximum entropy approach, MaxEnt does not assume nor require absence, data sets that confirm the absence of the phenomenon, it predicts presence based on a limited set of information. It uses the commonalities between the presence samples and applies it across a geographic area which its conditions have been defined by the incomplete set of data. The application of such commonalities results in an occurrence probability heat map. (Steven J. Phillips, 2008). While it is commonly used for conservation purposes, MaxEnt can be used for diverse purposes including climate change resilience planning, flood risk assessment, even healthcare management and disease control.

For this study, MaxEnt was used to assess the suitability of existing habitat for Sooty Falcon breeding based on data collected from three breeding season (2022, 2023, and 2024) surveys. Sooty Falcons exhibited varying nest re-occupancy rates during this period. It was noted that only 57.1% (8 of 15) of the active nests identified on the 2022 survey were re-occupied in 2023, whereas 76.9% (10 of 13) of the nests identified on the 2023 survey were re-occupied in 2024. Though these re-occupancy rates are influenced by various factors, including the birds' probability of survival, the appearance of new nests every year highlights the importance of focusing conservation efforts on the breeding habitat rather the identified nests.

Like any model, the accuracy of model outputs largely depends on the quality of the data used to set up and train the model. For this island, the resulting habitat map was tested against the identified nests from all breeding surveys. It was noted that 80% of the identified nests fall within areas identified as high suitability by the MaxEnt model.

Methodology

To provide an accurate output, MaxEnt requires three primary inputs:

- Study area
- Locations of known/confirmed presence points
- Explanatory variables which describe the environmental factors that may relate to presence across the study area.

A series of surveys, during breeding seasons, were undertaken to identify the location of nests. The surveys were undertaken in 2022, 2023, and 2024. Each survey was conducted in two stages, the first in August during the egg laying stage, and the second in September just before fledging. This approach was practiced on all three surveys to help assess breeding success.

The study area covered the entirety of the Island. For habitat suitability, high resolution variables are required to enhance the accuracy of the model. Thus, environmental variables were generated at a 12cm resolution based on Digital Terrain Model (DTM) and Digital Surface Model (DSM) layers created using a drone survey.

The set of variables that influence breeding habitat selection by the Sooty Falcons were identified through literature review, the same variables were used as inputs to the model. These variables are listed in Table 1 below.

Previous research has shown that Sooty Falcons prefer to nest in crevices facing north. This helps reduce their exposure to heat, which would be higher if the nest faced other directions (Jennings, 2010). To understand how much sunlight and heat a nest receives, a Heat Load Index (HLI) was calculated using DTM. The direction a slope faces (called A*spect*) was included in the analysis, as it affects how much heat the nest is exposed to.

Studies also observed that Sooty Falcons choose cliffs for nesting because they offer protection from predators. They tend to avoid areas that are too low, so elevation was included as another factor in the model (Jennings, 2010). SF also prefer nesting close to the sea, where they have better access to migrating and resident birds—main sources of food. Although some may nest on the ground in sheltered areas, so distance from the shoreline was another variable used in the model.

On the island, most nests were found in raised coral rock areas. To reflect this aspect, terrain *roughness*—which shows how uneven the land is—was added as a factor. Finally, the *Compound Topographic Index* was considered, which estimates how wet an area is based on slope and water flow. This is important because wetter areas are likely to have more vegetation, which attracts birds that the SF prey on (Kramer-Schadt et al., 2013).

Table 1 below lists model variables along with their calculation methodology.

