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Projected Distribution Shifts of *Rhincodon typus* Under Climate Change Scenario SSP5-8.5 by 2050

Introduction

The Whale Shark (*Rhincodon typus*) is the largest extant fish species, commonly reaching lengths of 12 meters (m) and occasionally exceeding 17–18 m (Hsu et al., 2014). The largest recorded individual measured approximately 20 m in total length and weighed an estimated 42 metric tons (Chen et al., 1997; Hsu et al., 2014), reported from Taiwan. Despite its massive size, the species is a filter feeder, consuming primarily plankton and small nekton, rendering it harmless to humans.

Described for the first time by Smith in 1828, the Whale Shark remained poorly documented for over a century. By 1985, only 320 confirmed sightings had been recorded (Wolfson, 1986), and our understanding of its biology remains limited due to its elusive and wide-ranging nature.

Whale Sharks exhibit a circumtropical distribution, inhabiting warm temperate and tropical seas globally excluding the Mediterranean Sea (Rowat & Brooks, 2012). The northernmost records include the Bay of Fundy, Canada (44°N)(Turnbull & Randell, 2006), and the Sea of Okhotsk, Japan (Tomita et al., 2014), while the southernmost sightings are from Victoria, Australia (37°S) (Wolfson, 1986). Approximately 75% of the global population is found in the Indo-Pacific region, with the remaining 25% occurring in the Atlantic Ocean. According to the Pierce et al (2016), the global population is estimated to have declined by more than 50% over the last 75 years.

Whale Sharks are found in both coastal and oceanic environments (Rowat & Brooks, 2012). In the Indian and Atlantic Oceans, sightings are strongly associated with sea surface temperatures ranging between 26.5°C and 30°C (Sequeira et al., 2012; 2014). They are highly migratory, traveling an average of 24–28 kilometers per day (Hueter et al., 2013). While they spend most of their time in the epipelagic zone, they are capable of diving to depths exceeding 1,900 meters (Tyminsky et al., 2015), though the reasons for such behavior remain unclear. Whale Shark aggregations often occur at predictable coastal sites during seasonal peaks in productivity, such as zooplankton blooms or fish spawning events (Rowat & Brooks, 2012).

The reproductive ecology of *R. typus* remains poorly understood. Pregnant females have been observed in the Eastern Pacific, particularly near Darwin Island (Galápagos) and the Gulf of California (Eckert & Stewart, 2001; Acuña-Marrero et al., 2014; Ramírez-Macías et al., 2012). To date, only one pregnant female has been physically examined, captured in Taiwan, containing 304 embryos at various stages of development, the largest litter size recorded for any shark species (Joung et al., 1996; Schmidt et al., 2010).

Whale Sharks face numerous threats, including targeted fishing, bycatch in industrial and artisanal fisheries, and collisions with vessels. Although commercial hunting has declined due to legal protections, incidental capture and illegal trade persist, particularly in southern China, where individuals are frequently retained when encountered (Li et al., 2012). Historically, directed fisheries in India, the Philippines, and Taiwan harvested hundreds of individuals annually until national protections were enacted (Rowat & Brooks, 2012). The Maldives also maintained a small-scale fishery until protections were implemented in 1995 (Anderson & Ahmed, 1993). Inappropriate tourism practices (e.g., crowding, provisioning) and large-scale pollution events, such as the Deepwater Horizon oil spill in 2010, pose additional risks to Whale Shark populations (Hoffmayer et al., 2005; McKinney et al., 2012).

Due to these cumulative threats and ongoing environmental changes, the Whale Shark is currently classified as Endangered on the IUCN Red List. The species is listed in Annex I of the United Nations Convention on the Law of the Sea (UNCLOS), Appendix II of the Convention on Migratory Species (CMS, 1999), and Appendix II of the Convention on International Trade in Endangered Species (CITES, 2002). These listings call for international cooperation in the conservation of the species.

