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# MaxEnt Projections of Green Sea Turtle (*Chelonia mydas*) Habitat Suitability in the Indonesian Archipelago under CMIP6 Climate Scenarios

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**Abstract**

The Indonesian Archipelago serves as a critical global stronghold for the green sea turtle (*Chelonia mydas*), yet the stability of its marine habitats is increasingly threatened by rapid climatic shifts. This study utilized Maximum Entropy (MaxEnt) modeling to evaluate current habitat suitability across Indonesian waters and projected potential distribution shifts under CMIP6 climate scenarios (SSP1-1.9, 2-4.5, and 5-8.5) for the 2045s and 2065s. Based on 446 curated occurrence records, primary productivity was identified as the most influential environmental driver, underscoring the species' specialized reliance on nutrient-rich neritic zones for foraging. Current high-suitability habitats are concentrated along the southern coast of Java, eastern Sumatra, and the Arafura Sea. However, future projections indicate a catastrophic habitat contraction across all tested pathways. By the 2065s, the high-emission SSP5-8.5 scenario predicts a net habitat loss of 81.57%, while even the sustainable SSP1-1.9 pathway shows reductions exceeding 73%. These findings reveal a "tropical squeeze" where minimal habitat gains fail to offset massive coastal losses, suggesting that climate inertia may already be pushing environmental variables beyond the species' physiological thresholds. The results emphasize an urgent need to pivot from static conservation to dynamic, climate-adaptive management that prioritizes identified refugia and mitigates local stressors to ensure the long-term persistence of *C. mydas* within Indonesian Archipelago.

**Keywords:** *Chelonia mydas*, Climate change, CMIP6, Habitat suitability, Indonesian Archipelago, MaxEnt modeling, Primary productivity.

## 1.Introduction

Green sea turtles (*Chelonia mydas*) are among the most widely distributed marine reptiles, occupying tropical and subtropical coastal waters worldwide (Seminoff, 2004; Hirth, 1997). As large herbivorous grazers, green sea turtles play a vital ecological role in maintaining the structure, productivity, and resilience of seagrass meadows and coral reef–associated ecosystems (Bjorndal, 1997; Christianen et al., 2014). Healthy seagrass habitats supported by green turtle grazing contribute to carbon sequestration, coastal protection, and biodiversity conservation (Fourqurean et al., 2012). The Indonesian Archipelago, located within the Coral Triangle, represents a critical region for *C. mydas*, providing essential feeding grounds, nesting beaches, and migratory corridors that support regional and global populations (Wallace et al., 2010; WWF-Indonesia, 2018).

Despite their ecological importance, green sea turtles are currently classified as endangered due to long-standing anthropogenic pressures, including habitat loss, coastal development, illegal harvesting of eggs and adults, and incidental capture in fisheries (IUCN, 2023; Hamann et al., 2010). In recent decades, climate change has emerged as an additional and increasingly significant threat to sea turtle populations. Rising sea surface temperatures, sea-level rise, ocean acidification, and changes in ocean circulation patterns can alter nesting beach characteristics, hatchling sex ratios, food availability, and the suitability of foraging habitats (Hawkes et al., 2009; Poloczanska et al., 2009). In archipelagic regions such as

Indonesia, where coastal and marine ecosystems are highly dynamic, these climate-driven changes may substantially affect the spatial distribution and persistence of suitable habitats for green sea turtles (Fuentes et al., 2013).

Understanding the current and future distribution of suitable habitats is essential for effective conservation and management strategies (Guisan & Zimmermann, 2000). Species distribution models (SDMs) provide a powerful framework for linking species occurrence data with environmental variables to estimate habitat suitability across broad spatial scales (Elith & Leathwick, 2009). Among SDMs, the Maximum Entropy (MaxEnt) model has gained widespread acceptance due to its robust predictive performance, capacity to handle complex ecological relationships, and suitability for presence-only datasets (Phillips et al., 2006; Phillips & Dudík, 2008). MaxEnt has been successfully applied to assess habitat suitability and potential distribution shifts for various marine taxa, including sea turtles, sharks, and marine mammals (Kaschner et al., 2011; Becker et al., 2020).

