Agr. Nat. Resour. 57 (2023) 869–876

AGRICULTURE AND NATURAL RESOURCES

Journal homepage: http://anres.kasetsart.org

Research article

Habitat suitability modeling of *Acropora* spp. distribution in Coral Triangle area of Maluku Waters, Indonesia under influence of future climate change and coastal pollution

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Article Info

Article history:
Received 30 June 2023
Revised 4 October 2023
Accepted 15 October 2023
Available online 31 October 2023

Keywords:
Acropora spp.,
Coral reef conservation,
Habitat degradation,
MaxEnt,
Projection model

Abstract

Importance of the work: The sustainability of coral reefs in the Maluku Waters, Indonesia is threatened by future coastal pollution and climate change. Thus, it is crucial to develop a mapping projection model as a baseline for conservation policies.

Objectives: To develop a habitat suitability prediction model for coral reefs in 2050, considering climate change scenarios and the cumulative impacts of water pollution.

Materials & Methods: The model utilized the habitat data of *Acropora* spp. from the Ocean Biodiversity Information System database and projected them using the maximum entropy algorithm (MaxEnt) based on environmental factors (temperature, salinity, current, chlorophyll, particulate organic carbon, particulate inorganic carbon, nitrate, phosphate and ultraviolet penetration).

Results: The study revealed a significant decline in spatial areas with high habitat suitability, decreasing from approximately 3,661 km² to only 64–226 km² in 2050 under the representative concentration pathway (RCP) scenarios 2.6, 6.0 and 8.5 Inter-governmental Panel on Climate Change AR5 projections. Chlorophyll concentration, an indicator of coastal pollution, had the highest correspondence with optimal coral habitat, followed by temperature and salinity.

Main finding: Besides contributing to international carbon emission reduction efforts, reducing coastal water pollution runoff is crucial for supporting the long-term sustainability of coral reefs, as indicated by the model's findings. This is due to the destructive effects of water pollution and future climate change. Policy adjustments and local wisdom are essential for conserving coral reef ecosystems.

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https://doi.org/10.34044/j.anres.2023.57.5.13

Introduction

Coral reefs in Maluku Waters at the center of the Tropical Coral Triangle ecoregion, Indonesia is one of the marine biodiversity hotspots in the world, containing more than 500 species that are both ecologically and economically important (Marwayana et al., 2022). Ecologically, the area is a foraging, breeding and nursery ground for various marine organisms, with an economic value of up to USD 11.96 million/ha (Haya and Fujii, 2019). Calculations by Ramadhan et al. (2017) show that the total economic value of protected coral reef areas in the Tropical Coral Triangle region is USD 10 million/ha/yr. Thus, the region is an important marine resource for tropical ecosystems and supports local economies.

However, as sessile animals, corals exhibit sensitivity toward environmental alterations. The repercussions of human-caused climate change include elevated greenhouse gas levels, which, in turn, contribute to a reduction in oceanic pH, commonly known as ocean acidification (Doney et al., 2009). The projected decline in pH caused by climate change has major implications for coral organisms because ocean acidification leads to a decline in calcification, which is essential for most coral organisms to build calcium carbonate skeletons (Guinotte and Fabry, 2008). In addition, the degradation of coastal habitats for coral reefs is due to the influx of pollutants from onshore sources and the use of unsustainable fishing methods that are detrimental to the environment (Edinger et al., 1998). Consequently, the composition of coral reef communities has changed significantly, as observed in numerous locations, including the tropical region of Indonesia at sites such as Wakatobi and the Alor Conservation Park (Januar et al., 2012, 2015).

