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# Assessing Potential Distributions of Bird Endemic Species: Case Studies of *Macrocephalon maleo* and *Rhyticeros cassidix* and Their Threats

**Abstract:** Maleo and knobbed hornbill are bird species that are endemic on the island of Sulawesi, which is highly threatened by forest fires. Fires tend to destroy any affected species; however, it is not possible to survey the entire range of the original distribution of the two endemic bird species that are affected by forest fires due to practical constraints. Species distribution modeling using maximum entropy is considered to be an alternative to understanding the potential distribution area of species against the threat of forest fires. The prediction model from MaxEnt all have AUC values of greater than 0.70, which means that the model is good enough to classify the records of the presence of *M. maleo* and *R. cassidix* along with the past forest fires. The environmental variables that affect the distribution of *M. maleo* are its distance from hot water, rivers, and roads, while the distribution of *R. cassidix* is strongly influenced by its distance from roads, settlements, and rivers. Forest fire distribution is mostly influenced by soil type, land-use land cover, and rainfall. It is predicted that around 238,690 and 677,070 ha of the potential distribution of *M. maleo* and *R. cassidix*, respectively, are potentially disturbed and affected by forest fires. However, this number much greater outside conservation areas. The results of this study can be used by the government of the Republic of Indonesia (especially the Ministry of Environment and Forestry) for determining conservation actions for both species in the future.

**Keywords:** potential distribution, *Macrocephalon maleo*, *Rhyticeros cassidix*, forest fire, maximum entropy

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## 1. Introduction

The island of Sulawesi features isolated faunae that have migrated from Asia and Australia. The isolation of the faunae that can be found in this region has created a combination of animals from the two continents. Sulawesi Island has various types of faunae, and it is home to several endemic species such as the maleo (*Macrocephalon maleo*) and the knobbed hornbill (*Rhyticeros cassidix*). The *M. maleo* species utilizes natural heat sources (geothermal) or stretches of sand on beaches to serve as nesting sites [1]. The knobbed hornbill lives in high primary forests, swamp forests, and secondary forests [1]. These two endemic species are known to prefer living in pairs and are more terrestrial [1–3]. The characters and behaviors of these species describe their living environments, which are from forest and far from all forms of human activity.

The International Union for Conservation of Nature (IUCN) categorizes the statuses of *M. maleo* as critically endangered (CR) and *R. cassidix* as vulnerable (VU). These statuses indicate high levels of threat and carry the potential of becoming extinct if no immediate conservation actions are taken. These two species are also protected under the Decree of the Minister of Agriculture of the Republic of Indonesia No. 421/KPTS/UM/8/1970, the Decree of the Minister of Agriculture Number 90/KPTS/UM/2/1997, Law No. 5 of 1990 concerning the Conservation of Natural Resources and their Ecosystems, and Government Regulation No. 7 of 1999 concerning the Preservation of Wild Plants and Animals [4, 5].

Based on data from BirdLife International, the global populations of *M. maleo* and *R. cassidix* are estimated to have declining trends [1, 6, 7]. Habitat degradation and hunting are known to have damaged and displaced the habitats and populations of these endemic species in their natural environments [6, 7–12].

The maleo and knobbed hornbill share one common threat; namely, forest fires [6, 13]. Forest fires occur in three main forms based on the ways that they spread and their positions on the ground; namely, surface fires, crown fires, and ground fires [14, 15]. The vegetation type and density are the two most important floristic factors in forest fire ignition [16]. The summer warming and low annual rainfall in recent decades that can be attributed to climate change have increased the frequency and severity of forest fires [17, 18]. Fires tend to influence the floristic composition of ecosystems by selectively selecting fire-adapted species and destroying non-fire-resistant species [19].

The study of Ferry Slik et al. [20] showed that there was a significant effect of the number of forest structures on the numbers of trees and species. In 2000 and 2004, forest fires affected Tangkoko Dua Saudara Nature Reserve, destroying 180 ha and 130 ha, respectively, and rendering dense regrowth areas impenetrable to *M. maleo* [13]. The extraordinary fires of 1997 demonstrated a significant reduction in the breeding success and recruitment of knobbed hornbill populations in the subsequent years [6].

Maximum entropy is a method that is used to estimate the distribution of species [21]; however, its development has led to the processing of data on biodiversity and disaster aspects by utilizing the locations of events and the parameters that describe the environmental characteristics of the objects that are being studied.

A study that was conducted by Chitale and Behera [22] on the impact of forest fires on the distribution of endemic plants in the Himalayas found that there was a significant reduction in the geographic distribution of indicator species under the forest fire scenario.

The research conducted by Devineau et al. [23] studied the savanna fire regime and its relationship to the distribution of plant species in Burkina Faso and found that accounting for mutual information made it possible to separate species more frequently in landscapes with little or no fire exposure and species in burnt areas.

Studies on *M. maleo* (e.g., Ambagau [24], Gazi [25], and Laban [26]) and *R. cassidix* (e.g., Mangi et al. [27], Nur [28], and Asrianny et al. [29]) were specifically carried out in a relatively narrow area coverage.