Recent developments in climate modeling, particularly the Coupled Model Intercomparison Project Phase 6 (CMIP6), have enhanced the reliability and resolution of future climate projections (Eyring et al., 2016). CMIP6 incorporates updated climate sensitivities and socioeconomic pathways through Shared Socioeconomic Pathways (SSPs), allowing researchers to evaluate potential ecological responses under different future emission scenarios (O'Neill et al., 2016). Integrating MaxEnt modeling with CMIP6 projections provides an effective approach to assess how climate change may reshape habitat suitability patterns over time and identify areas that may function as climate refugia or become increasingly vulnerable (Araújo et al., 2019).

Therefore, this study aims to model the current habitat suitability of green sea turtles (*Chelonia mydas*) across Indonesian waters using the MaxEnt approach and to project future habitat suitability under selected CMIP6 climate scenarios, in order to support conservation planning, marine spatial management, and climate-adaptive strategies (Elith et al., 2011; Fuentes et al., 2016).

## 2. Materials and Methods

### *2.1. Species Data Collection and Processing*

Occurrence data for the green sea turtle (*Chelonia mydas*) were retrieved from the Global Biodiversity Information Facility (GBIF, https://www.gbif.org/) (GBIF.org, 2025) and the Ocean Biodiversity Information System (OBIS, https://obis.org/) (Diveboard, n.d.; Woehler & OBIS Australia, 2025). Data filtering was performed by applying a geographic filter covering Indonesian waters and adjacent interconnected maritime regions. The selected occurrence data consisted of direct observation reports of *C. mydas* presence, excluding tracking or area mapping data. A total of 2,783 occurrence points were processed through spatial thinning and duplicate elimination. This was achieved by rounding the decimal coordinates to one decimal place and removing records with identical coordinates to reduce spatial autocorrelation. Following this curation process, 446 occurrence points of *C. mydas* were retained for further analysis (Figure 5).

### *2.2. Environmental Variable Processing*

Environmental raster variables for this study were sourced from the Bio-ORACLE database (https://www.bio-oracle.org/) (Assis et al., 2024; Tyberghein et al., 2012). From the nine initial environmental components obtained, a Pearson correlation analysis was conducted using Microsoft Excel to address multicollinearity by eliminating variables with high correlations (Pearson's $|r| \geq 0.8$) (Figure 1) (Wang et al., 2018). Based on the correlation test results, six variables were selected as environmental raster data for modeling and projection: pH acidity, primary productivity, salinity, sea water direction, sea water speed, and sea water potential temperature.