Hence, an optimal conservation policy based on scientific principles is essential to sustain the coral reef ecosystem. Species distribution models (SDMs) can provide a scientific foundation for policymakers to uphold natural resource value, including for coral reefs (Benson et al., 2017). However, marine species distribution models have gained traction more slowly than terrestrial ones, mainly since 2005. Fish, mammal, mollusk and seaweed distribution has been more researched (21–37 publications) than stony coral (15 publications) according to the review by Melo-Merino et al. (2020). The current study aimed to provide a baseline for policymakers on predicting coral distribution facing climate change in the Tropical Coral Triangle, using a MaxEnt model of future reefs in Maluku waters. Maximum The maximum entrophy (MaxEnt) algorithm is the most common SDM for marine biota (46%), followed by generalized additive models (GAMs) and generalized linear models (GLMs) according to Melo-Merino et al. (2020). MaxEnt's algorithmic simplicity and reliability with sparse, irregular data make it a popular species distribution modeling tool (Bedia et al., 2011; Kramer-Schadt et al., 2013; Srivastava et al., 2019). For the current study, *Acropora* spp., widely distributed in tropical regions, was chosen as a bioindicator species for the SDM.

The study used the prediction scenarios of representative concentration pathway (RCP) 2.6, 6.0, and 8.5 at 2050 from the Inter-governmental Panel on Climate Change (IPCC) AR5 marine conditions, as the most recent IPCC Sixth Assessment Report (IPCC 2021) data were unavailable in the Bio-Oracle 2.2 database for future environmental conditions. The AR6 updates focus on anthropogenic socioeconomic influences, predicting higher CO_2 levels of about one step above AR5. Bodeker et al. (2022) indicated relatively similar 2050 CO_2 estimates for SSP1-1.9 AR6 and RCP 2.6 AR5, SSP1-2.6 AR6 and RCP 4.5 AR5, and SSP3-7.0 AR6 and RCP 8.5 AR5. Despite CO_2 value variations, Slangen et al. (2023) found relatively small differences in the sea level rise model results between AR5 and AR6. Therefore, RCP AR5 data are still used despite limitations on CO_2 emission accuracy since some oceanic parameters lack spatio-temporal predictive data. Anthropogenic pollutants, such as chlorophyll and UV light were added to the model, given the absent oceanic data and AR6's socioeconomic focus.

Materials and Methods

Study area

The study area was located in the coral reef region in Maluku Waters, located in the central zone of the Coral Triangle on the eastern side of Indonesia (Fig. 1). The area includes 1,340 islands covering 54.185 km^2 of land area, which is 8% of the total area. The remaining 92% (approximately 658,300 km^2) is sea, with a coastline stretching 10,662 km around the islands (Ubwarin, 2018).