Numerous countries, including Australia, Belize, Djibouti, Honduras, India, the Maldives, Mexico, the Philippines, Seychelles, Taiwan, Thailand, and the United States, have adopted national Whale Shark protection measures (Rowat, 2010). However, further research and management efforts are urgently needed to ensure the long-term survival of this iconic marine species, particularly regarding its reproductive biology and habitat use.

Objective of this Study

This analysis aims to model the potential habitat distribution of *Rhincodon typus* for the year 2050 under the SSP5-8.5 climate change scenario. The goal is to assess how projected environmental changes may affect the species' spatial distribution and to identify areas where habitat suitability may increase, decrease, or remain stable over the next 25 years.

Methodology

Study Area and Environmental Variables

The study focused on the global marine distribution range of *Rhincodon typus*, emphasizing tropical and subtropical waters. To model the species' ecological niche, five environmental variables were selected based on ecological relevance and data availability from Bio-ORACLE:

- Sea surface temperature (°C)
- Salinity (psu)
- Chlorophyll-a concentration ($mg \cdot m^{-3}$)
- Dissolved oxygen ($mol \cdot m^{-3}$)

- pH

Current climate layers and projected data for the year 2050 under the SSP5-8.5 scenario were used. All layers were resampled to a common resolution and extent and cropped to a coastal marine mask using a bathymetric filter (depth < 200m) to improve ecological **plausibility.**

Occurrence Data

Presence-only data for *Rhincodon typus* were downloaded from GBIF and cleaned using the scrubr and CoordinateCleaner R packages. Duplicated records and points with missing or invalid coordinates were removed. Final data were converted to spatial objects (sf) and used to extract corresponding environmental values.

Background Points

To improve model accuracy, 10,000 pseudo-absence (background) points were generated along the coastline, constrained to a 200 km buffer from land. This was done to reflect the species' neritic affinity and to reduce commission errors in the open ocean.

Modeling Approach

The distribution model was built using the maxnet algorithm, implemented via the dismo and maxnet R packages. The model was trained with 70% of the occurrence data and evaluated using the remaining 30%. Predictor collinearity was checked and reduced by removing variables with Pearson correlation coefficients > 0.7.

Model performance was assessed using the Area Under the Receiver Operating Characteristic Curve (AUC), and binary thresholds were determined using the "maximum TPR + TNR" criterion.

Future Projections

The model was projected onto future climate layers for 2050 under the SSP5-8.5 scenario. The same variable preprocessing steps were applied. A binary map was generated using the same threshold as in the current model for comparability.

Results

Model Performance

The ecological niche model for *Rhincodon typus*, calibrated with MaxNet, demonstrated excellent predictive performance, achieving an AUC of 0.992, indicating high discrimination capacity between presence and background points. This suggests a strong relationship between the selected environmental variables and the whale shark’s known occurrences.

Current Habitat Suitability

The present-day prediction (see Figure 1) shows high habitat suitability in:

- The Western Indo-Pacific, particularly around the Philippines, Indonesia, and Papua New Guinea
- The Western Indian Ocean, along the coasts of Mozambique, Madagascar, and India
- The Eastern Pacific, especially near Mexico and Central America