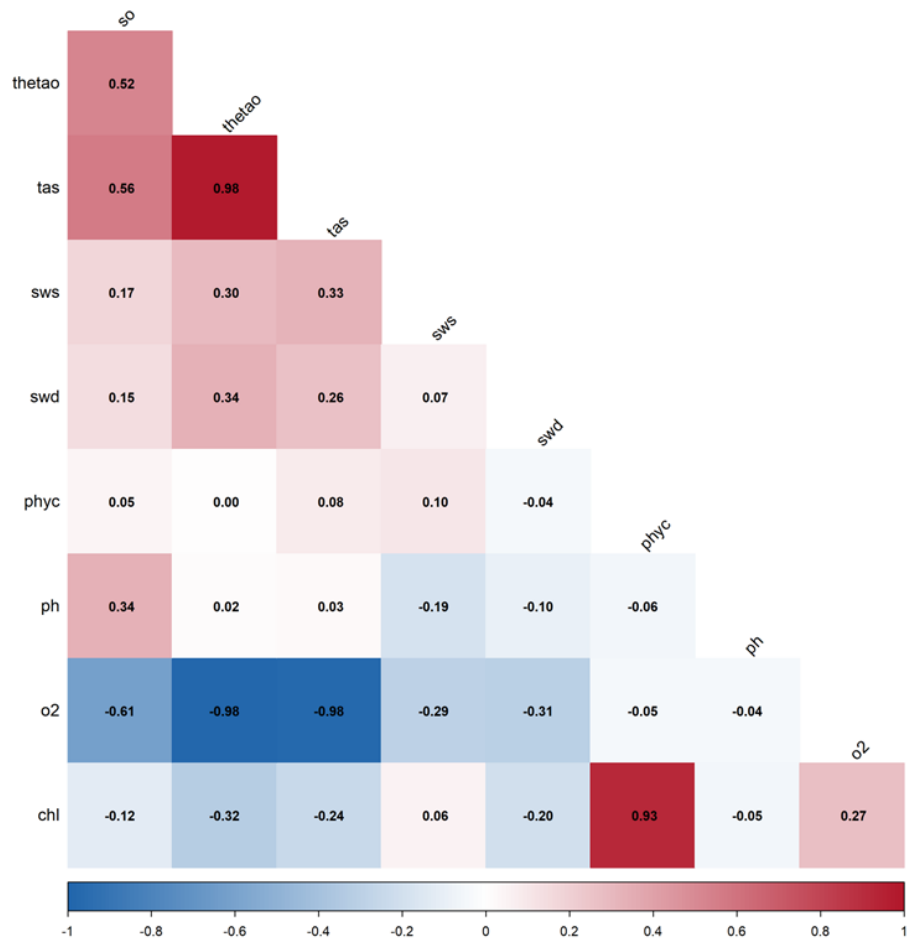


**Figure 1.** Heatmap of Pearson correlation coefficients (*r*) for the initial suite of environmental variables. The color scale indicates the strength of the relationship, ranging from blue (negative correlation) to red (positive correlation). Based on this analysis, variables showing high multicollinearity ($|r| \geq 0.8$) were filtered out, leading to the selection of six independent variables for the final MaxEnt model.

### *2.3. MaxEnt Modeling and Projection*

The modeling was conducted using Bio-ORACLE v3.0 environmental raster variables for current conditions (2010–2020) and future projections based on Shared Socioeconomic Pathway (SSP) scenarios 1-1.9, 2-4.5, and 5-8.5 for the periods 2040–2050 and 2060–2070, respectively. Modeling was performed using 446 occurrence records of *C. mydas* and six environmental variables in MaxEnt software version 3.4.3 (Phillips et al., n.d.). The dataset was partitioned into a training set (75%) and a random testing set (25%) (Liu et al., 2021). Ten replicates were executed to ensure the robustness and stability of the resulting models (Liu et al., 2021). The contribution of each environmental variable to habitat suitability was evaluated using the Jackknife test (Liu et al., 2021). Contribution values are presented in graphs showing the mean values across all modeling replicates. Model performance and accuracy were assessed based on the Area Under the Curve (AUC) and Receiver Operating Characteristic (ROC) analysis (Peterson et al., 2008).

### *2.4. Habitat Suitability Mapping and Area Change Analysis*

Habitat suitability maps were generated based on the MaxEnt model outputs and further processed using Quantum GIS Desktop (QGIS) version 3.44.5 (QGIS Development Team, 2026). Habitat suitability was categorized into four levels: highly suitable ($> 0.6$), moderately suitable (0.4–0.6), poorly suitable (0.2–0.4), and unsuitable ($\leq 0.2$). Maps and tables illustrating habitat area changes were derived from current suitability models projected onto environmental rasters for each SSP scenario and visualized in QGIS. Analysis of stable, decreasing, and increasing habitat areas across each SSP scenario was based on a Suitability Index threshold of $SI \geq 0.2$.

## 3. Results

### *3.1. Model Performance and Environmental Variable Importance*

To ensure the parsimony and predictive robustness of the MaxEnt model, a Pearson correlation analysis was conducted to identify and eliminate redundant environmental variables (Figure 1). High multicollinearity was observed among several parameters, most notably between Sea Water Potential Temperature (thetao) and Air Temperature (tas) with a correlation coefficient of $r = 0.98$, and between Primary Productivity (phyc) and Chlorophyll (chl) with $r = 0.93$. Additionally, Dissolved Oxygen (o2) exhibited a strong negative correlation with temperature-related variables ($r = -0.98$). To prevent over-fitting and ensure that each predictor provides unique information, variables with correlation values exceeding the threshold of $|r| \geq 0.8$ were excluded. Consequently, a final subset of six non-redundant variables—Primary Productivity, pH Acidity, Salinity, Sea Water Potential Temperature, Sea Water Direction, and Sea Water Speed—was retained for the species distribution modeling.