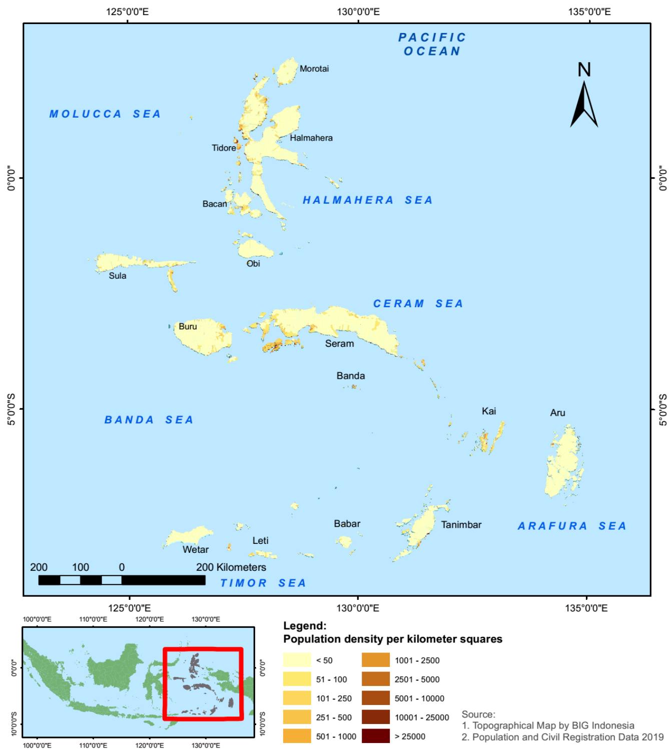

Fig. 1 Maluku Waters, eastern Indonesian archipelago

The Maluku Islands, consisting of North Maluku (Halmahera) and Maluku (encompassing the central to southern waters regions), are considered a less prosperous Indonesian province with uneven development, jobs and infrastructure (Kuncara et al., 2021; Saptenno et al., 2021). There are approximately 3 million people inhabiting the Maluku Islands based on 2022 data (BPS Maluku, 2023; BPS North Maluku, 2023). The economy depends on agriculture, forestry and fisheries. Most residents live on the northern Ternate-Tidore Islands, central Ambon Island and the southern Aru Islands (Pattiasina et al., 2021). High human activity plus inadequate environmental law enforcement have substantially polluted the water, especially around Ambon City, South Buru, East Seram and Central Maluku (BPS Maluku, 2023; BPS North Maluku, 2023).

Data collection

Data were collected using the maximum entropy algorithm (MaxEnt) to develop a model of future habitat suitability for a specific organism, *Acropora* spp., that serves as a bioindicator of coral reef distribution in Maluku Waters. The selection was based on the dominance of this species as a reef builder, particularly in tropical regions (Roff, 2020; Safuan et al., 2020). Distribution data for *Acropora* spp. were obtained from two databases, the Ocean Biodiversity Information System (OBIS) and the Global Biodiversity Information Facility (GBIF). Data were filtered and processed to eliminate spatial autocorrelation points. Filtered data from the polygonal area of water bodies yielded 3,727 records from the OBIS database (OBIS, 2023) and 4,571 from the GBIF database (*Acropora* Oken, 1815 in GBIF Secretariat, 2023). Both data types were combined and further processed to eliminate spatial autocorrelation points, based on Brown et al. (2017).

Environmental data were collected using the method of Simon-Nutbrown et al. (2020), which combined future projections of marine environmental variables, including sea surface temperature, salinity, and ocean current, under the RCP 2.6, 6.0, and 8.5 scenarios for the year 2050. In addition, current spatial data of environmental variables associated with direct terrestrial anthropogenic discharges were included, such as dissolved oxygen, ultraviolet (UV) light penetration, pH, water productivity, dissolved oxygen and chlorophyll. Several other variables were not included in the analysis due to limitations in the available environmental prediction data for the 2050 or because they exhibited spatial autocorrelation with existing variables, such as sedimentation rate and turbidity. Data related to the turbidity variable are correlated with UV-light penetration, as Dias et al. (2020) suggested. The model was built assuming that the runoff of wastes from the mainland will continue through 2050 without any mitigation. The environmental data were obtained from the Bio-ORACLE 2.2, NASA Moderate Resolution Imaging Spectroradiometer (MODIS) OCSMI and GMED databases.

Model development

The modeling process involved modeling software using the maximum entropy (MaxEnt) approach (Phillips et al., 2006) to predict the abundance and distribution of *Acropora* spp. Modeling was conducted in response to environmental variables under different climate change scenarios (RCP 2.6, 6.0 and 8.5) for 2050, based on the method proposed by Freeman et al. (2013). The occurrence data were split into 70% for training the model and 30% for testing it. The reliability and accuracy of the model were evaluated using the average area under the curve (AUC). The AUC index, which ranges from 0 (performance worse than random) to 1 (perfect discrimination) with values greater than 0.5 serving as a threshold for random (Tittensor et al., 2009). Modeling results included species distribution maps and environmental variables affecting their distribution. Raster data analysis was performed using the GIS software ArcMap 10.8 (ESRI, 2021). In the final phase, conclusions were drawn based on the outputs generated from the modeling process. These conclusions provided more detailed information from the data collected and analyzed, contributing to the overall understanding of the habitat suitability model for future coral reefs in Maluku waters.

Results and Discussion

Contributing factors

The findings of this study provided valuable insights into the habitat suitability of coral reefs in Maluku waters and the potential impacts of future environmental changes. The AUC analysis produced excellent results, with values exceeding 0.9, indicating a reliable model for predicting the distribution of *Acropora* (Fig. 2).

