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MORALITY BEFORE KNOWLEDGE

A spatial and temporal assessment of Maleo (*Macrocephalon maleo*) nesting behavior and habitat preferences through integrated field and modeling approaches

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ABSTRACT
Background: The Maleo (*Macrocephalon maleo*) is a Sulawesi-endemic bird with high conservation concern due to habitat degradation and population decline. The Panua Nature Reserve is a key Maleo habitat in Gorontalo Province, yet lacks updated data on habitat use and distribution patterns. This study aims to analyze Maleo presence in nesting grounds, evaluate habitat utilization, predict its distribution, and provide conservation recommendations. **Methods:** The research used direct surveys via camera traps and spatial modeling using the Maximum Entropy (MaxEnt) algorithm. Data were collected over five months, and analysis included the Relative Abundance Index (RAI) and occupancy modeling to assess habitat suitability and species detection. **Finding:** Maleo nesting pairs increased by 68.52% from 2022 to 2023. The species exhibited bimodal daily activity (peaks at 06:00–09:00 and 16:00–18:00), with habitat preference for geothermal zones and coastal forests. The RAI was 9.33%, and occupancy rate was estimated at 55%. MaxEnt modeling revealed 7,544.78 ha of highly suitable habitat, concentrated in grids N10, J13, K14, and M09, with an AUC of 0.826, indicating high predictive accuracy. **Conclusion:** Maleo birds in Panua Nature Reserve are showing a positive nesting trend. However, habitat fragmentation and human activities continue to threaten their sustainability. Strategic management is needed to maintain habitat integrity and support species conservation. **Novelty/Originality of this article:** This study integrates field-based camera trap data with predictive spatial modeling to provide a comprehensive habitat suitability analysis for the endangered Maleo in Panua Nature Reserve—an approach not yet applied in this location. The findings offer actionable conservation insights and prioritize critical zones for protection.

KEYWORDS: Maleo; habitat suitability; occupancy modeling; maxent; conservation.

1. Introduction

The Maleo (*Macrocephalon maleo*) is one of the most unique and ecologically significant bird species endemic to Sulawesi, Indonesia. It belongs to the Megapodiidae family and is best known for its unusual reproductive behavior. Unlike most bird species, the Maleo does not incubate its eggs with body heat but instead utilizes geothermal or solar-heated sand to bury its eggs for natural incubation(Baussa et al., 2025). This adaptation is both a marvel of evolutionary biology and a critical vulnerability. It means that any disruption to nesting habitats, especially areas with geothermal activity can have devastating effects on the species' survival (Afandi et al., 2022; Wantogia et al., 2024).

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Maleos exhibit monogamous mating systems, with pairs often remaining together for life. Their reproductive rate is also relatively low, laying only 8–12 eggs per pair per year, with a long incubation period of approximately 60–90 days depending on temperature conditions (Phillips & Dudi, 2008; Bashari et al., 2021). Their role in ecosystems extends beyond reproduction; they act as important seed dispersers and contribute to the regeneration of tropical forests (Muhi et al., 2021). However, the species is listed as *Critically Endangered* by the IUCN due to drastic population declines driven by egg poaching, illegal hunting, habitat degradation, and fragmentation (BirdLife International, 2023).

The geographic range of the Maleo is limited to Sulawesi, and its populations are patchily distributed across protected areas such as Bogani Nani Wartabone National Park, Lore Lindu National Park, and Panua Nature Reserve. Among these, Panua Nature Reserve in Pohuwato Regency, Gorontalo Province, holds a particularly vital population. Despite being officially designated as a conservation area since 1982, the Panua Reserve has experienced significant pressure from anthropogenic activities, such as gold mining, land conversion, road construction, and aquaculture expansion (Rosalia et al., 2024). As a result, the nesting area within Panua has declined sharply from 6 hectares in 2010 to merely 2 hectares in 2023.

The current conservation strategies have yet to be optimized due to a lack of spatially explicit data on habitat use and species distribution. Traditional monitoring efforts have not incorporated advanced ecological modeling or high-resolution spatiotemporal data. Therefore, this research introduces an integrated approach combining camera trapping, occupancy modeling, and Maximum Entropy (MaxEnt) species distribution modeling. These techniques provide robust analytical frameworks for estimating the probability of species presence and identifying environmental variables that influence habitat suitability (Phillips et al., 2017; Merow et al., 2013).

MaxEnt modeling has gained widespread application in biodiversity conservation due to its effectiveness in predicting species distribution using presence-only data (Aldiansyah et al., 2024). It uses environmental variables such as temperature, elevation, land cover, and proximity to anthropogenic disturbances to create probability maps of species presence. When combined with occupancy modeling which accounts for imperfect detection this dual approach enhances ecological inference and conservation planning. Furthermore, camera traps provide high-resolution data on species occurrence, activity patterns, and community composition (O'Connell et al., 2019). These methods have proven effective for elusive and diurnal species like the Maleo (Andriwibowo & Maarif, 2023).

