



Modeling Potential Habitat of Whale Shark (*Rhincodon typus*) to Support Conservation Efforts in Indonesia

Bagas Arja Theona¹, Gita Shanaya Sihombing¹, Nisa Fitriani Nur Azizah¹, Novantiara Mike Ardianata¹

¹ Study Program of Biology, Faculty of Military Mathematics and Natural Sciences, The Republic of Indonesia Defense University, Indonesia Peace and Security Center (IPSC) Sentul Complex, Bogor 116810, Indonesia.

* Correspondence: theonabagas@gmail.com

Abstract

The whale shark (*Rhincodon typus*) is a protected marine species that plays an important ecological role and has high economic value through marine ecotourism. However, global climate change has the potential to affect the distribution and habitat suitability of this species through changes in oceanographic parameters. This study aims to model the habitat suitability of whale sharks in Indonesian waters under current conditions (2000–2014) and predict habitat changes in the future period (2040–2050) under the RCP 8.5 climate change scenario. Modeling was carried out using the MaxEnt-based Species Distribution Model with 95 whale shark occurrence points obtained from the Global Biodiversity Information Facility (GBIF). Marine environmental variables were obtained from Bio-Oracle version 2.2, including sea surface temperature, salinity, and sea current velocity. Spatial analysis and visualization of habitat suitability maps were performed using QGIS version 3.44.6. The results showed that the MaxEnt model has high performance with an AUC value > 0.9. Highly suitable habitat under current conditions is primarily concentrated in eastern Indonesian waters, particularly areas with high aquatic productivity. Future projections indicate changes and fragmentation of suitable habitat, with spatial shifts closely related to changes in sea surface temperature, salinity, and ocean current dynamics. Variable ocean current speeds play a crucial role in shaping feeding hotspots through oceanographic fronts and upwelling mechanisms. Climate change-based habitat suitability modeling is an important tool in supporting adaptive whale shark conservation planning. Information on changes in habitat distribution can provide a scientific basis for establishing and evaluating marine conservation areas and managing sustainable whale shark ecotourism.

Keywords: GBIF, Whale Shark (*Rhincodon typus*), Habitat Suitability, MaxEnt, Southern Waters, Climate Change, and QGIS.

1. Introduction

The whale shark (*Rhincodon typus*) is a highly migratory tropical species, with the majority of its global population occurring in the Indo-Pacific region. Significant population declines have been reported in this region as a result of fisheries pressure, bycatch, vessel strikes, and ongoing habitat degradation (Pierce & Norman, 2016). Despite its ecological importance, the behavioral ecology of whale sharks remains poorly understood, particularly in relation to movement patterns, feeding behavior, social interactions, and responses to increasing human activities (Martin, 2007).

The whale shark (*Rhincodon typus*) is globally classified as Endangered on the IUCN Red List, with population declines particularly evident in the Indo-Pacific region where most of the global population occurs (Pierce & Norman, 2016). Indonesian waters represent important habitats for whale sharks, supporting seasonal aggregations in productive coastal and offshore areas. Studies conducted in Indonesia have demonstrated that whale shark presence is strongly influenced by environmental factors such as sea surface temperature and food availability (Herdianti *et al.*, 2024; Rahman *et al.*, 2021). In addition, recent habitat modeling studies in the Indian and Atlantic Oceans have shown that whale shark habitat suitability is closely associated with environmental variables, including sea surface temperature, chlorophyll-a concentration, and bathymetric conditions. These findings emphasize the critical role of Indonesian marine habitats in whale shark conservation and highlight the need for habitat-based management approaches (Petatán-Ramírez *et al.*, 2020).

Therefore, the Species Distribution Model (SDM) approach is essential for predicting spatial changes in suitable habitats for whale sharks under future climate scenarios. This study follows the approach of (Liu et al., 2021), which applied the MaxEnt model to predict species habitat suitability under climate change conditions. Using whale shark occurrence data and oceanographic variables obtained from Bio-ORACLE version 2.2, this study aims to model whale shark habitat suitability in Indonesian waters under current conditions (2000–2014), to project changes in habitat suitability for a future period (2040–2050) under the RCP 8.5 scenario, and to identify key environmental factors influencing whale shark distribution as a basis for conservation planning. The results of this study are expected to provide a scientific foundation for climate-adaptive management and conservation planning of whale sharks, particularly in the context of the designation and evaluation of marine protected areas.