However, our study is limited to research areas, exploration outside the natural habitat, and time and costs. This study is based on environmental parameters and the distribution of the occurrence of the studied aspects as obtained from open and public data sources.

This study aims to:

– model the potential spread of *M. maleo* and *R. cassidix* (not only in their natural habitat but outside their natural habitat as well),
– model forest fires throughout the Sulawesi region,
– look at the impact of the spread of forest fires on the spatial distribution of the potential populations of *M. maleo* and *R. cassidix* throughout Sulawesi.

## 2. Material and Methods

### 2.1. Research Site

The presence records of *M. maleo* and *R. cassidix* as well as one of the serious threats to these two species were obtained from direct field surveys, the Global Biodiversity Information Facility (GBIF) database, and the Moderate Resolution Imaging spectroradiometer (MODIS) active-fire-data database. There were 351 records of the presence of *M. maleo* from 1840–2023 [30], 1547 records of the presence of *R. cassidix* from 1875–2023 [31], and 18,518 records of forest fires per one decade with a confidence level of 80% [32].

The points of the presence of this species were recorded in almost all parts of Sulawesi Island, with distribution concentrations in North Sulawesi and Central Sulawesi (Fig. 1).

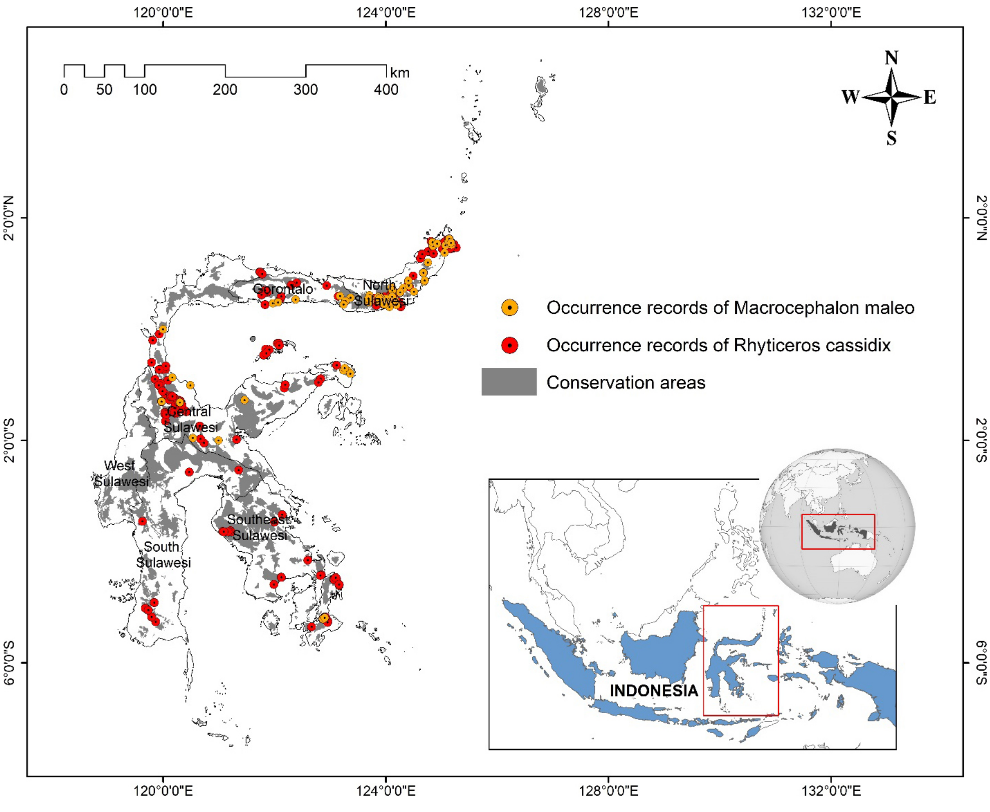


**Fig. 1.** Occurrence records of *M. maleo* and *R. cassidix* in Sulawesi

## 2.2. Species-distribution Modeling

The distribution-potential data for the species-distribution modeling (SDM) was obtained from previous studies and downloaded from available websites. The data that was used included: elevation, slope, distance from settlements, distance from roads, distance from rivers, normalized difference vegetation index (NDVI), land-use land cover (LULC), land surface temperature (LST), and distance from hot water (for the distribution-modeling of the species) along with wind speed, elevation, soil type, distance from settlements, distance from roads, rainfall, NDVI, LULC, and LST (for the modeling of the distribution of forest fires).

The elevation data was derived from digital elevation model (DEM) data from the Shuttle Radar Topography Mission (SRTM), with a resolution of 30 seconds (1 $km^2$). The slope was calculated from the elevation data. The data regarding the roads and rivers were from the Indonesian Geospatial Information Agency; this data was available on a scale of 1:250,000 [33]. NDVI, LULC, and LST were obtained from processing on the Google Earth Engine (GEE) using Landsat 8 with a resolution of 30 m. LULC was validated using the confusion-matrix method concerning a kappa coefficient >0.7 [34]. The hot-water data was collected from Program Wildlife Conservation Society Indonesia (WCS-IP), and the wind data was obtained from the Global Wind Atlas (in the form of the average wind speed for 2022) [35]. The soil-type data was obtained from the Center for Research and Development of Agricultural Land Resources (BBSDLP), with the latest data updated in 2016. Finally, the rainfall data was obtained from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), with a resolution of 5 km for the average during the period of 1981–2022.