The predictive performance of the Maximum Entropy (MaxEnt) model for *Chelonia mydas* was evaluated using the Receiver Operating Characteristic (ROC) analysis. The model achieved a mean Area Under the Curve (AUC) value of 0.883 (Figure 2). According to established ecological modeling scales, an AUC value between 0.8 and 0.9 is classified as "good" to "very good" predictive accuracy, indicating that the selected environmental variables possess a strong discriminatory power in identifying suitable habitats for the species. The low standard deviation (indicated by the blue shading around the mean red curve) suggests that the model is stable across multiple iterations. The relative contribution of each environmental predictor was assessed using the Jackknife test of regularized training gain (Figure 3). Among all variables, Primary Productivity (phyc) emerged as the most significant predictor. It provided the highest gain when used in isolation, indicating that it contains the most useful information for characterizing the distribution of *C. mydas*.

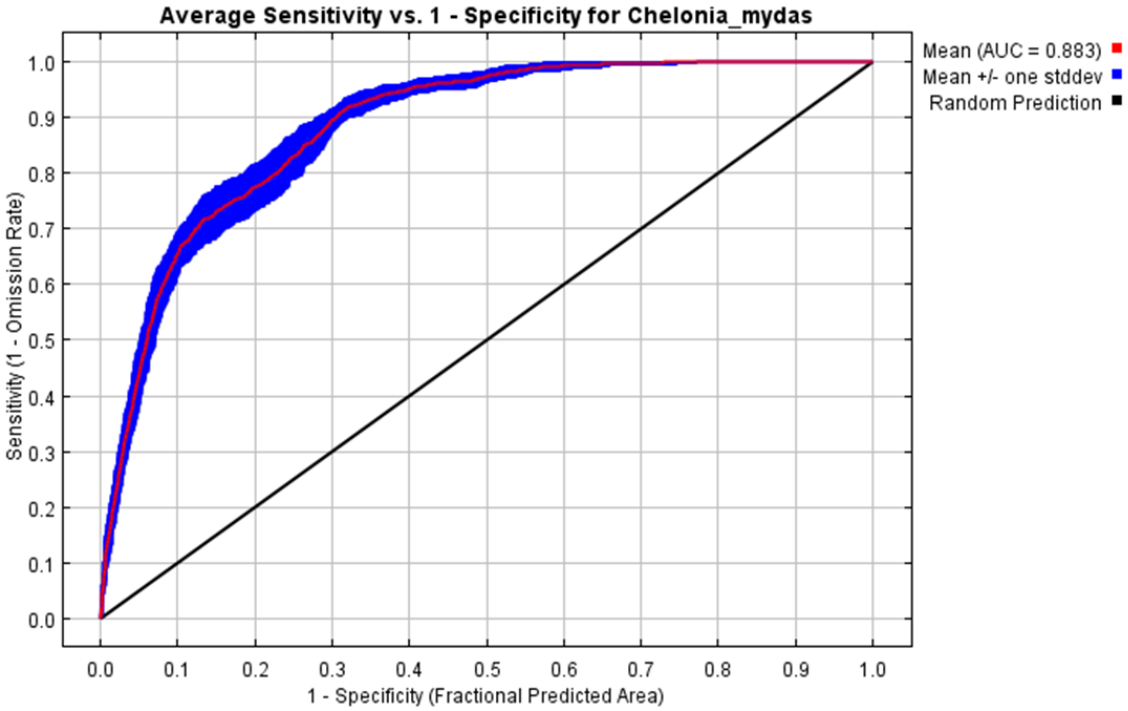


**Figure 2.** Receiver Operating Characteristic (ROC) curve for the *Chelonia mydas* distribution model. The red line represents the mean Area Under the Curve (AUC) value of 0.883 across replicate runs, indicating high predictive performance. The blue shaded area indicates the standard deviation, while the diagonal black line represents a random prediction (AUC = 0.5).