2. Materials and Methods

2.1. Species Occurrence data

Whale shark (*Rhincodon typus*) occurrence records were obtained from the Global Biodiversity Information Facility (GBIF) and complemented with additional secondary data sources. All available records were subjected to a rigorous data-cleaning process to remove duplicate entries, coordinate errors, and records with high spatial uncertainty. After validation, a total of 95 occurrence points were retained and used as presence-only data for habitat suitability modeling. All occurrence points were spatially restricted to the southern Java Sea study area to ensure consistency between species records and environmental variables (Figure 1).

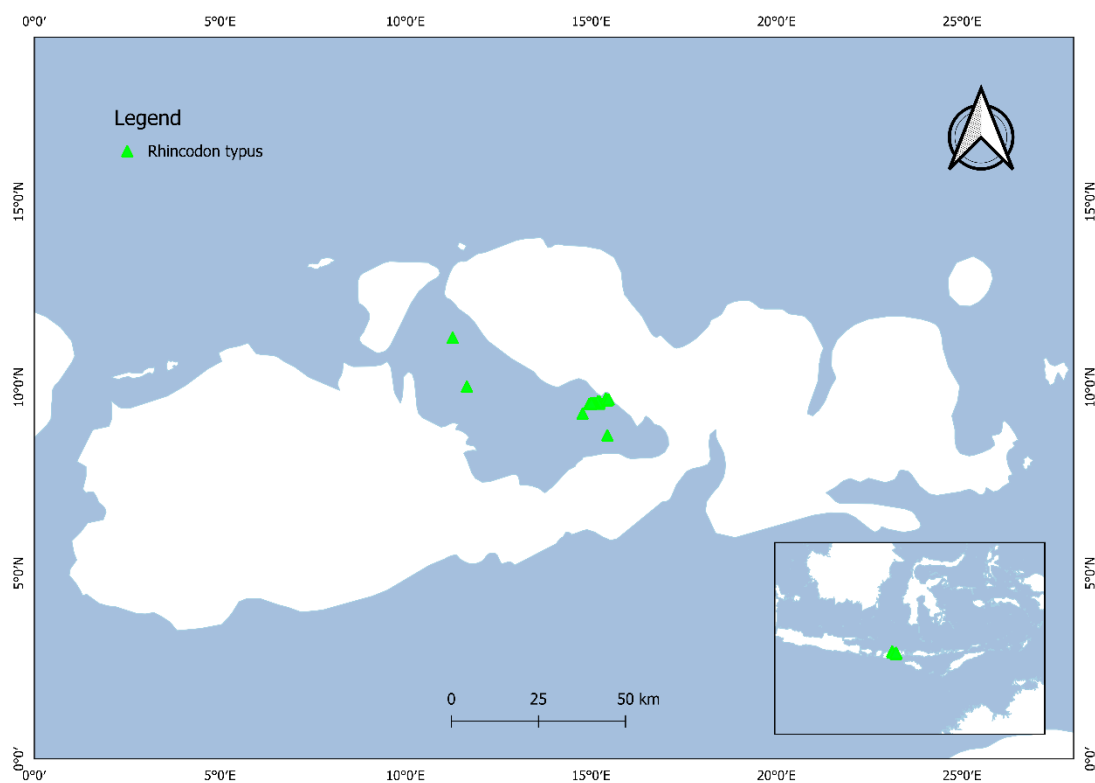


Figure 1. Map of the distribution of *Rhincodon typus* in Southern Waters

2.2. Environmental Variables

Marine environmental variables were obtained from Bio-ORACLE version 2.2, which provides globally consistent oceanographic raster datasets at a uniform spatial resolution. The variables selected for this study included sea surface temperature (SST), salinity, and sea current velocity, all of which are ecologically relevant to the distribution of whale sharks (*Rhincodon typus*) as plankton-feeding species. These variables were used to model habitat suitability of whale sharks in Indonesian waters under current environmental conditions (2000–2014) and to project potential changes in habitat distribution for a future period (2040–2050) under the climate change scenario RCP 8.5.

2.3. Habitat Suitability Modeling

Habitat suitability modeling was conducted using MaxEnt software version 3.4.1, a widely used tool for species distribution modeling based on presence-only data. A total of 75% of the occurrence records were used for model training, while the remaining 25% were reserved for model testing. Model performance was evaluated using the Area Under the Curve (AUC) of the Receiver Operating Characteristic (ROC) curve. The relative contribution of each environmental variable was assessed using jackknife tests, allowing the identification of key oceanographic factors influencing the distribution of whale sharks (*Rhincodon typus*).