The potential distribution was modeled using the MaxEnt software (Version 3.4.4) for both the endemic bird species and the threats using a machine-learning technique called maximum entropy (MaxEnt) [22]. Maximum entropy is one of the SDMs that is widely used for species-distribution analysis; for example, it is used to assess distributions or associations among species [36]. In addition, MaxEnt was used to analyze the effects of the land-use change [37], assess the species distributions due to the effects of climate change [38–40], assess the disaster risk [41–43], and assess the invasive species [44]. The default settings were applied to the MaxEnt Java program; however, the model-assessment procedure was done with little locality and a jackknife (or 'leave-one-out'). The model was built using the remaining $n - 1$ localities; therefore, $n$ separate models were created for the testing for the presence data with $n$ observed locations [45]. For the MaxEnt setting, the following settings were used: random test percentage – 1; regularization multiplier – 1; number of background points – 104; replicate run type (cross-validation); maximum iterations – 500; convergence threshold – 10–5; prevalence value – 0.5.

The predicted potential distributions for *M. maleo*, *R. cassidix*, and forest fires were made to cross each other in order to create two intersection areas (*M. maleo* and forest fires, and *R. cassidix* and forest fires). The crossing areas of each species and their threats were then overlaid with conservation areas to identify any potential distributions within the conservation areas that were affected by potential forest fires. The class-potential distribution was grouped into two classes (probability 0.5) using the equal interval method.

## 3. Result

The MaxEnt modeling of *M. maleo* and *R. cassidix* for the threat (namely, forest fires) was evaluated using the area under curve (AUC) value, which represented the predictive ability of the model on a 0–1 basis. The prediction model for *M. maleo* had an AUC value of 0.896, *R. cassidix* had a value of 0.837, and forest fires had a value of 0.953. The outputs from each model were used to map the potential distribution across Sulawesi (Fig. 2).