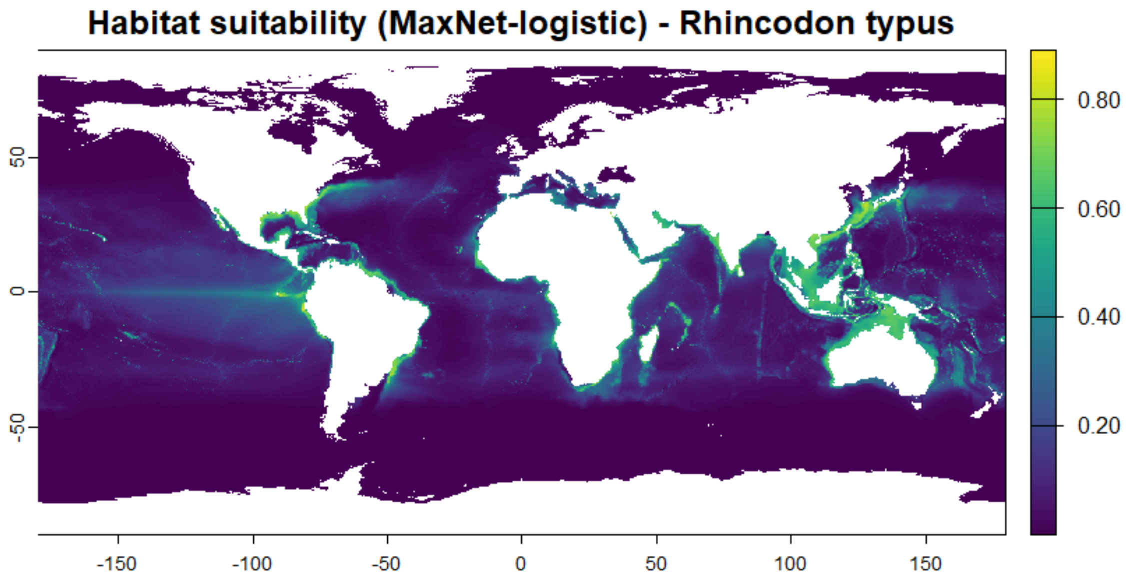

Figure 1 Current habitat suitability for Rhincodon typus using MaxNet.

These areas coincide well with known whale shark aggregation sites, supporting the ecological validity of the model.

Future Projection (2050 – SSP5-8.5 Scenario)

Under the high-emissions scenario SSP5-8.5, the projected suitability for *Rhincodon typus* in 2050 (see Figure 2) remains largely stable across its current distribution. Notable observations include:

- Slight expansion of suitable habitat into higher latitudes (e.g., northern Australia, southern Japan)
- Limited loss in equatorial areas, indicating moderate resilience to climate stressors

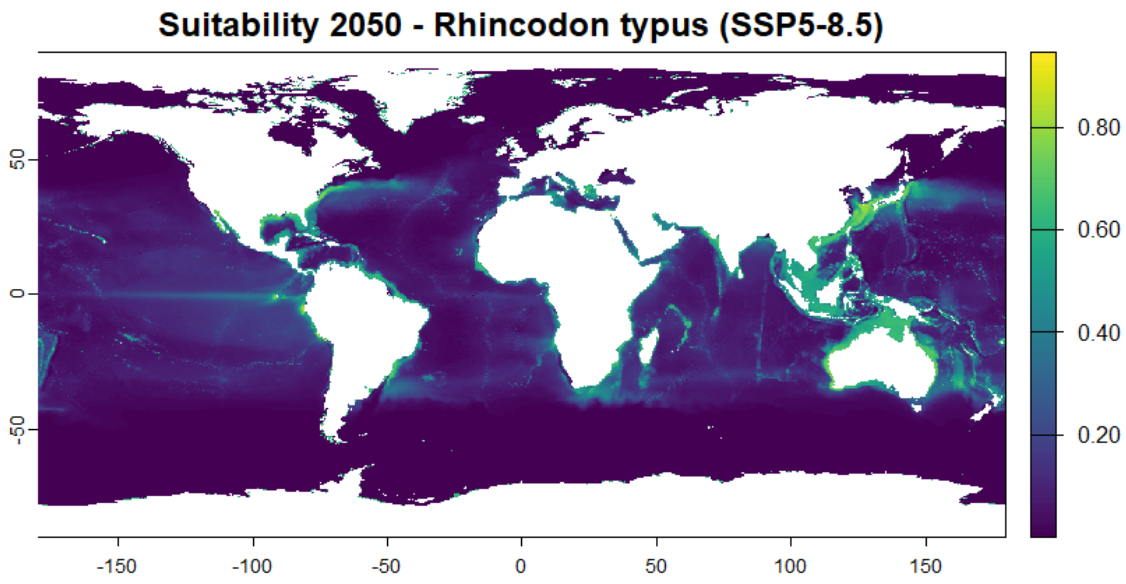

Figure 2 Projected habitat suitability for 2050 under SSP5-8.5.