Another critical dimension in Maleo conservation is the role of community engagement. Studies globally emphasize that conservation success is often contingent on the active involvement of local communities (Zafra-Calvo et al., 2019). In Sulawesi, hatchery programs, community-based egg monitoring, and environmental education have shown promise in improving reproductive success and reducing poaching (Kumaji et al., 2024). However, these interventions need scientific backing and spatial targeting, which this study aims to provide.

A recent study by Kremen et al. (2021) emphasized that integrative conservation strategies blending ecological modeling with community stewardship are more sustainable than purely top-down enforcement. In the case of Panua, local communities have limited formal roles in habitat monitoring and egg relocation, presenting an opportunity for co-management. Furthermore, habitat suitability maps from this research can guide the establishment of buffer zones, optimize patrol routes, and identify restoration priority areas.

This study also addresses a notable research gap. While previous efforts have documented Maleo nesting behavior and distribution in parts of North Sulawesi and Central Sulawesi, there is a lack of empirical data from Gorontalo, particularly within Panua Nature Reserve. By integrating ecological and spatial analysis, this study provides the first high-resolution habitat suitability assessment for Maleo in Panua, offering crucial insights for adaptive management and conservation policy development.

Furthermore, the findings from this research are relevant to broader conservation discourses on endemic island species, whose survival is increasingly threatened by habitat encroachment and climate variability. As noted by Andermann et al. (2020), island endemics exhibit high extinction risks and require tailored conservation frameworks based on detailed ecological data. This aligns with the objectives of this study, which seeks to not only document current conditions but also to forecast future habitat scenarios under varying levels of disturbance.

In summary, this study serves three main purposes to analyze the current distribution and nesting behavior of Maleo in Panua Nature Reserve using empirical field data; to model habitat suitability using MaxEnt and identify the most influential environmental variables; and to provide actionable conservation recommendations that bridge scientific findings with local policy implementation. Through this integrative approach, we aim to contribute to both the academic discourse and the practical conservation of one of Indonesia's most iconic and endangered bird species.

2. Methods

This study was conducted in the Panua Nature Reserve, located in Pohuwato Regency, Gorontalo Province. Geographically, this reserve lies between 0°25'28.93" – 0°30'1.93" North Latitude and 121°44'27.60" – 121°47'00.44" East Longitude, covering an area of approximately 36,575 hectares. This region represents one of the main habitats for the Maleo bird (*Macrocephalon maleo*) in Sulawesi. The research was carried out over a period of five months, from May to October 2024, including several phases: preliminary studies, preparation, field data collection, data analysis, and report writing.

A descriptive quantitative method with an ecological and spatial analysis approach was used. This approach enables a comprehensive description of habitat utilization patterns and spatial distribution of the Maleo, as well as their relationships with environmental factors (Phillips et al., 2017; Hallstan, 2011). The research design employed a purposive random sampling method, where study sites were deliberately selected based on high habitat suitability potential for Maleo presence. Selected locations were then divided into 2 km × 2 km grids.

In each selected grid, camera traps were systematically installed to detect Maleo and other wildlife species. The camera trap models used were Reconyx HC500 and Cuddeback Black Flash E3. These cameras were mounted at a height of 50 cm above ground level in areas with evidence of animal activity such as tracks, droppings, or nesting traces (Burton et al., 2015; O'Connell et al., 2019). The cameras were left in place for approximately 100 days. During this period, regular checks were conducted to inspect battery condition, download image data, and document additional field notes (Kays et al., 2021).

In addition to primary data obtained from camera traps, secondary data were also utilized. These secondary data included Maleo egg relocation records from hatchery programs and direct encounter records collected by the North Sulawesi BKSDA patrol teams. These data sources strengthened the field observations and improved analysis accuracy (Beaudrot et al., 2016; Rovero & Zimmermann, 2016).

Data analysis included calculation of the Relative Abundance Index (RAI), occupancy rates, and habitat suitability modeling using the MaxEnt (Maximum Entropy Modeling) approach. The RAI was used to quantify species abundance at each camera trap site, providing a relative measure of activity intensity (Wearn & Glover-Kapfer, 2017). Occupancy modeling estimated the proportion of area occupied by Maleo, taking into account detection probabilities, which are often less than one (MacKenzie et al., 2002; Tyre et al., 2003).

The MaxEnt model was used to predict suitable habitats for Maleo within Panua Nature Reserve. The model incorporated Maleo presence data along with environmental variables such as temperature, elevation, distance from settlements, distance from roads, proximity to geothermal heat sources, and land cover types (Phillips et al., 2017; Merow et al., 2013).

MaxEnt is particularly effective for presence-only data and has shown high predictive performance in conservation studies of rare and elusive species (Elith et al., 2011; Araújo et al., 2019).

All camera trap images were tagged using Adobe Bridge software. Metadata such as species identification, number of individuals, and timestamp were added to each image. Images were then classified into separate folders by species for easier analysis and reporting (Ahumada et al., 2011). In addition to spatial and statistical analyses, ecological interpretation of daily Maleo activity patterns was also conducted. Temporal data from camera traps allowed analysis of diurnal activity peaks, which are important for understanding Maleo behavior and for designing conservation interventions such as patrol schedules and disturbance mitigation (Bridges et al., 2022).