2.4 Map Visualization

All spatial analyzes and map visualizations were conducted using QGIS version 3.44.6. Habitat suitability maps for current and future periods were compared to identify potential spatial shifts in the distribution of whale shark (*Rhincodon typus*) habitats.

3. Results

3.1 MaxEnt Model Performance

The modeling results show that the MaxEnt model performs very well in predicting whale shark habitat suitability in the study area. The AUC value obtained was above 0.9, indicating a very high model capability in distinguishing between suitable and unsuitable habitats. This value indicates that the combination of occurrence data and oceanographic variables used is able to accurately represent the ecological preferences of whale sharks (Figure 2).

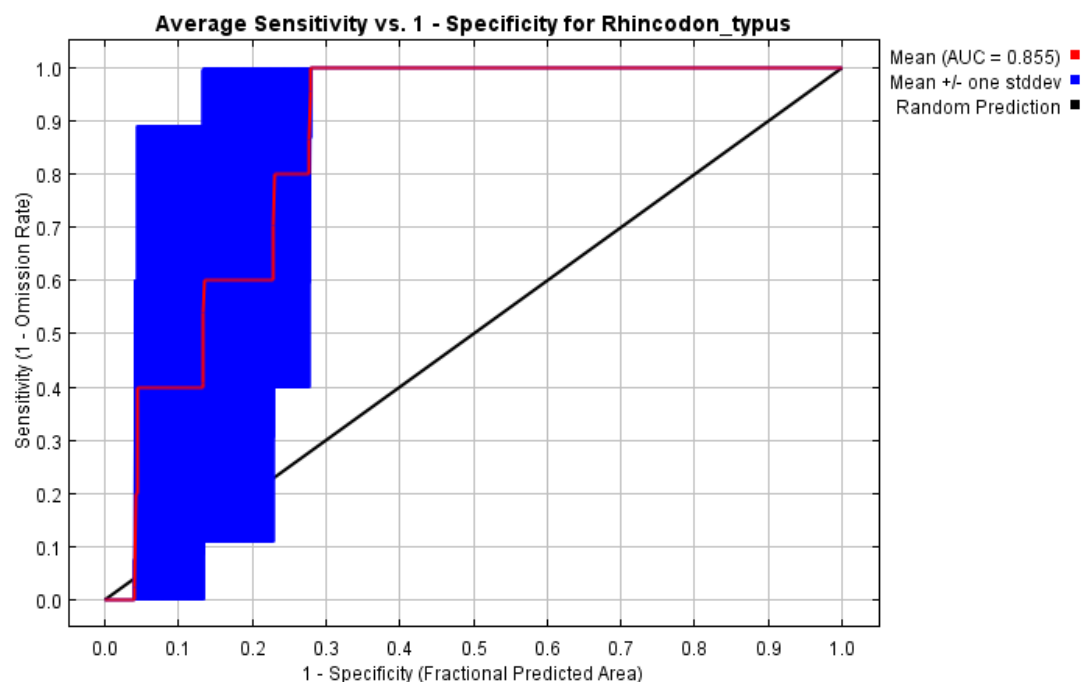


Figure 2. Reliability test of the distribution model created for *R Rhincodon typus*

3.2 Contribution of Environmental Variables

Based on the variable contribution graph and jackknife test, several Bio-Oracle v2.2 variables showed a dominant contribution to model development (Figure 3). The most influential oceanographic variables were sea surface temperature (SST) and sea current velocity (SCV). The high contribution of chlorophyll-a indicates that whale shark distribution is closely related to waters with high productivity and abundant food availability.

The variable response graph shows that the probability of whale shark presence increases within a range of relatively warm and stable sea surface temperatures, medium to high chlorophyll-a concentrations, and specific Sea Current Velocity (SCV) values that support plankton accumulation and feeding aggregation. Conversely, under extreme temperature conditions or low productivity, the probability of whale shark presence decreases significantly.