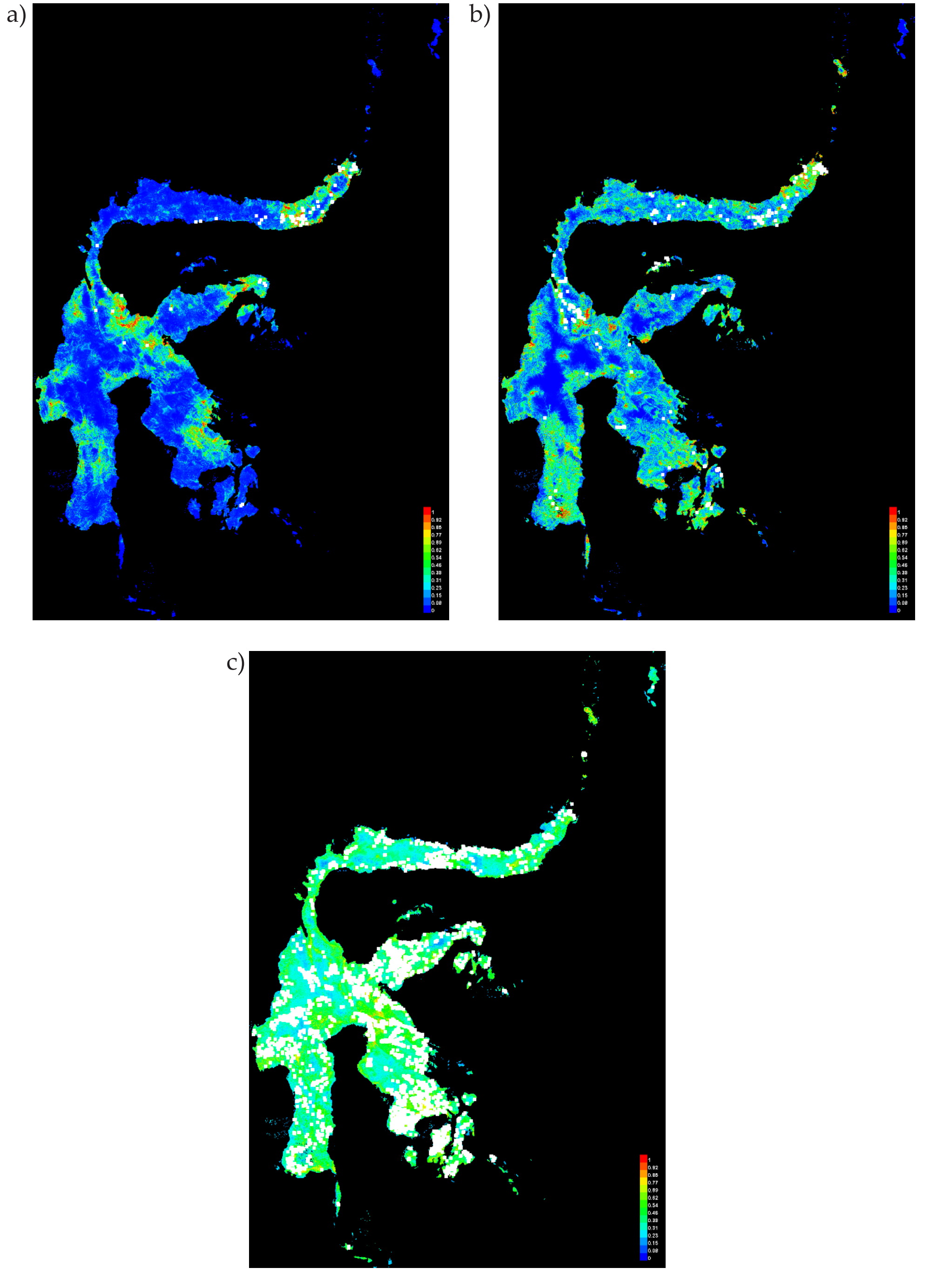


**Fig. 2.** Predicted potential distribution provided by MaxEnt models:
a) *M. maleo*; b) *R. cassidix*; c) forest fires

The predicted potential distribution for *M. maleo* covered an area of 629,503 ha, *R. cassidix* covered an area of 1,322,452 ha, and forest fires (as one of the threats) covered an area of 3,379,626 ha throughout Sulawesi. A prediction of the potential distributions of *M. maleo* and *R. cassidix* that had the potential to experience forest fires was determined. The potential distribution intersection area between *M. maleo* and forest fires covered an area of 238,690 ha, and the area between *R. cassidix* and forest fires covered an area of 677,070 ha (Fig. 3 on the interleaf).

Those areas that had the potential to experience forest fires based on the crossing area of the species with a forest fire threat were mostly located outside the conservation area. The total area that was affected by forest fires outside the conservation area covered 807,849 ha (88%), while the total area that was affected by forest fires inside the conservation area covered 107,912 ha (12%). The intersection area between *M. maleo* and forest fires within the conservation areas across Sulawesi covered 23,594 ha (22%), while the junction area between *R. cassidix* and forest fires covered 84,317 ha (78%) (Fig. 4 on the interleaf).

There are nine functions of conservation areas in Sulawesi that are identified as potential distribution areas of *M. maleo* and *R. cassidix*. There are seven conservation area functions for *M. maleo* and nine conservation area functions for *R. cassidix* (Table 1).

**Table 1.** Identified conservation areas of potential distribution of *M. maleo* and *R. cassidix* with their threats

| Areas status | Intersection areas [ha] | |
|---|---|---|
| | *M. maleo* and forest fire | *R. cassidix* and forest fire |
| Nature Reserve | 327 | 3,158 |
| Protected Forest | 18,159 | 63,267 |
| Nature Reserve Forest | 284 | 7,951 |
| Nature Reserve Area/ Nature Conservation Area | 605 | 5,303 |
| Wildlife Reserve | 4 | 118 |
| Grand Forest Park | – | 324 |
| Hunting Park | – | 607 |
| National Park | 4,190 | 2,175 |
| Nature Recreation Park | 25 | 1,414 |

The MaxEnt modeling also made it possible to identify the relative influence of environmental variables on the potential distribution. The three most important variables that affected the distribution of *M. maleo* were the distances from hot water, rivers, and roads. Meanwhile, *R. cassidix* was most affected by the distances from roads, settlements, and rivers. The distribution of the potential forest fire-prone areas was influenced most by soil type, land-use land cover, and rainfall (Fig. 5).