Through the integration of primary data, secondary data, statistical analyses, and spatial modeling, this study aimed to provide a comprehensive understanding of habitat utilization patterns, occupancy rates, and priority conservation areas for the Maleo in Panua Nature Reserve. The outcomes are expected to serve as a scientific foundation for policy development in habitat management and to support broader biodiversity conservation goals (Sutherland et al., 2021).

3. Results and Discussion

Nature Reserves are designated conservation areas primarily intended for the preservation of biodiversity, including plant and animal species, along with their ecosystems. These areas also function as critical life-support systems. A nature reserve is characterized by unique ecological features, including distinctive flora, fauna, and ecosystems that require protection and are allowed to evolve naturally. Within nature reserves, activities such as scientific research and development, environmental education and awareness, carbon sequestration and storage, as well as certain supporting cultivation activities, are permitted in accordance with Law No. 5 of 1990 concerning the Conservation of Biological Natural Resources and Their Ecosystems.

The Panua Nature Reserve is one of the most significant conservation areas located in Pohuwato Regency, Gorontalo Province, Indonesia. Covering an area of 36,575 hectares, it plays a vital role in maintaining ecological balance in the region, particularly through the protection of its unique biodiversity. As a conservation area, the Panua Nature Reserve is designated to safeguard endangered flora and fauna, preserve ecosystem functions, and indirectly support the livelihoods of surrounding communities through the ecosystem services it provides.

The biodiversity within the Panua Nature Reserve is exceptionally rich, largely due to its inclusion in the characteristic tropical forest ecosystem. Several endemic and notable species inhabit this reserve, including the maleo bird (*Macrocephalon maleo*), tarsier (Tarsius supriatnai), babirusa (Babyrousa celebensis), and anoa (*Bubalus* spp.). This study focuses on the encounter points of the maleo (*Macrocephalon maleo*), which are extrapolated in relation to the environmental conditions of the encounter sites, in order to identify and characterize the habitat utilized and deemed suitable for the species within the Panua Nature Reserve. Data on encounter points were collected using camera traps, supplemented by secondary data obtained from patrol encounter records and camera trap detections conducted by personnel of the Panua Nature Reserve Resort—North Sulawesi Natural Resources Conservation Agency/*Balai Konservasi Sumber Daya Alam (*BKSDA). The data collection was carried out across eight (8) grid cells where camera traps were installed within the Panua Nature Reserve, as presented in Table 1.

Table 1. Wildlife detection results from camera traps in Panua nature reserve

Num.	GRID	Days of Camera Installation	Days of Camera Active	Number of species	Species
1	N10	183	183	7	*Macrocephalon maleo*

					Gallus gallus *Bos* sp. *Felis silvestris* *Megapodius cumingii* *Sus celebensis* *Varanus salvator*
2	J13	111	87	5	*Macrocephalon maleo* *Macaca hecki* *Gallus gallus*
3	K14	115	83	12	*Macrocephalon maleo* *Macaca hecki* *Muridae* *Gallicolumba tristigmata* *Gallus gallus* *Gymnocrex rosenbergii* *Megapodius cumingii* *Mulleripicus fulvus* *Sciuridae* *Spilornis rufipectus* *Tarsius supriatnae* *Viverra tangalunga*
4	M09	90	56	3	*Macrocephalon maleo* *Macaca hecki* *Sus celebensis*
5	G15	112	112	2	*Macaca hecki* *Sus celebensis*
6	I14	81	81	6	*Macaca hecki* *Muridae* *Canis familiaris* *Sciuridae* *Varanus salfator* *Viverra tangalunga*
7	L10	90	52	6	*Macaca hecki* *Muridae* *Sciuridae* *Sus celebensis* *Tarsius supriatnai* *Canis familiaris*
8	M10	186	0 (eror)	0	-

This study detected the presence of the maleo (*Macrocephalon maleo*) using camera traps installed in eight grid locations within the Panua Nature Reserve. The results showed that maleo was detected in four locations: Grid N10, J13, K14, and M09. The other four locations did not detect maleo, with one camera trap malfunctioning and three others only detecting other wildlife species. Description of Maleo Detection Sites: 1Grid N10, located in a coastal forest at 0–5 masl, serves as a key nesting habitat for the Maleo (*Macrocephalon maleo*). The area features open, porous sandy substrates ideal for natural egg incubation via solar or geothermal heat. Surrounding vegetation—including trees, shrubs, and grasses—supports vital ecological functions such as foraging, shelter, and predator protection, making it a highly suitable microhabitat for Maleo nesting activity. Grid M09 recorded the presence of the Maleo (*Macrocephalon maleo*) in a secondary dryland forest characterized by gently sloping topography. The area is dominated by dense vegetation, consisting of small to medium-sized trees and shrubs. Much of this site overlaps with community-managed agricultural land and is located near the Trans-Sulawesi highway. The camera trap was installed in a section of the area with relatively dense vegetation, positioned away from direct human activity to minimize disturbance. Grid K14 is situated in a secondary dryland forest with flat to slightly steep topography. This location is close to community plantations, but maleo has been detected here multiple times. Grid J13 is a secondary dryland forest area that remains protected from human activities. Maleo was detected both through camera traps and direct encounters by patrol officers.