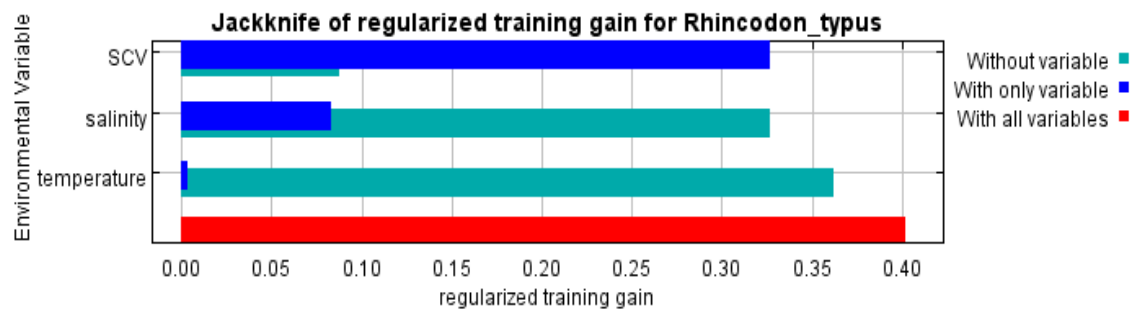


Figure 3. Jackknife test of variable importance for *Rhincodon typus*

3.3 Current Spatial Patterns of Habitat Suitability (2000–2014)

The habitat suitability map for the period 2000–2014 shows that highly suitable habitat is concentrated in several key areas, particularly in western Indonesian waters, such as the Java Sea and parts of Sulawesi (Figure 3). These areas are characterized by relatively stable oceanographic conditions, high primary productivity, and dynamic ocean currents that support plankton accumulation.

Habitats with moderate to low suitability are more widely distributed, particularly in areas with greater environmental variability or impacts from anthropogenic factors. This pattern reflects the whale shark's ecological preference for habitats that consistently provide food sources.

3.4 Projection of Future Habitat Suitability (2040–2050, RCP 8.5)

Based on the graphs and projection maps for the 2040–2050 period under the RCP 8.5 scenario, changes in the spatial distribution of whale shark habitat are evident (Figure 4). Some areas show increased habitat suitability, while others experience a decline.

In general, there has been a shift in highly suitable habitat areas toward specific waters predicted to have more stable environmental conditions in the future. The comparison graph shows that while the total area of suitable habitat remains relatively large, its distribution is becoming more fragmented. This indicates that climate change has the potential to alter whale shark aggregation patterns and migration routes in Indonesian waters.