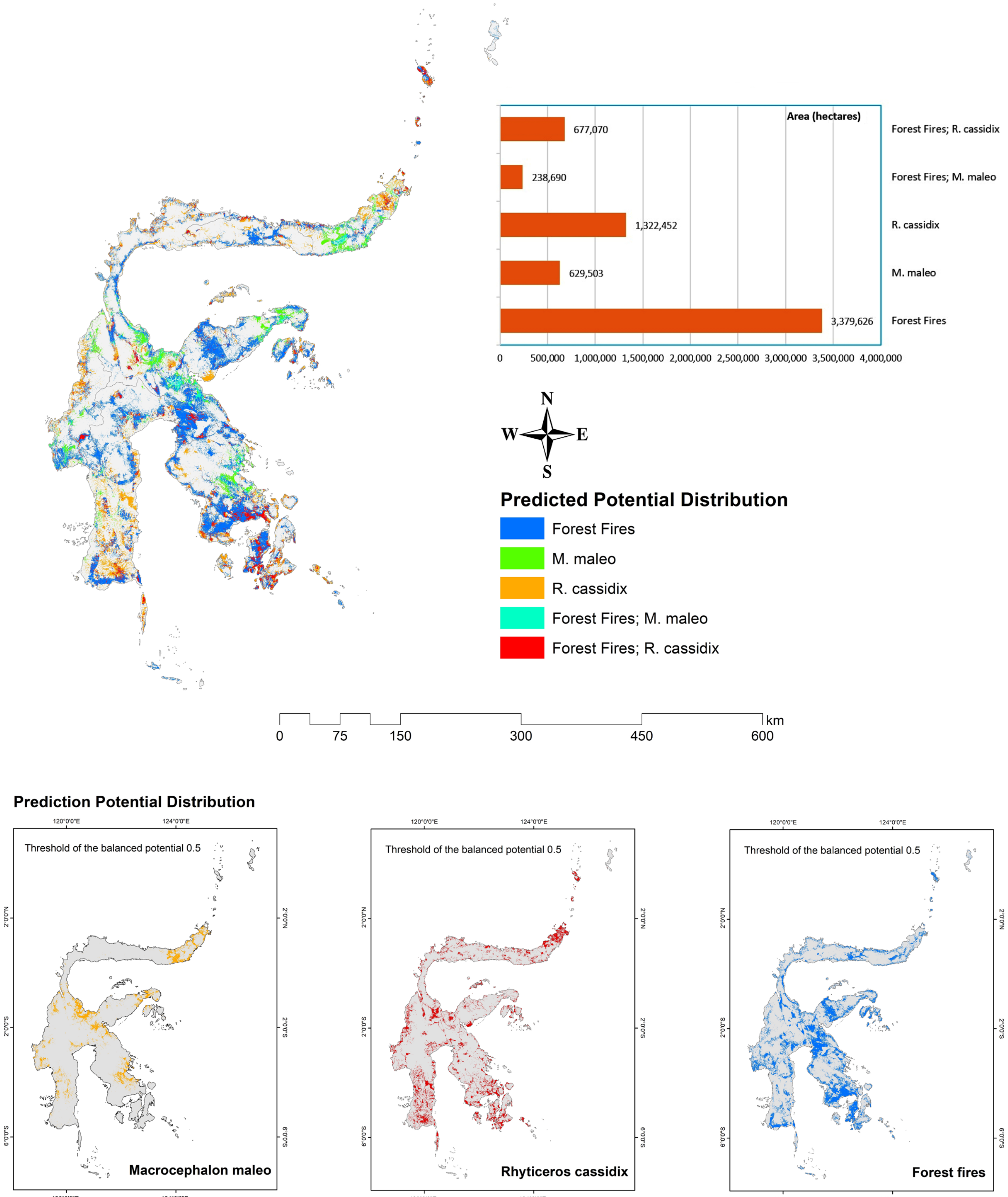


**Fig. 3.** Predicted intersection areas of *M. maleo* and *R. cassidix* with their threats

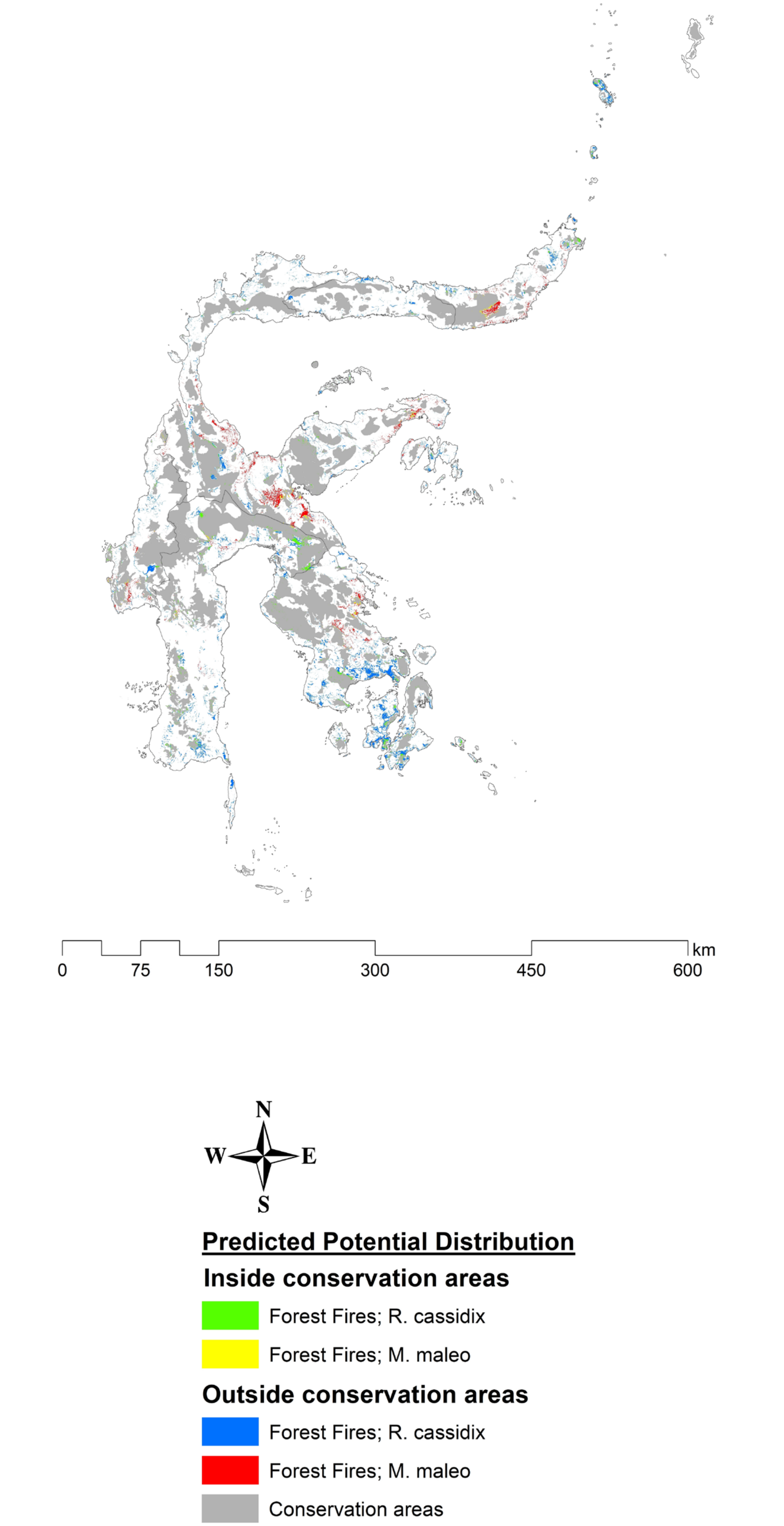


**Fig. 4.** Predicted intersection areas of *M. maleo* and *R. cassidix* with their threats that are located inside and outside conservation areas