Change in Suitability (2050 vs Present)

The continuous change map (Figure 3) reveals:

- Small-scale positive shifts in habitat suitability (green areas), mainly along coastal and temperate boundaries
- Very limited negative shifts (brown areas), primarily in some tropical zones

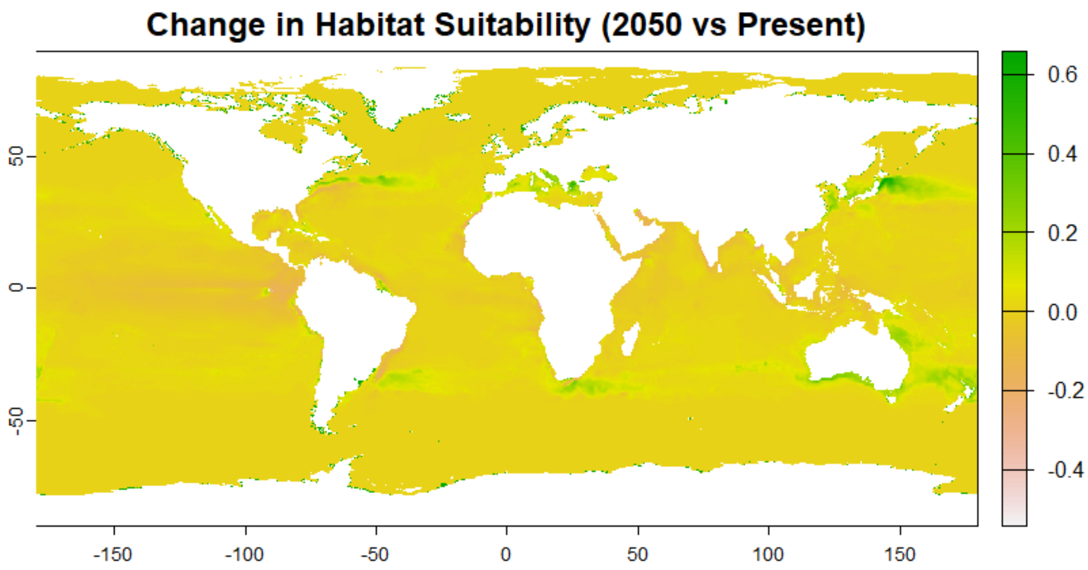

Figure 3 Continuous difference in habitat suitability (2050 – Present).

Binary Distribution Changes

When comparing binary presence/absence maps (thresholded), the distributional change breakdown is as follows (see Figure 4):

- Gained areas: 1.46%
- Lost areas: 0.4%
- Stable areas: 98.14%

This indicates that the vast majority of currently suitable habitats are projected to remain suitable, with only minor distributional shifts.