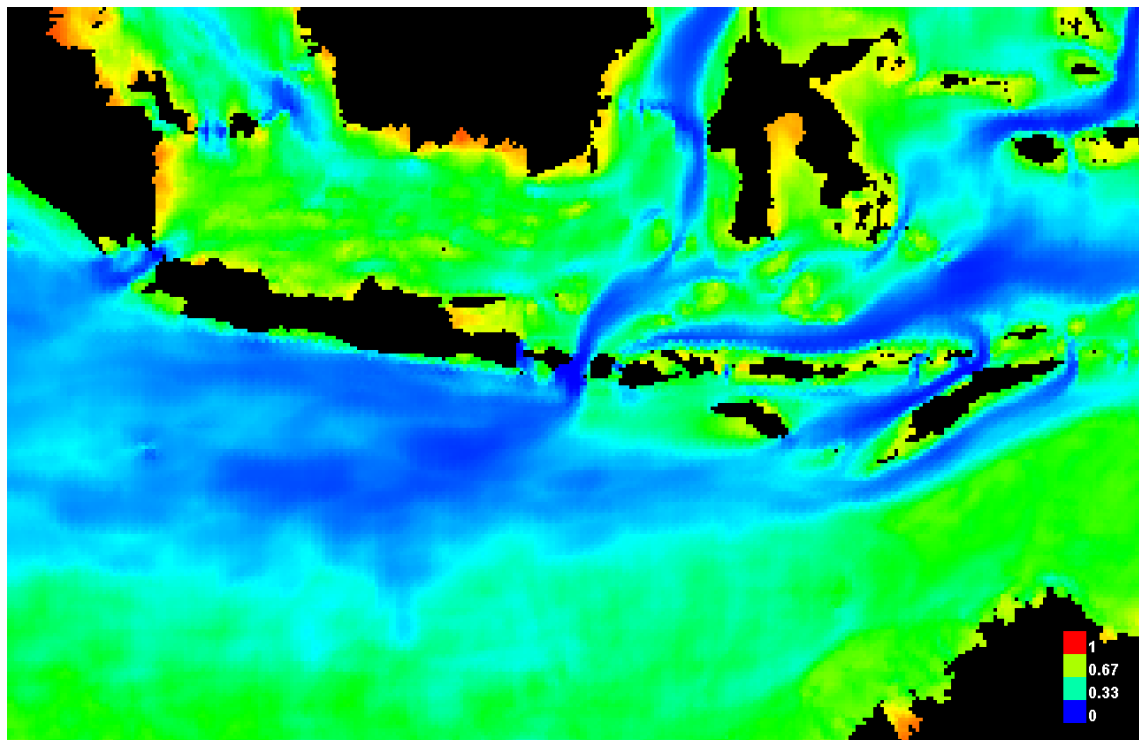


Figure 4. Habitat of *Rhincodon typus* period 2000–2014

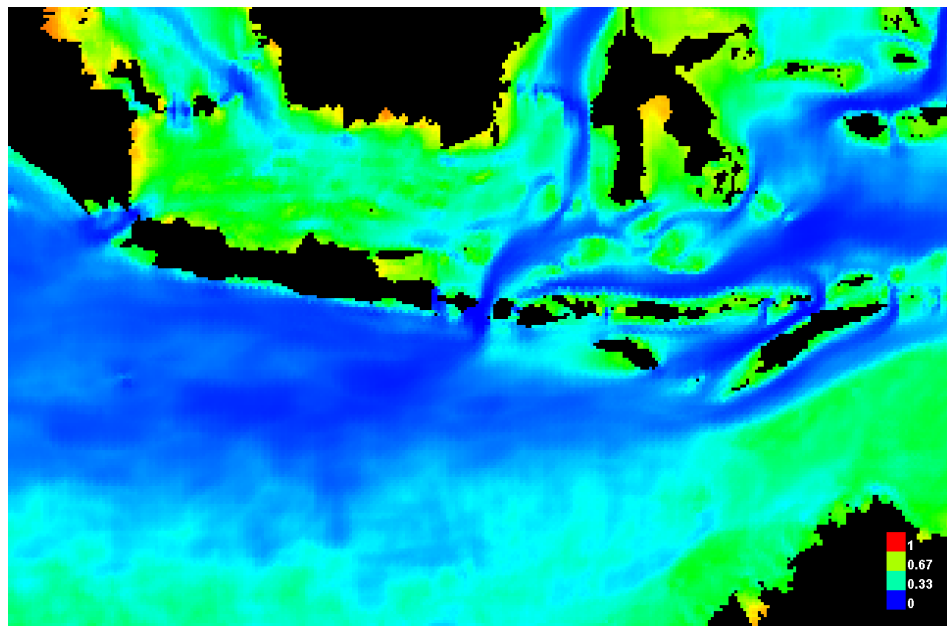


Figure 4. Habitat of *Rhincodon typus* period 2040-2050

The sea surface temperature response curve shows that the probability of whale shark presence increases at relatively warm and stable sea temperatures, then decreases at temperatures that are too low or too high (Figure 5). This pattern reflects whale sharks' preference for thermal conditions that support physiological activity and food availability. The salinity response curve shows that the probability of whale shark presence is highest at moderate to relatively stable salinity levels, while the probability decreases at salinity levels that are too low or too high. This indicates that whale sharks tend to avoid waters with extreme salinity fluctuations, such as areas heavily influenced by freshwater influx or oceanographic processes that cause drastic salinity changes. Stable salinity conditions play a crucial role in maintaining plankton community structure and supporting the sustainability of whale shark food sources. Meanwhile, the ocean current velocity response curve shows that the probability of whale shark presence is highest at moderate current velocity levels. Optimal current velocity supports the formation of oceanographic fronts and plankton accumulation, while currents that are too strong or too weak tend to reduce habitat suitability.