Further testing revealed that three variables (chlorophyll, temperature and salinity) substantially influenced the suitability of the coral reef habitat for *Acropora* spp. Chlorophyll levels in coastal areas made the most substantial contribution of 57.5%, indicating the importance of nutrient availability, particularly phosphate levels (Kadim et al., 2019). Chlorophyll is a vital indicator of primary productivity, providing essential nutrients and energy for coral reef ecosystems' growth, oxygen production and calcification (Sinutok et al., 2011; Fisher-Pool et al., 2016).

However, high nutrient levels can indicate the presence of erosion runoff, sedimentation, domestic waste, inappropriate agricultural practices and other factors; therefore, chlorophyll levels are often associated with various factors, primarily anthropogenic activities that can reduce aquatic habitat quality for organisms (Hou et al., 2019). High chlorophyll levels will increase competition between algae and zooxanthellae (symbionts of coral animals that play a major role in providing their food), thus reducing the food supply for coral animals. Data have shown a shift in coral reef coverage, transitioning from hard stony coral to dead coral with algae or even rubble in conditions where there are high nutrient levels in the water (Crehan et al., 2019; Adam et al., 2021).

Fig. 2 demonstrates the important roles temperature and salinity play, contributing 7.2% and 6.1% to coral reef habitat suitability, respectively, by influencing the physiological processes and tolerance limits of coral organisms. The pH of seawater contributed only 0.1% to the habitat suitability model. Climate change affects temperature and salinity by increasing CO_2, a significant greenhouse gas, while rising sea surface temperatures have been detected and correlated with greenhouse gas levels in the atmosphere (Dhage and Widlansky, 2022).

Despite sea temperature and salinity not being identified as main drivers of coral reef habitat suitability, predictions suggest a trend of decreasing sea surface salinity that is expected to occur twice as fast in the Indonesian and East China Seas compared to the global average (Jin et al., 2023). Fluctuations in sea surface temperature may create temporary opportunities for coral recovery, as corals can recover relatively quickly from high temperatures (Simpson and Wadsworth, 2021). However, coral bleaching events in the Coral Triangle area are highly likely during an El Nino phase (Kleypas et al., 2015; Wouthuyzen et al., 2018), leading to increased coral mortality and a decrease in fish density after disturbances (Pendleton et al., 2016; Triki and Bshary, 2019).

Furthermore, ongoing anthropogenic pollution is a constant threat to coral reefs. This may explain why chlorophyll, as an indicator of pollution, substantially affected the suitability of the *Acropora* habitats in the current study. The combination of rising temperatures due to future climate change and nutrient

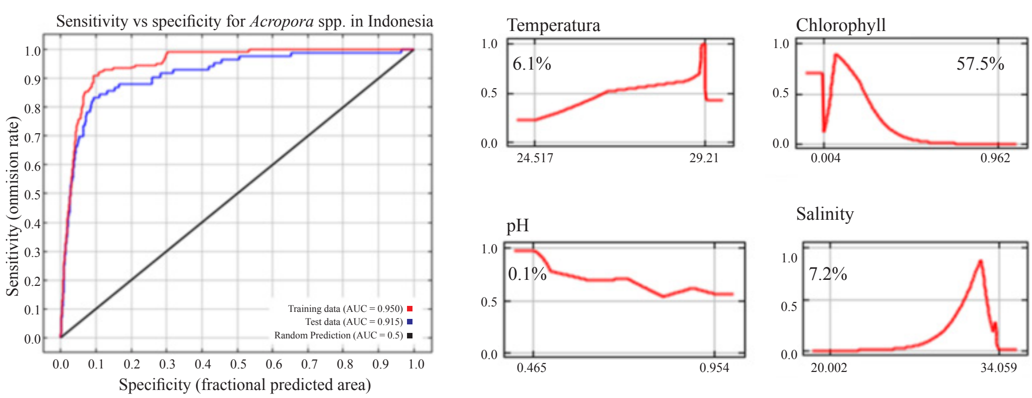

Fig. 2 Area under the curve (AUC) values and contribution of water variables to coral reef habitat suitability in Maluku Waters