Table 1: Model variables and methods of calculation

Variable	**Definition**	**Method of Calculation**
Roughness	A measure of the surface texture	Terrain Ruggedness Index ArcMap 10.8
Distance to shoreline	The distance from the nest/potential nest to the shoreline.	Euclidean distance tool ArcMap10.8
Variable	**Definition**	**Method of Calculation**
Slope	Measure of steepness.	Slope tool in ArcMap 10.8
Aspect	The direction in which slope is facing.	Aspect tool in Surface Analysis ArcMap 10.8
Habitat types	The habitat types recorded on the Island.	Field Survey, mapped using ArcMap 10.8
Compound Topographic Index	Is a function of both the slope and the upstream contributing area per unit width orthogonal to the flow direction and is a quantification of catenary topographic convergence	ArcMap 10.8
Heat Load Index (HLI)	Folding the aspect of the cooling capacity of the environment so that the highest values are facing southwest, and the lowest values are facing northeast.	HLI=($[1-\cos(\theta-45)]/2$
Elevation	Distance above sea level.	Drone Survey
Nesting space	Presence or absence of nesting space in a grid.	Identified during field survey and digitized using ArcMap 10.8

Analysis

The nesting habitat suitability model was first undertaken for the Island in 2022 utilizing data from the breeding season survey undertaken the same year. The model has been updated in 2023 and 2024 to include the findings of the breeding season surveys of each corresponding year, in addition to data collected the previous years. The latest results of the nesting habitat suitability model are mapped in Figure 4, showing Sooty Falcon highly suitable nesting locations in red pixels and low suitability locations in blue. The variable which had the highest contribution to the suitability of nesting is roughness, which contributed 75.1% to the nesting choices on the Island. Distance to shoreline is the second highest contributor to the nesting habitat suitability, along with aspect. The produced raster showing the model results were overlayed on the Island DEM layer indicated that most of high suitability distribution overlaps with cliffs on the Island. All cliffs on the Island had a suitability index higher than 50%, and almost all suitable nesting locations exist on cliffs. Cliffs north of the Island showed high suitability for Sooty Falcon nesting, but the southern side of the Island noticeably has the highest concentration of suitable nesting location. The distribution of suitable nesting locations in the south is in concordance of the higher number of nests recorded in that region. Based on the model results almost 75% of habitat with suitability higher than 80% exist on the southern cliffs. The identification of spatial distribution of suitable nesting habitat provides directions to the application of the mitigation hierarchy during construction and operation phases.

The outputs of the model were utilized to develop a zoning plan which informs the development footprint across the Island. The plan is based on the mitigation hierarchy and introduces avoidance measures by establishing a protected area in the south and avoidance buffers across the island.

Table 2: Variables and their percentual contribution to nesting habitat suitability

Variable	Percent contribution
Roughness	75.1
Distance to shoreline	8.3
Slope	5.4
Aspect	5.1
Habitat types	3.5
Compound Topographic Index	1.4
Heat Load Index (HLI)	0.5
Elevation	0.4
Nesting space	0.3