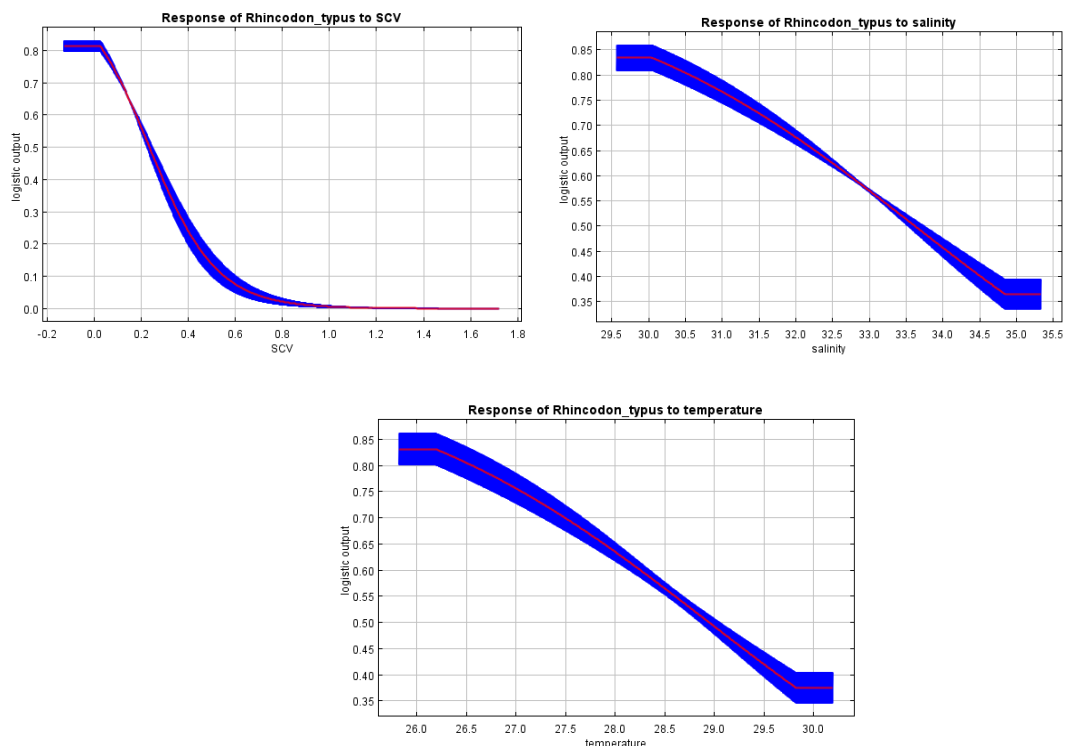


Figure 5. Response curves of probability of presence for *R. typus*

4. Discussion

The results of this study confirm that the distribution of whale sharks in Indonesian waters is significantly influenced by oceanographic factors, particularly sea surface temperature and water productivity. This pattern aligns with the whale shark's ecology as a plankton-feeding species that relies heavily on areas with high food concentrations. The shift in habitat suitability shown in the RCP 8.5 projection graph is consistent with the findings of Liu et al. (2021), who showed that climate change can drive a species' habitat shift to more environmentally suitable areas. In the case of whale sharks, this shift is likely related to changes in ocean temperature patterns and the distribution of primary productivity due to global warming.

Habitat fragmentation identified in the 2040–2050 period has important conservation implications. Fragmented habitat can increase the risk of whale shark interactions with human activities, such as capture fisheries and vessel traffic. Furthermore, changes in the location of core habitats have the potential to reduce the effectiveness of currently designated marine protected areas.

The Sea Current Velocity (SCV) identified in the model indicates that ocean current dynamics are a critical factor in determining whale shark habitat suitability. Optimal ocean current velocity contributes to the formation of oceanographic fronts, upwelling processes, and the accumulation of nutrients and plankton in an area. These conditions create feeding hotspots that whale sharks frequently utilize for feeding activities. Changes in ocean current patterns due to global warming have the potential to shift the location of oceanographic fronts and upwelling zones, thereby affecting whale shark aggregation and migration patterns. Therefore, the SCV variable is an important indicator in predicting future changes in whale shark habitat and needs to be seriously considered in planning marine conservation areas based on dynamic oceanography. Areas that consistently emerge as highly suitable habitats under both current and future conditions should be prioritized as core conservation areas.

Habitat suitability modeling results indicate that the MaxEnt model has an AUC value exceeding 0.9 and demonstrates a very high level of performance (Domene et al. 2015). This indicates that the whale shark occurrence point coordinate data and the oceanographic variables used are capable of describing the whale shark's ecological preferences. This high AUC value strengthens the modeling validity in analyzing marine species distributions, which generally have limited occurrence data, as well as interpreting habitat suitability patterns, both under current conditions and in future temporal projections.

Analysis of environmental variable contributions revealed that sea surface temperature and current velocity are the primary factors influencing whale shark habitat suitability. Furthermore, the significance of ocean current velocity suggests that oceanographic processes play a crucial role in the formation of potential feeding hotspots, contributing to increased plankton concentrations (Sequeira et al. 2012). These results confirm that whale shark distribution is not determined by a single physical parameter in isolation, but rather by complex interactions between oceanographic variables that collectively influence aquatic productivity.