Description of locations without maleo detection, gridsL10, I14, G15, and D11 did not detect maleo, despite having potentially suitable habitats. The main reasons could be the suboptimal placement of camera traps or the areas not being part of maleo's movement routes. Grids M10 and G09 did not detect maleo in this study; however, previous data from the North Sulawesi BKSDA indicated maleo presence in these locations. Grid D11 is a primary forest area that remains highly pristine and is far from human activities. Camera traps in this location have detected maleo as well as other wildlife such as monkeys, Sulawesi wild boars, and babirusa.

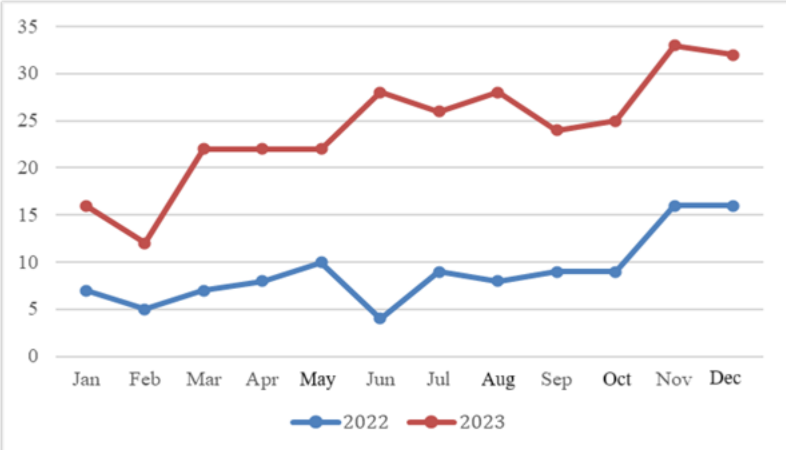

Fig. 1. Diagram of fluctuations in the number of maleo eggs every month in Panua CA in 2022-2023

The highest concentration of detected maleo birds (*Macrocephalon maleo*) was found in their natural nesting habitat (nesting ground) within coastal forests with white sand substrate, located at the southern end of the Panua Nature Reserve, bordering Maleo Village. The relocation of maleo eggs from a 2-hectare nesting ground in the Panua Nature Reserve to a hatchery within the reserve resulted in the collection of 108 eggs in 2022 and 182 eggs in 2023, totaling 290 maleo eggs over the two-year period (2022–2023). The maleo bird (*Macrocephalon maleo*) lays between 8 to 12 eggs per year and always nests in pairs. Therefore, to estimate the number of nesting maleo pairs, the lowest estimate is calculated by dividing the total number of eggs in a year by 12, the highest estimate by dividing by 8, and the average estimate by dividing by 10

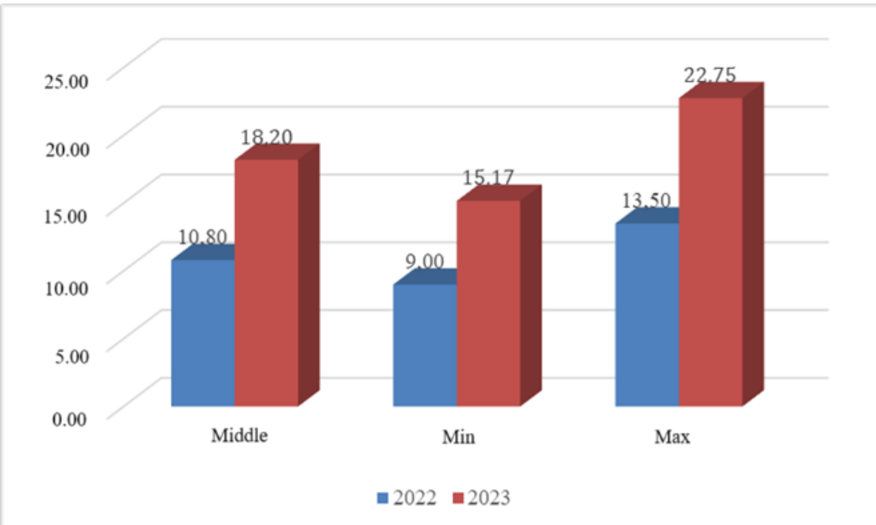

Fig. 2. Diagram of the number of maleo pairs laying eggs on the nesting ground of CA Panua

Based on Figure 3, it is observed that the number of maleo bird pairs visiting the nesting ground in Panua Nature Reserve in 2022 ranged from a minimum of 9 pairs to a maximum of 13 pairs, with an average of 11 pairs. In 2023, the number increased, ranging from a minimum of 15 pairs to a maximum of 23 pairs, with an average of 18 pairs. Given the recorded number of eggs in 2022 and 2023, the Annual Pair Visit Trend (APVT) of maleo birds in Panua Nature Reserve was calculated, yielding a result of 68.52%. This indicates that from 2022 to 2023, the number of maleo pairs visiting the nesting ground for egg-laying increased by 68.52%.