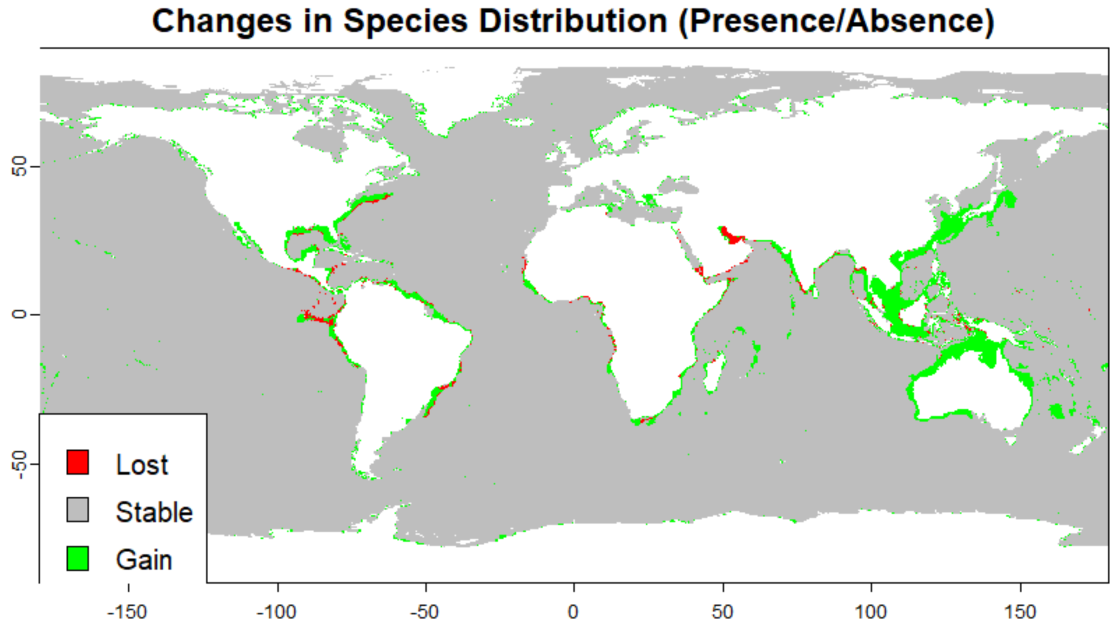

Figure 4 Binary classification of distributional changes (gain, loss, stable).

Discussion

The high-performance MaxNet model developed in this study (AUC = 0.992) indicates a strong correlation between *Rhincodon typus* occurrences and environmental variables such as sea surface temperature, chlorophyll-a concentration, and dissolved oxygen. The results suggest that under the SSP5-8.5 climate scenario, the species' core distribution will remain largely stable, with limited loss (0.4%) and moderate gain (1.46%) in habitat suitability by 2050.

This relatively conservative shift contrasts with broader trends projected for other pelagic megafauna, many of which are expected to undergo substantial range redistributions due to ocean warming and deoxygenation. The Whale Shark's apparent ecological stability may be linked to its broad thermal tolerance, highly mobile behavior, and capacity to exploit a variety of coastal and open-ocean environments.

Nevertheless, the small but measurable poleward expansion observed in this study aligns with empirical reports of increasing Whale Shark sightings near the edges of their traditional range. This includes sightings in continental Europe (Afonso et al., 2014)), the waters off Japan (Tomita et al., 2014), and parts of the Eastern Atlantic (Afonso et al., 2014). Although such individuals may currently be considered seasonal vagrants, they may represent the early stages of a range shift, a phenomenon increasingly observed among marine species in response to climate change.

These observed and predicted poleward movements are further supported by previous ecological niche modeling efforts (Sequeira et al., 2014), suggesting that warming sea surface temperatures will likely expand the seasonal suitability of higher latitude habitats, potentially allowing for new foraging or migratory routes.

Importantly, while the model projects high habitat stability, it does not account for anthropogenic threats, such as overfishing, bycatch, vessel strikes, or pollution, all of which may limit the species' ability to exploit new suitable habitats.

Thus, while climate projections provide a cautiously optimistic outlook for *R. typus*'s habitat stability, active conservation efforts remain crucial to safeguard the species' future. Protective measures must be reinforced in both current and emerging suitable areas, especially in regions where threats from fishing and marine traffic are most pronounced.

Conclusions

This study provides a climate-informed spatial projection of Whale Shark (*Rhincodon typus*) distribution under a high-emissions future (SSP5-8.5) by 2050. Results indicate:

- High habitat stability (98.14% of current range remains suitable)
- Minor losses (0.4%) in tropical areas
- Some expansion (1.46%) toward higher latitudes

These findings suggest that *R. typus* may be more resilient to projected environmental change than other pelagic species, at least in terms of broad-scale habitat suitability. However, the model's ecological optimism must be tempered by the reality of human-induced threats that are not captured in the model, such as overexploitation, habitat degradation, and pollution.

Given the ongoing pressures facing this endangered species, climate-driven range shifts must be anticipated in marine spatial planning. Future conservation strategies should incorporate:

- The protection of future suitable habitats, especially at higher latitudes
- Mitigation of threats in key aggregation and migratory corridors
- Investment in long-term monitoring to validate these predictions and detect early signs of range change

By combining robust modeling with proactive management, we can support the survival of this emblematic species and promote resilience in tropical marine ecosystems as global conditions continue to change.

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