Habitat suitability projections for the 2040–2050 period based on the RCP 8.5 scenario indicate spatial changes and increased fragmentation of suitable habitat areas, which have significant implications for whale shark conservation efforts in Indonesian waters. This habitat fragmentation has the potential to modify whale shark aggregation patterns and migration routes, while increasing the likelihood of interactions with fisheries and shipping activities. Furthermore, future shifts in core habitat locations could create mismatches between projected whale shark distribution and currently established marine protected area boundaries. Therefore, this modeling emphasizes the urgency of implementing adaptive conservation strategies based on climate change projections, utilizing spatial information on habitat suitability as a scientific basis for the evaluation and planning of dynamic marine protected areas.

From an adaptive conservation perspective, these results demonstrate the need for a dynamic, climate-prediction-based management approach. Areas that consistently emerge as highly suitable habitat under both current and future conditions should be prioritized as core conservation areas. Meanwhile, areas predicted to become new habitats in the future should be considered for adaptive management and long-term monitoring.

5. Conclusions

This study demonstrates the effectiveness of the MaxEnt model in predicting whale shark habitat suitability in Indonesian waters. Under the RCP8.5 climate change scenario, whale shark habitat distribution is projected to undergo significant spatial changes. This information is crucial as a scientific basis for planning whale shark conservation that adapts to climate change, particularly in establishing marine protected areas and long-term management strategies.

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Conflicts of Interest: The authors declare no conflicts of interest.

References

- Domene, A.H., Rincon, R.O.M., Galvan-Magana, F., Cardenas, N. (2015). Habitat suitability and environmental factors affecting whale shark (*Rhincodon typus*) aggregations in the Mexican Caribbean. *Environmental Biology of Fishes*. 98(8). DOI:10.1007/s10641-015-0413-5
- GBIF.org (07 January 2026) GBIF Occurrence Download <https://doi.org/10.15468/dl.5zv7x2>
- Liu, L., Guan, L., Zhao, H., et al., 2021. Modeling habitat suitability of *Houttuynia cordata* Thunb (Ceercao) using MaxEnt under climate change in China. *Ecological Informatics*, 63, 101324.
- Herdianti, T.P., Yulius, Y., Agus, S.B., Arifin, T., Putra, A., Prihantono, J., Heriati, A., Hartati, S.T., Akhwady, R., Suryono, D.D., Rahmania, R., Ramdhan, M., Hilmawan, A., Ningsih, A., Sadad, S., Mudjijono, M. and Asyiri, A. (2025) 'Habitat assessment of whale sharks (*Rhincodon typus*) in Saleh Bay, Indonesia: linking chlorophyll-a and sea surface temperature using Aqua MODIS data', *Geographia Technica*, 20(2), pp. 52–64. https://doi.org/10.21163/GT_2025.202.04
- Martin, R. A. (2007). A review of the behavioral ecology of whale sharks (*Rhincodon typus*). *Fisheries Research*, 84(1), 10–16. <https://doi.org/https://doi.org/10.1016/j.fishres.2006.11.010>
- Petátán-Ramírez, D., Whitehead, D.A., Guerrero-Izquierdo, T., Ojeda-Ruiz, M.A., & Becerril-García, E.E. (2020). Habitat suitability of *Rhincodon typus* in three localities of the Gulf of California: Environmental drivers of seasonal aggregations. *Journal of Fish Biology*, 97 (4), 1177–1186. <https://doi.org/10.1111/jfb.14496>
- Pierre, S. J., & Norman, B. (2016). *Rhincodon typus*. IUCN Red List of Threatened Species. <https://doi.org/10.2305/IUCN.UK.2016-1.RLTS.T19488A2365291.en>
- Rahman, R., Suyasa, IN, Syamsuddin, A. and Pahlezi, RS (2025) 'Population structure, site fidelity, and residency patterns of whale sharks (*Rhincodon typus*) in Botubarani waters, Gorontalo Province, Indonesia', *HAYATI Journal of Biosciences*, 32(4), pp. 908–919. <https://doi.org/10.4308/hjb.32.4.908-919>
- Sequeira, A., Mellin, C., Rowat, D., Meekan, M.G., Bradshaw, C.J.A. (2012). Ocean-scale prediction of whale shark distribution. *Diversity and Distributions*. 18, 504–518. DOI:10.1111/j.1472-4642.2011.00853.x