Based on the analysis of wildlife detection from camera trap data, a total of 17 species were recorded, including the maleo bird (*Macrocephalon maleo*). The three species with the highest abundance were *Macaca hecki*, Muridae (forest rat group), and the maleo bird. Conversely, the species with the lowest abundance were cattle, domestic rats, and cats, which are domesticated animals. The abundance data was further analyzed by calculating the Relative Abundance Index (RAI) at each camera trap location. The results of the RAI calculations are presented in Figure 4.5. According to the diagram, camera trap K14 had the highest RAI at 78.16% for *Macaca hecki*, indicating that the area around K14 has a higher level of *Macaca hecki* activity compared to other locations.

At camera trap N10, which is a maleo nesting ground, other species such as the Philippine scrubfowl (*Megapodius cumingii*) (5.46%), wild boar (2.73%), and monitor lizards (4.37%) were also detected. The dominant species detected across most camera trap locations were *Macaca hecki* and Muridae (forest rats), suggesting that the habitat in this area supports their presence. On the other hand, camera traps such as G15 and M09 showed lower species abundance. Wildlife activity at these locations was predominantly composed of species such as *Macaca hecki* and *Sus celebensis*, while maleo bird detections were relatively scarce, with sightings recorded only at M09. These results provide a detailed picture of the distribution of wildlife activity in the Panua Nature Reserve. Cameras with the highest RAI indicate locations with intense wildlife activity, which can be a conservation focus to protect key species such as the Maleo Bird. Conversely, areas with lower RAI may require additional management strategies to improve habitat quality and support the presence of other important wildlife.

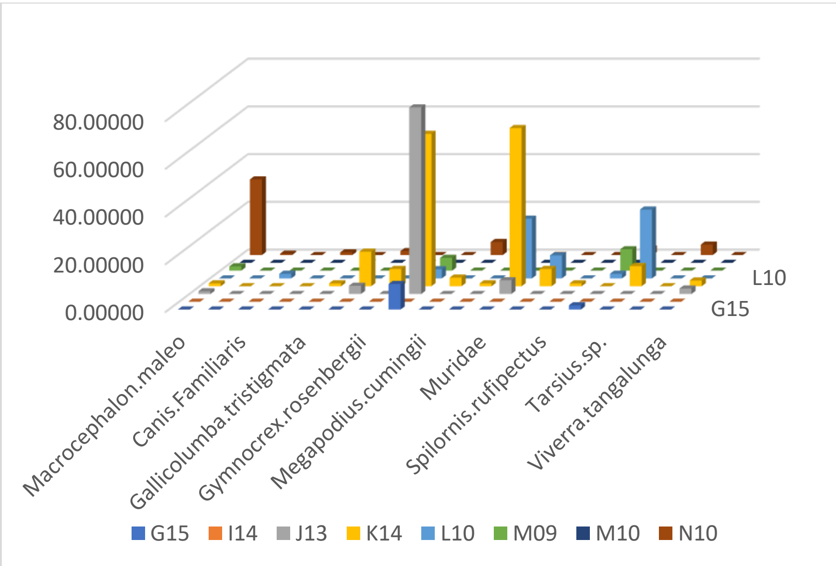

Fig. 3. Percentage of Relative Abundance Index (RAI) per camera point in Panua CA

These results provide a detailed overview of wildlife activity distribution within the Panua Nature Reserve. Camera points with the highest Relative Abundance Index (RAI) indicate areas of intense wildlife activity, which may serve as priority sites for conservation efforts, particularly in protecting key species such as the Maleo (*Macrocephalon maleo*). Conversely, areas with lower RAI values may require additional management strategies aimed at improving habitat quality and supporting the presence of other important wildlife species.

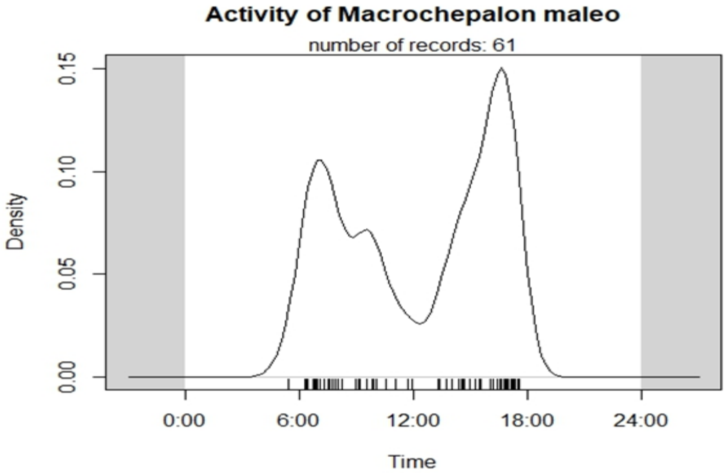

Fig. 4. Percentage of Relative Abundance Index (RAI) per camera point in Panua CA

Based on the analysis of the activity patterns of the maleo bird (*Macrocephalon maleo*), its activity exhibits a distinct temporal distribution throughout the day, following a bimodal pattern. The graph indicates two primary activity peaks: in the morning (06:00–09:00) and in the late afternoon (16:00–18:00). Morning activity is likely associated with foraging and territorial behaviors, facilitated by cooler environmental conditions. The late afternoon activity serves as a secondary foraging period or a preparation phase before resting, corresponding with decreasing temperatures after midday. Activity declines sharply at midday due to high temperatures and increased sun exposure, prompting maleo birds to seek shade to avoid thermal stress. At night, maleo birds remain inactive as they are diurnal species that rest during nighttime.