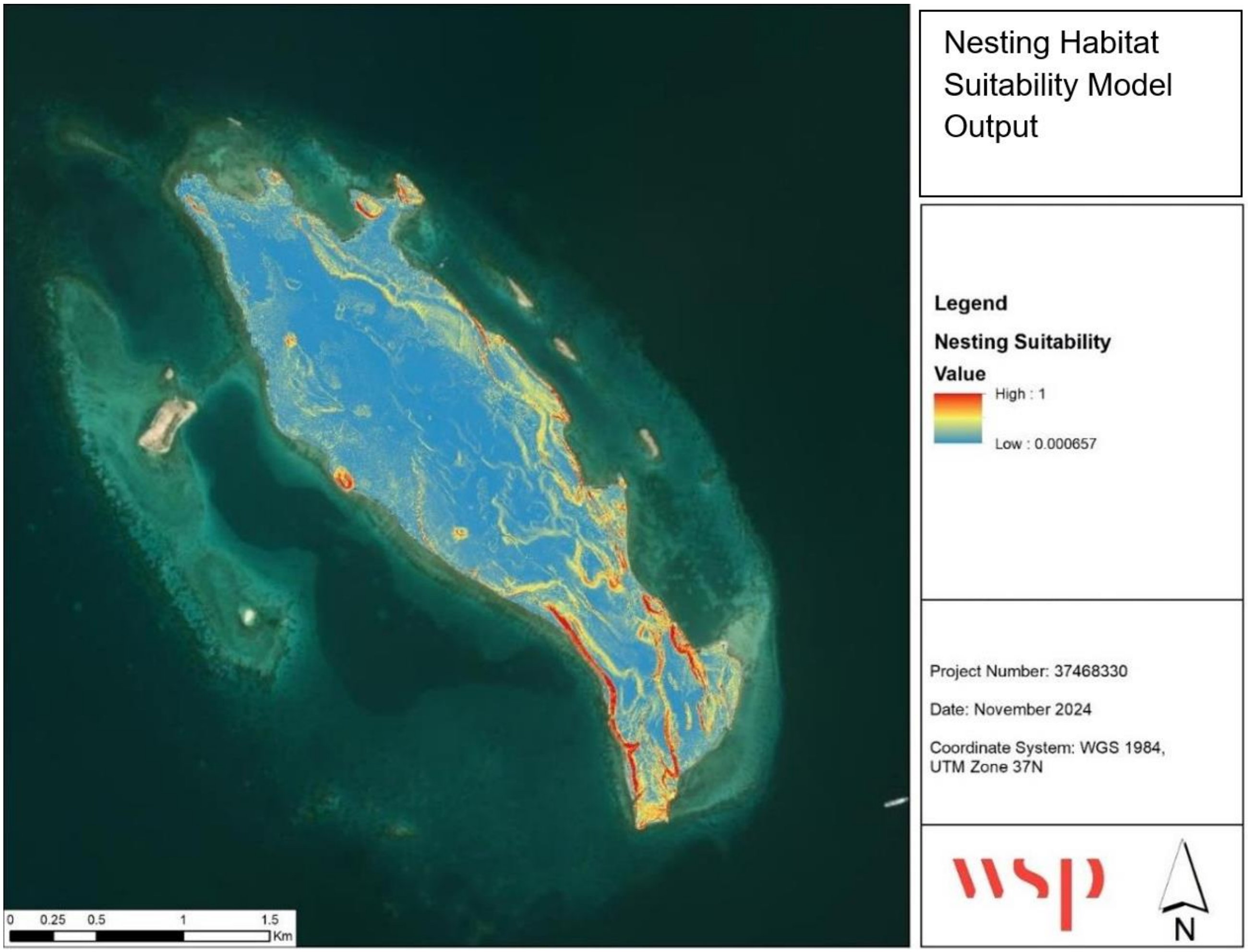

Figure 4: Nesting habitat suitability model output

Discussion & Recommendations

The study concludes that in the absence of credible & long-term primary data on the species distribution and habitat quality, Species Distribution Modeling (SDM) is a useful tool to model the Sooty Falcon's breeding habitat suitability. Also, SDM conducted in one area can be used to predict habitat suitability in another area or extrapolate over larger area.

Credible field survey data over multiple breeding cycles helped to set up and train the model to improve accuracy/predictability of the SDM. Though model predictability was validated through the presence (breeding survey data on the island), it is recommended that validation through a different study area within Red Sea is undertaken.

It was evident that breeding habitat is more appropriate basis to design conservation measures rather than identified nests. Apart from the field survey data, remote sensing data with high resolution variables are required to enhance the accuracy of the model. Hence environmental variables based on Digital Terrain Model (DTM) and Digital Surface Model (DSM) layers were created using a drone survey.

Among the multiple variables that contributed to the nesting habitat suitability, the highest contribution was the roughness, which contributed 75.1% to the nesting choices on the Island.

Distance to shoreline was the second highest contributor to the nesting habitat suitability, along with the aspect.

As roughness has the highest contribution to nesting suitability, it was evident that cliffs (signify roughness) both in the North and South showed high suitability for Sooty Falcon nesting, but the southern side of the Island noticeably has the highest concentration for nesting suitability (75% of habitat with suitability higher than 80% are in the South). These results also inform the application of the mitigation hierarchy during construction and operation phases. The modelling helped spatial avoidance of SF nesting habitat, through measures distributed across the Island, with observed clustering in the south, protecting and conserving nests, perching and feeding habitats.

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