runoff will produce a notably greater impact when contrasted with the effects of each factor in isolation. Experiments conducted by Thummasan et al. (2021) demonstrated that while a high level of an individual nutrient (nitrate) did not significantly affect coral organisms, the combination of elevated nitrate levels and increased temperature leads to substantial disruptions in coral physiology. The interplay between climate change, particularly sea surface temperature, and elevated nutrient levels severely impacts coral organisms (Humanes et al., 2016). The cumulative impact of these two factors can result in reproductive disturbances, inhibited growth, compromised health and reduced coral resilience (Ellis et al., 2019).

However, these results have limitations related to the absence of some environmental factor interactions that can play a major role in distribution, resulting in the current research only identifying chlorophyll as an important factor in the model. One example of such a factor is related to the life forms of coral species. Different life forms may respond differently to varying environments and *Acropora* spp. is known to have various life forms with different environmental tolerances, with the branching type generally less resilient to physical environmental pressures than the massive form (Xu et al., 2020; Watt-Pringle et al., 2022; Tavakoli-Kolour et al., 2023). In addition, responses to temperature and sedimentation can vary. The model in the current study is limited to the global correspondence between the input of environmental conditions in the presence of distribution, despite the life form.

Habitat suitability model

The GIS analysis revealed that the current total coral reef habitat area in the waters of Maluku was approximately 6,775 km^2. Projecting this information using the maximum entropy algorithm showed that under current environmental conditions (based on 2020 environmental data), the habitat deemed "very suitable" (Probability Coefficient, $R > 0.75$) was substantial, encompassing over one-half of the coral reef habitat (Table 1).

The future projections paint a concerning picture. The current habitat suitability condition of the coral reefs is expected to decline substantially by 2050 due to projected shifts in environmental variables. The area classified as "less suitable" ($0.25 < R \leq 0.5$) will encompass one-half of the total habitat area, while the "very suitable" area will constitute less than 5% of its current extent. The projected changes in the area extent from 2020 to 2050 are depicted spatially in Fig. 3. Notable changes were observed in predicted maps, where a previously large area classified as "very suitable" habitat declines to "suitable" or even "less suitable."

The waters surrounding the Maluku Islands comprise diverse coral reef habitats, including atolls, exposed outer reefs and sheltered coasts with mangrove forests. These habitats face various local human-induced pressures (Allen and Werner, 2002). When evaluating the ocean exposure characteristics, the predictive map indicates that coral reef habitats more exposed to the open sea, primarily situated in the southern islands from the Tanibar Islands to Wetar Island, will experience higher pressures than sheltered coast ecosystems. Conversely, favorable habitats will concentrate within sheltered coast ecosystems, particularly in regions around southwest Halmahera, Tidore, the Bacan Islands and central areas encompassing Ambon Island, the western part of Seram and the Kei Islands. These areas are known to harbor mangrove forests on their main islands. These mangrove forests act as filters, reducing anthropogenic pressures from the main islands, including sediment, erosion and nutrient runoff (Susilo et al., 2017; Ulumuddin et al., 2021). Regions with mangrove forests are suitable to help strengthen the resilience and sustainability of coral reef ecosystems. However, these regions also host concentrated human populations on the Maluku Islands. Anthropogenic coral reef degradation has been observed on islands with higher population density within the Maluku Coral Reef archipelago. This degradation occurs indirectly due to land-based water pollution, as well as directly through activities, such as coral mining and destructive fishing practices (Titaheluw et al., 2020; Lessy et al., 2021; Limmon and Manuputty, 2021; Limmon et al., 2023).