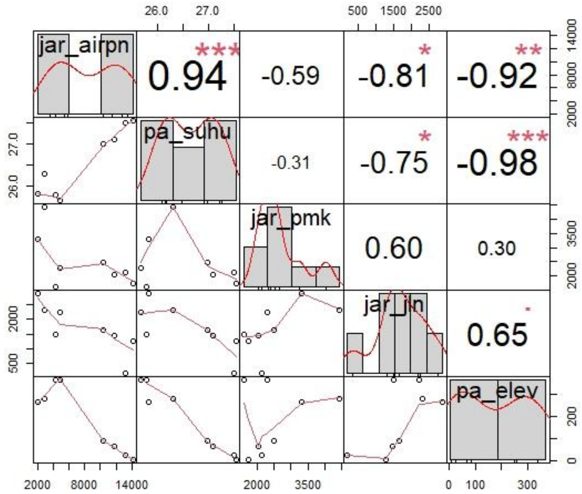

Fig. 5. Percentage of Relative Abundance Index (RAI) per camera point in Panua CA

The habitat suitability modeling for the Maleo bird (*Macrocephalon maleo*) in Panua Nature Reserve using MaxEnt produced a probability range of 0.2076 to 0.4757. A probability of 0.2076 indicates low presence likelihood, while 0.4757 represents the highest likelihood of Maleo presence in the area. Based on the 10-percentile training presence logistic threshold of 0.3689, areas with lower probability values are classified as unsuitable, whereas those above the threshold are considered suitable for Maleo habitat.

The analysis was then conducted using RStudio, resulting in an estimated occupancy rate of maleo birds in Panua Nature Reserve of 0.55 (95% CI: 0.19–0.85). This indicates that 55% of the surveyed area in Panua Nature Reserve serves as a habitat for maleo birds, with a 95% confidence level and a detection probability of 29%. The correlation analysis among covariates influencing the occupancy of the maleo bird (*Macrocephalon maleo*) revealed significant and strong relationships, both positive and negative. The variables tested included distance from hot springs (jar_aipn), temperature (pa_suhu), distance from settlements (jar_pmk), distance from roads (jar_jln), and elevation (pa_elev). A very strong negative correlation (r = -0.92*) was observed between distance from hot springs and elevation, indicating that locations closer to hot springs tend to be at lower elevations. This relationship is significant and should be considered in the occupancy modeling of maleo birds. A very strong negative correlation (r = -0.98**) was found between temperature and elevation, suggesting that higher elevations correspond to lower temperatures, which aligns with general altitudinal temperature patterns. A strong negative correlation (r = -0.81) was detected between distance from hot springs and distance from roads, indicating that locations near hot springs are generally more remote and less accessible. A strong negative correlation (r = -0.75) was identified between temperature and distance from roads, suggesting that cooler areas (likely at higher elevations) tend to be located farther from roads. This factor is essential in understanding habitat connectivity for maleo birds, which may rely on more isolated locations. A moderate positive correlation (r = 0.60) was observed between distance from settlements and distance from roads, indicating that areas farther from settlements tend to be farther from roads as well. This correlation highlights accessibility constraints that may influence maleo bird occupancy. These findings provide crucial insights into the environmental and accessibility factors affecting the distribution and habitat preferences of maleo birds.

The habitat suitability modeling for the Maleo bird (*Macrocephalon maleo*) in Panua Nature Reserve using MaxEnt produced a probability range of 0.2076 to 0.4757. A probability of 0.2076 indicates low presence likelihood, while 0.4757 represents the highest likelihood of Maleo presence in the area. Based on the 10-percentile training presence logistic threshold of 0.3689, areas with lower probability values are classified as unsuitable, whereas those above the threshold are considered suitable for Maleo habitat. Habitat suitability modeling for the Maleo (Macrocephalon maleo) in the Panua Nature Reserve was conducted using the MaxEnt (Maximum Entropy) model, which produced a probability range of species presence between 0.2076 and 0.4757. A probability value of 0.2076 indicates low habitat suitability, whereas a value of 0.4757 reflects the highest probability of Maleo presence in the reserve. Using the 10 percentile training presence logistic threshold of 0.3689, areas with probability values below this threshold were classified as unsuitable, while those above were categorized as suitable Maleo habitats.

Based on the model, the total area classified as highly suitable for the Maleo was 7,544.78 hectares, representing approximately 20.6% of the total area of the Panua Nature Reserve (36,575 ha). This indicates that only a relatively small portion of the reserve provides optimal environmental conditions to support key activities of the Maleo, such as nesting and foraging. These findings suggest that the species' habitat has been impacted by environmental pressures, including land fragmentation, forest degradation, and anthropogenic disturbances in surrounding areas.