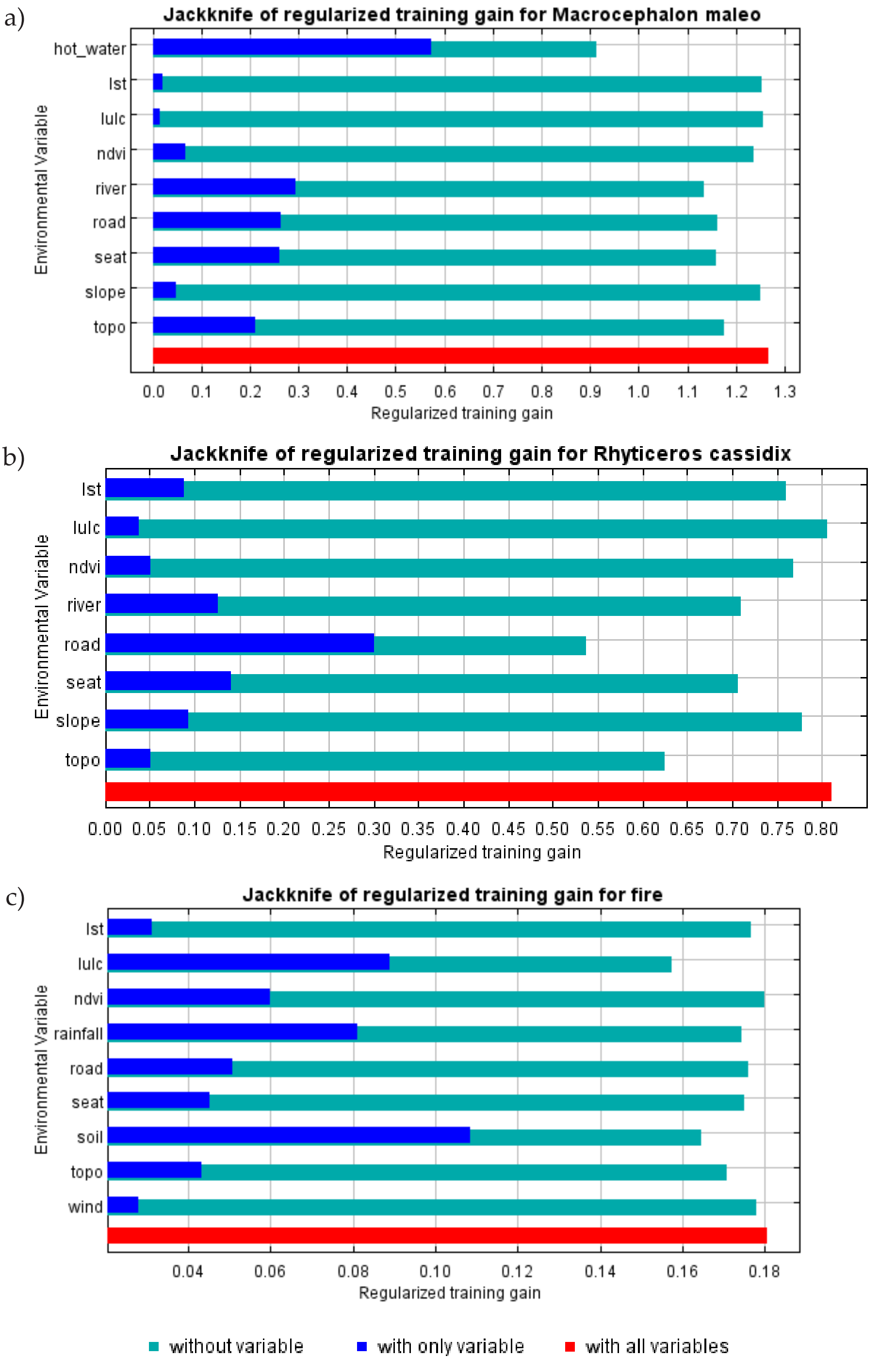


**Fig. 5.** Importance variables that affect *M. maleo* (a) and *R. cassidix* (b) with their threats (c)

## 4. Discussion

According to notes that were observed regarding *M. maleo* and *R. cassidix*, one of the threats to their existence is fire. The *Macrocephalon maleo* species is distributed in areas that have sand covers and can be found in coastal areas. Meanwhile, *R. cassidix* is spread throughout almost the entire landscape of Sulawesi and can most easily be found in primary and secondary forest areas that have large trees. The location of a forest fire area can be observed by looking at the types of vegetation that are flammable (such as shrubs or other types of plants). The records of the species' presence and the occurrences of forest fires were used to model the potential distribution of both endemic bird species and their threats. There were three criteria for selecting the actual data points: 1) using the actual data point coordinates of the target species' locations; 2) selecting data points with detailed information on the target species' locations; and 3) excluding data points that were located in built-up areas and human cultivation zones. The presence data still allowed for a bias, which could have been affected by the accuracy of the data, the method of the sampling, and the likelihood of the species' detection [46].

The selection of environmental variables is also important in the modeling process. The process of selecting the right environmental variables when determining the presence of endemic bird species and their threats is still a challenge [47]. The use of meaningful predictors is very important in determining the potential distribution of these endemic species [48, 49]. In the prediction of this model, there were four predictor groups (topography, temperature, land cover, and human disturbance) for the endemic bird species and five predictor groups (topography, climate, soil, land cover, and human disturbance) for the forest fire threats that were used as inputs. We considered these variables to be significant in determining the potential distribution of these endemic bird species and one of their threats (namely, forest fires). The distance from hot water was not included in the *R. cassidix* data, as there has been no accurate study of the effect of this variable on the distribution of this species; on the other hand, the *M. maleo* data showed the importance of this variable. Both models of the endemic bird species showed that the human-disturbance variable was one that could not be ignored and was the most relevant for all of the groups. Likewise, the variables of land cover, soil, and climate are natural variables that cause forest fires; these are important and were relevant in this study.