Table 1 Areas (square kilometers) of coral reef habitat suitability in the Maluku waters based on probability ranges (where R is the probability coefficient) for the current (2020) and future (2050) environmental conditions under different representative concentration pathway (RCP) scenarios

Habitat suitability	Current (2020)	2050		
		RCP 2.6	RCP 6.0	RCP 8.5
Less suitable ($0.25<R\leq0.5$)	1,207.76	3,098.65	3,177.91	2,789.16
Suitable ($0.5<R\leq0.75$)	1,905.99	2,189.06	1,932.41	1,921.09
Very suitable ($R>0.75$)	3,661.01	226.45	143.42	64.16

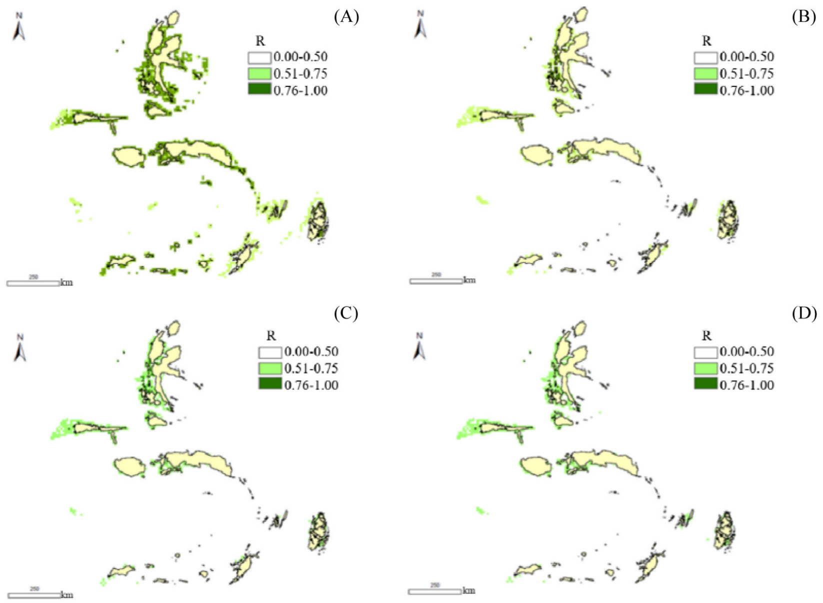

Fig. 3 Probability (R, where R is probability coefficient) area plots of *Acropora* habitat suitability in Maluku waters for: (A) current climate (2020); and future environmental conditions under scenarios: (B) representative concentration pathway (RCP) 2.6; (C) RCP 6.0; (D) RCP 8.5

The habitat suitability model illustrated that the combined effects of future climate change dynamics and direct anthropogenic impacts, such as increased nutrient runoff in coastal waters, will substantially reduce habitat suitability for coral reefs. Therefore, it is imperative to prioritize optimal coastal conservation efforts to bolster coral reef resilience against impending climate change. Disruptions to the balance of coastal ecosystems, such as the degradation of mangrove forests, can exceed their capacity to absorb runoff, thereby profoundly affecting coral reefs, as discussed earlier.

Policy adjustments are essential to set practical targets for sustaining coral reef ecosystems. Mitigating and reducing terrestrial runoff and the regular monitoring of pollution levels are critical to bolster coral reef resilience in the face of climate change. Efforts to conserve Maluku's coral reefs have included establishing Marine Protected Areas (Ceccarelli et al., 2022). The effectiveness of conservation should be enhanced through the involvement of local wisdom from the coastal communities of the Maluku islands, contributing to the preservation of biological resources in coastal and marine ecosystems (Beruat et al., 2014; Touwe, 2020; Farah, 2022). However, considering that the current study was based on data from IPCC AR5, there are certain limitations regarding the accuracy of the CO_2 emission levels in the corresponding RCP models, the environmental variables applied in this research and the consideration of the actual life form of the species. Further studies utilizing the SSP factors in AR6 and specification of the life-form within a species in the presence of distribution input to the model will provide updated predictive patterns for habitat suitability for tropical coral reefs in response to future climate changes.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

Dr. Sutomo and Mr. Hadi Saputra, as our fellow scientists in the Ecological Modeling Research Group, provided valued comments regarding the interpretation of the research findings that strengthened the analysis.

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