The MaxEnt model achieved an Area Under the Curve (AUC) value of 0.826 with a standard deviation of 0.099, indicating excellent model performance and a high level of predictive accuracy. Thus, the model provides a robust basis for understanding Maleo habitat suitability within the reserve. However, the limited extent of highly suitable habitat underscores the serious threat faced by Maleo populations regarding the sustainability of their habitat. The predictive distribution map generated from the MaxEnt model categorized habitat suitability into three levels: high (7,544.78 ha), medium (11,313.90 ha), and low (17,716.33 ha). Highly suitable areas are concentrated in coastal sandy forest ecosystems, which serve as nesting grounds and are regularly visited by 1–4 Maleo pairs per day, or approximately 15 pairs per month, with a total adult nesting population estimated at 15–23 pairs. Medium suitability areas consist of secondary dryland forests, shrublands, parts of primary forest, and agricultural zones. Low suitability areas are located in higher elevation primary forests above 400 meters above sea level.

The designation of Panua as a nature reserve was initially based on the discovery of Maleo nesting grounds and the species' presence within the forest. MaxEnt modeling now serves as a strategic tool to identify priority areas for further monitoring, by extrapolating environmental variable patterns to guide efficient and focused conservation efforts. The habitat suitability categories shown in the predictive map (Figure 4.7) represent a management-oriented approach to identifying potential Maleo habitats. Although the entire Panua Nature Reserve was historically known to support the Maleo since its discovery in the Gorontalo forests (now Pohuwato Regency) in 1938 and its official protection status in 1984, the categorization helps target conservation interventions. Areas of high suitability (marked in red) are closely associated with frequent sightings at nesting grounds and their surroundings. Medium suitability areas (yellow) are distributed along habitat corridors linking the primary forest in the north with nesting grounds in the south. These corridors are crucial, as they are assumed to act as movement pathways connecting nesting and protected habitats. Without functional corridors, Maleos in protected forests may not reach nesting grounds, disrupting reproduction. Conversely, newly hatched individuals may fail to return to the forest, inhibiting population growth. Low suitability areas (green) comprise the expansive primary forest in the northern portion of the reserve—covering nearly two-thirds of the total area—with minimal human disturbance, thus offering a secure refuge. The Maleo's nesting–foraging cycle involves traveling distances estimated at up to 80 kilometers. Given this ecological dynamic, preserving the ecological integrity of the entire Panua Nature Reserve must remain a priority to ensure the long-term conservation of the Maleo population.

Panua Nature Reserve was established based on the discovery of Maleo nesting grounds and their presence in the forest. The MaxEnt model helps identify key areas for targeted monitoring and conservation efforts. The classification in the distribution map serves as a practical approach for assessing potential conservation sites. Although the entire reserve serves as Maleo habitat, the categorization highlights critical areas: 1) high-suitability zones (red) correspond to frequently observed nesting grounds in sandy coastal forestsl; 2) moderate-suitability zones (yellow) function as corridor areas connecting the northern primary forests with the southern nesting grounds. These corridors are essential for ensuring Maleo movement between sheltering forests and nesting sites, which is crucial for population regenerationl; 3) low-suitability zones (green) represent the extensive northern primary forests, covering nearly two-thirds of the reserve, where minimal human disturbance ensures a secure habitat for Maleo. Maleo birds are estimated to travel up to 80 km between primary forests and nesting grounds. Maintaining the ecological integrity of Panua Nature Reserve is vital for sustaining the Maleo population and ensuring the continuity of their life cycle.

4. Conclusions

The Maleo (*Macrocephalon maleo*) is a critically endangered bird species endemic to Sulawesi whose unique reproductive strategies, ecological importance, and narrow habitat requirements make it especially vulnerable to anthropogenic threats. This study, conducted in the Panua Nature Reserve of Pohuwato Regency, Gorontalo Province, represents one of the first integrative attempts to document and model Maleo habitat utilization, activity patterns, and spatial distribution using a combination of field data (camera traps), occupancy modeling, and species distribution modeling via MaxEnt. Based on the findings of this study conducted in the Panua Nature Reserve, Pohuwato Regency, Gorontalo Province, several important conclusions can be drawn regarding the presence, habitat utilization, distribution, and protection strategies of the Maleo bird (*Macrocephalon maleo*).

Our findings indicate that Panua Nature Reserve remains a viable habitat for Maleo conservation, though only a fraction (approximately 7,544.78 ha or 20.6%) of its total area

(36,575 ha) qualifies as highly suitable based on MaxEnt modeling. The occupancy rate for the species in the surveyed areas was estimated at 0.55, indicating that over half the reserve is actively used or traversed by the Maleo. Importantly, the species shows clear habitat preferences for geothermal zones, sandy coastal forests, and areas with minimal human disturbance.

Temporal activity data derived from camera traps revealed a consistent bimodal pattern, with activity peaks during early morning and late afternoon behavior consistent with other diurnal tropical birds and reflective of thermoregulatory and foraging needs. Such information is crucial for designing effective protection mechanisms, including optimal patrol times and reduced human activity during sensitive hours. The observed increase of 68.52% in Maleo pair visits between 2022 and 2023 at the main nesting ground underscores a potential recovery trend. However, this rebound remains fragile and conditional upon immediate and sustained conservation interventions.