The potential-distribution-prediction model for *M. maleo* and *R. cassidix* each had an AUC value >0.80, which indicated that the two models enjoyed good performance. Meanwhile, the forest fire model had an AUC value >0.90, which indicated very good model performance. The AUC values were grouped into several categories based on the performance of the model: AUCs within a range of 0.9–1.0 were considered to be very good, 0.8–0.9 (good), 0.7–0.8 (fair), 0.6–0.7 (poor), and 0.5–0.6 (failed) [50]. In addition, a prediction model that had an AUC value within a range of 0.7–0.8 was considered to be acceptable; 0.8–0.9 was considered to be very good [49]. The resuls that were obtained by the forest fire variable were very good (with an AUC value of >0.90), as the trained fire-record data was spread evenly throughout the landscape.

The jackknife (or 'leave-one-out') procedure was adopted to model the locations of *M. maleo*, *R. cassidix*, and the forest fires. A high and significant success rate can be obtained when using the jackknife test with a large sample size [46]; however, if the location is <60, the success rate tends to be poor in other cases [46]. No critical difficulties were found in this study, as the number of locations that were used was considered to be sufficient. However, each model still had additional locations that were added.

The potential distribution of each species and its threats was represented by a value that ranged from 0 to 1. Those areas with values that were greater than 0.5 indicated that the area represented a potential distribution for this species. This also applied to one of the threats; namely, forest fires. Most of the potential distribution for *M. maleo* was in the North Sulawesi region; namely, in Bogani Nani Wartabone National Park, Duasaudara Nature Reserve, and Panua Nature Reserve. In Central Sulawesi, the species could be found from the coast of Parigi to Puna, Pati-Pati Nature Reserve, Morowali Nature Reserve, Lore Lindu National Park, and Pinjan Tanjung Matop Wildlife Reserve. In the Southeast Sulawesi region, it could be found in Tanjung Peropa Wildlife Reserve, Tanjung Batikolo Wildlife Reserve, Rawa Aopa Watumahai National Park, and Mangolo Nature Tourism Park. The potential distribution model of *M. maleo* also highlighted the eastern part of South Sulawesi; namely, around Lake Towuti and East Luwu. The potential distribution for *R. cassidix* was nearly throughout the Sulawesi Island and the surrounding islands, including Lembeh Island, the Togean Islands, Muna Island, and Buton Island. However, the distribution was very limited at the elevation height of the highlighted model (which is not more than 1800 meters above sea level). The distribution that was potentially affected by forest fires highlighted those areas that had land cover in the form of open lands that were overgrown with flammable lush vegetation, ferralsol soil types, and areas with low rainfall levels. The observed location data points were sometimes not predicted, as the potential distributions were very likely to be potential due to data limitations. When evaluating the performance of the model, there were two types of errors (commission errors, and omission errors). The commission errors of absences were incorrectly predicted as presence [50], while the omission errors were observations of presence that incorrectly predicted absence [49]. Both types of errors could have affected the accuracy of the model in predicting the potential spatial distribution of the target species and their threats in this study.