The study reaffirms that habitat degradation remains the most significant threat to Maleo populations. From 2010 to 2023, the area of viable nesting grounds within Panua shrank from 6 hectares to just 2 hectares largely due to illegal mining, land encroachment, deforestation, aquaculture, and road construction. Such fragmentation not only reduces nesting opportunities but also increases the vulnerability of nests to predation and poaching. Data spatial and statistical analyses also revealed strong correlations between habitat suitability and environmental variables such as proximity to geothermal heat sources, elevation, temperature, and distance from roads and settlements. These findings reinforce the importance of preserving core nesting habitats and establishing buffer zones that limit disruptive human activity.

The presence of domestic and invasive species (e.g., Canis familiaris, Felis catus, and feral livestock) near nesting zones further exacerbates the problem, increasing the risk of egg predation and habitat competition. The integration of camera trap data allowed for the identification of such species, highlighting the need for comprehensive management that includes predator control and community-based livestock regulation. This study contributes significantly to conservation science in several ways. Firstly, it establishes a reproducible model for integrating field-based data and spatial analysis to assess habitat suitability for endangered and elusive species. Secondly, it expands the scientific literature on Maleo ecology in a region that has received comparatively little research attention. Thirdly, by using MaxEnt in tandem with occupancy modeling, the study provides a more nuanced understanding of Maleo distribution and presence across heterogeneous landscapes.

Moreover, the use of Relative Abundance Index (RAI) provided insights into community assemblages, allowing for the identification of zones with high conservation value beyond the focal species. Such areas could serve as biodiversity hotspots within Panua and inform broader conservation prioritization strategies. The results of this study present significant implications for the development and implementation of conservation policies targeting the critically endangered Maleo (*Macrocephalon maleo*) in Panua Nature Reserve. The ecological and spatial data generated through this research not only provide an accurate depiction of the species' current distribution and habitat use but also offer a scientific basis for zoning, enforcement strategies, community engagement, and habitat restoration. Firstly, the high-resolution habitat suitability map produced using MaxEnt modeling serves as a valuable tool for guiding zoning strategies within the reserve. Areas identified as highly suitable for Maleo should be designated as core protection zones, as they represent key nesting and foraging sites critical for the species' reproductive success. Meanwhile, areas classified as moderately suitable may function as ecological corridors, facilitating movement between isolated populations and supporting landscape-level biodiversity. Secondly, considering that many threats to Maleo habitats originate from adjacent human activities, it is essential to formalize buffer zones surrounding the core conservation areas. Such zones should be developed through community-inclusive conservation approaches, incorporating environmental education, incentive-based programs (such as payments for ecosystem services), and participatory monitoring initiatives. Engaging local residents not merely as beneficiaries but as active stewards of conservation will enhance the effectiveness and sustainability of protection efforts. Thirdly, the bimodal daily activity pattern observed in Maleo behavior with peaks in the early morning (06:00–09:00) and late afternoon (16:00–18:00), provides critical information for optimizing patrol schedules and enforcement operations. Targeting ranger patrols during these peak periods can increase the likelihood of intercepting illegal activities such as poaching or habitat encroachment, while minimizing disturbances during less sensitive times. Fourthly, the integration of camera traps into long-term wildlife monitoring protocols offers a non-invasive and systematic method for tracking Maleo population trends. The establishment of permanent camera trap stations in key grids, such as N10 and K14 where high activity has been recorded, is recommended to support continuous data collection. Such protocols can serve as part of an adaptive management system, allowing for timely and evidence-based policy adjustments. Fifthly, certain areas such as Grids D11 and M10, which did not yield Maleo detections during this study but were historically known to support the species, should not be overlooked. These sites may benefit from targeted habitat restoration efforts, including reforestation with native vegetation, control of invasive species, and landscape rehabilitation. Restoration of these degraded areas can improve habitat connectivity, reduce population isolation, and potentially expand the available range for Maleo re-colonization in the future.

While the findings are robust, the study is not without limitations. The presence-only nature of MaxEnt, though compensated by occupancy modeling, still lacks certain behavioral and demographic data. Future studies should consider banding, satellite tracking, or genetic analysis to understand population structure, dispersal patterns, and genetic diversity across Sulawesi. Moreover, seasonal variations were not fully captured due to the five-month data collection window. Longer-term monitoring is necessary to understand annual trends, particularly in response to climatic variability. Finally, integration with socio-economic surveys around Panua could enrich the analysis of human-wildlife interactions and help tailor community-based conservation models

In conclusion, the Panua Nature Reserve remains a critical stronghold for the conservation of Maleo birds in Gorontalo. The integration of ecological monitoring, spatial modeling, and community engagement provides a promising pathway for sustainable conservation. The positive trend in nesting activity observed between 2022 and 2023 is encouraging but must not lead to complacency. Urgent, science-based conservation actions are needed to prevent further habitat loss and to secure the future of this remarkable species. By leveraging tools like MaxEnt, camera traps, and community science, stakeholders including local governments, conservation agencies (e.g., BKSDA), academic institutions, and residents can work collaboratively to turn data into action.

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