The most important variable that contributed to the distribution of *M. maleo* was the distance from hot water, followed by the distances from rivers and human disturbances (roads and settlements). The *M. maleo* species utilizes natural heat sources (geothermal) or stretches of sand on beaches as spawning locations [1]. This species requires special natural conditions with soil surface temperatures of around 29.4–36°C (obtained from either solar or volcanic heat) [2, 3]. Sometimes, *M. maleo* can also be found on the banks of lakes or rivers [51]. Human disturbance is a serious threat to

*M. maleo* [1, 52–54]; generally, these events are associated with forest fragmentation, the degradation of primary forest habitats, and uncontrolled egg collection [1, 53, 54]. The most important variables that contribute to the distribution of *R. cassidix* are the proximity of human disturbance (the distances from roads and settlements) and the distance from rivers. The *R. cassidix* species is threatened by habitat destruction with forest loss and land degradation in Sulawesi [6, 55]. *Rhyticeros cassidix* is known to take advantage of forests that provide large and tall trees to make nests (usually in the middle of a forest far away from human activity). There is an association between *R. cassidix* and ebony trees in the fruiting season [27]. The existence of ebony trees is often associated with the supply of springs, as these plants can absorb water in large-enough amounts [56]. The most important variables that contribute to forest fires are ferrosol soil types, land-use land cover, and topography. Ferrosol soils are weathered andosols; soil-type ferrosol is often used for agriculture, as it has a good levels of fertility, absorption, and soil structure [57]. According to the Ministry of Environment and Forestry [58], forest and land fires were reported to cover 204,894 ha in Indonesia during the year of 2022. Forest fires significantly change the structures of forests by reducing the numbers of trees and species in forested areas [20]. The fires in the study area also occurred in the lowlands. It is undeniable that low rainfall due to global climate change is the key to the high intensity of fires.

The map of the potential distribution of *M. maleo*, *R. cassidix*, and one of their threats (namely, forest fires) that resulted from this study may not accurately predict the locations of the species' presence and the locations of the areas that have been affected by forest fires, as it only depends on the variables that were used. Other factors such as the history of a site can also be important. Although predicting the potential distribution of a site may be successful, there are many reasons why a species may not be found in this location. There is the possibility that the species could not have spread to this location. Unidentified biotic interactions may have inhibited recruitment or survival at some sites. It is possible that a species was once found in an area in question but has since disappeared from this area. Failing to find species even when they are present may be due to dormancy. Conversely, the model may predict that a certain region is a potential distribution but that the species may occur in this location. Some species can spread to a location and adapt physiologically to less-suitable areas [59]. Given the difficulty in taking full samples to pinpoint the locations of endangered species, this is important. MaxEnt modeling is useful for assessing the potential distributions of *M. maleo*, *R. cassidix*, and their threats.

This research can be used by the Government of the Republic of Indonesia (especially the Ministry of Environment and Forestry) in order to determine the monitoring of those protected areas that have the potential to be affected by forest fires and improve their conservation-based management; it can also help inform and update the distributions of *M. maleo* and *R. cassidix* on the IUCN Red List in the future. Further studies can include more specific climate variables given the very strong association of these species with these aspects.

## 5. Conclusions

The predicted potential distributions for *M. maleo* and *R. cassidix* were approximately 629,503 and 1,322,452 ha, respectively. Approximately 238,690 and 677,070 ha of potential distribution for *M. maleo* and *R. cassidix*, respectively, in conservation areas can potentially be disturbed and affected by forest fires. However, this number is smaller when compared to those areas outside the conservation area.

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**CRediT Author Contribution**

S. A.: conceptualization, methodology, software, image processing, validation, formal analysis, visualization, writing – original draft preparation.

R.: collection field data, writing – review and editing.

R. A. S.: collection field data, validation, visualization, and editing.

**Declaration of Competing Interest**

We all state that none of us have any competing interests with this article.

**Data Availability**

Public Data: The data sets analyzed during the following research are available on the Fire Information for Resource Management System (FIRMS). Can be accessed after being registered and approved by FIRMS via the following link: https://firms.modaps.eosdis.nasa.gov/active_fire/. Data on species presence is available at the Global Biodiversity Information Facility (GBIF). Can be accessed via the following link: https://doi.org/10.15468/dl.yqmj2p (*M. maleo*); and https://doi.org/10.15468/dl.z4ydfp (*R. cassidix*).

Restricted Data: Conservation area data that supports the findings of this research is available from the Ministry of Environment and Forestry of the Republic of Indonesia. Restrictions apply to the availability of data, which was used under license for this research. The data presented in this article is courtesy of the Ministry of Environment and Forestry of the Republic of Indonesia.

**Use of Generative AI and AI-assisted Technologies**

No generative AI or AI-assisted technologies were employed in the preparation of this manuscript.

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