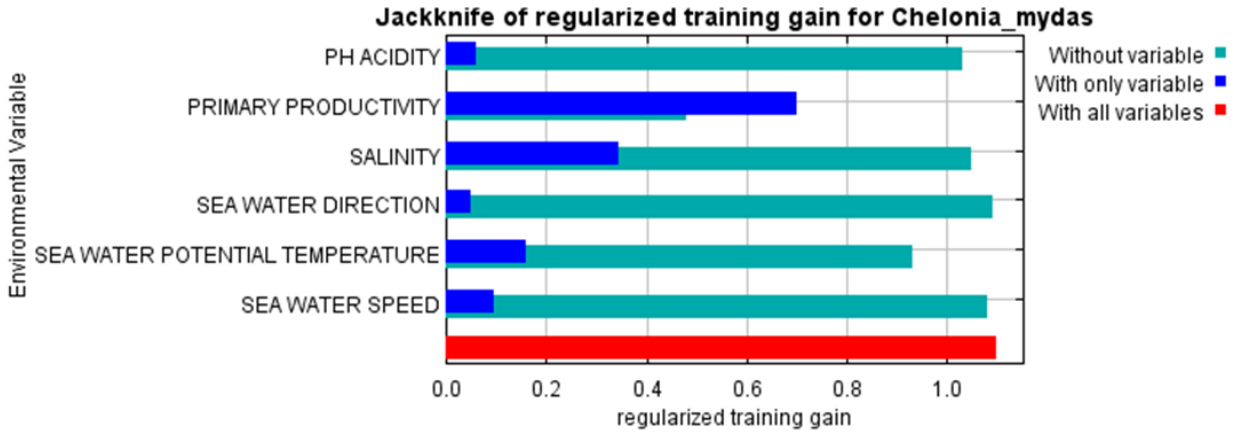


**Figure 3.** Jackknife test results showing the relative contribution of environmental variables to the MaxEnt model for *Chelonia mydas*: (a) regularized training gain and (b) test AUC. The blue bars represent the gain when using only the specific variable, the teal bars indicate the gain when the variable is omitted, and the red bar shows the total gain with all variables included. Primary Productivity emerged as the most significant individual predictor.

Furthermore, Salinity and Sea Water Potential Temperature demonstrated moderate importance. Notably, the omission of Primary Productivity resulted in the most substantial decrease in the model's training gain, confirming its role as a fundamental limiting factor in the species' ecological niche. Conversely, variables such as Sea Water Speed and Sea Water Direction contributed the least to the model's overall gain, suggesting a more secondary influence on the broad-scale distribution of the green sea turtle in the study area.

### *3.2. Analysis of Environmental Response Curves*

The marginal response curves illustrate the quantitative relationship between the predicted probability of *Chelonia mydas* occurrence and the specific gradients of the six primary environmental predictors (Figure 4). These curves reveal critical ecological thresholds and optimal habitat ranges for the species within the study area. Regarding biological productivity, the model indicates a sigmoidal relationship between primary productivity and habitat suitability. Suitability remains negligible at low productivity levels but exhibits a sharp increase once values exceed 1.2 mg/m³ before reaching a plateau, suggesting that a minimum nutrient threshold is fundamental to supporting the foraging grounds of the green sea turtle.

Furthermore, the species demonstrates a highly specialized response to ocean chemistry and salinity. Suitability for *C. mydas* peaks sharply at a pH of approximately 8.05, with a rapid decline observed as the environment becomes more acidic or excessively alkaline. The response to salinity is characterized by a bimodal distribution, where optimal suitability is identified at lower ranges (24–25 PSU) and a secondary peak at approximately 34 PSU. Notably, habitat suitability drops precipitously once salinity exceeds 35 PSU, potentially indicating a physiological or ecological preference for specific brackish-to-marine transitions or estuarine-influenced foraging areas.

The physical and hydrodynamic parameters also exhibit complex influences on species distribution. The thermal response is multi-peaked, with high suitability recorded at 26.8°C, 29.0°C, and 30.3°C, which likely reflects a wide thermal window adapted to different life stages or seasonal movement patterns. Oceanographic current dynamics further refine this distribution; the highest probability of occurrence corresponds to a sea water direction of approximately 300° (Northwest), a factor potentially linked to hatchling dispersal or migratory corridors. Finally, the species shows a preference for two distinct hydraulic conditions: near-stagnant waters (0 m/s) and moderate current speeds peaking at 0.65 m/s. Suitability gradually decreases as current speeds exceed 1.0 m/s, suggesting that high-energy marine environments may be less favorable for residency compared to calmer coastal waters.

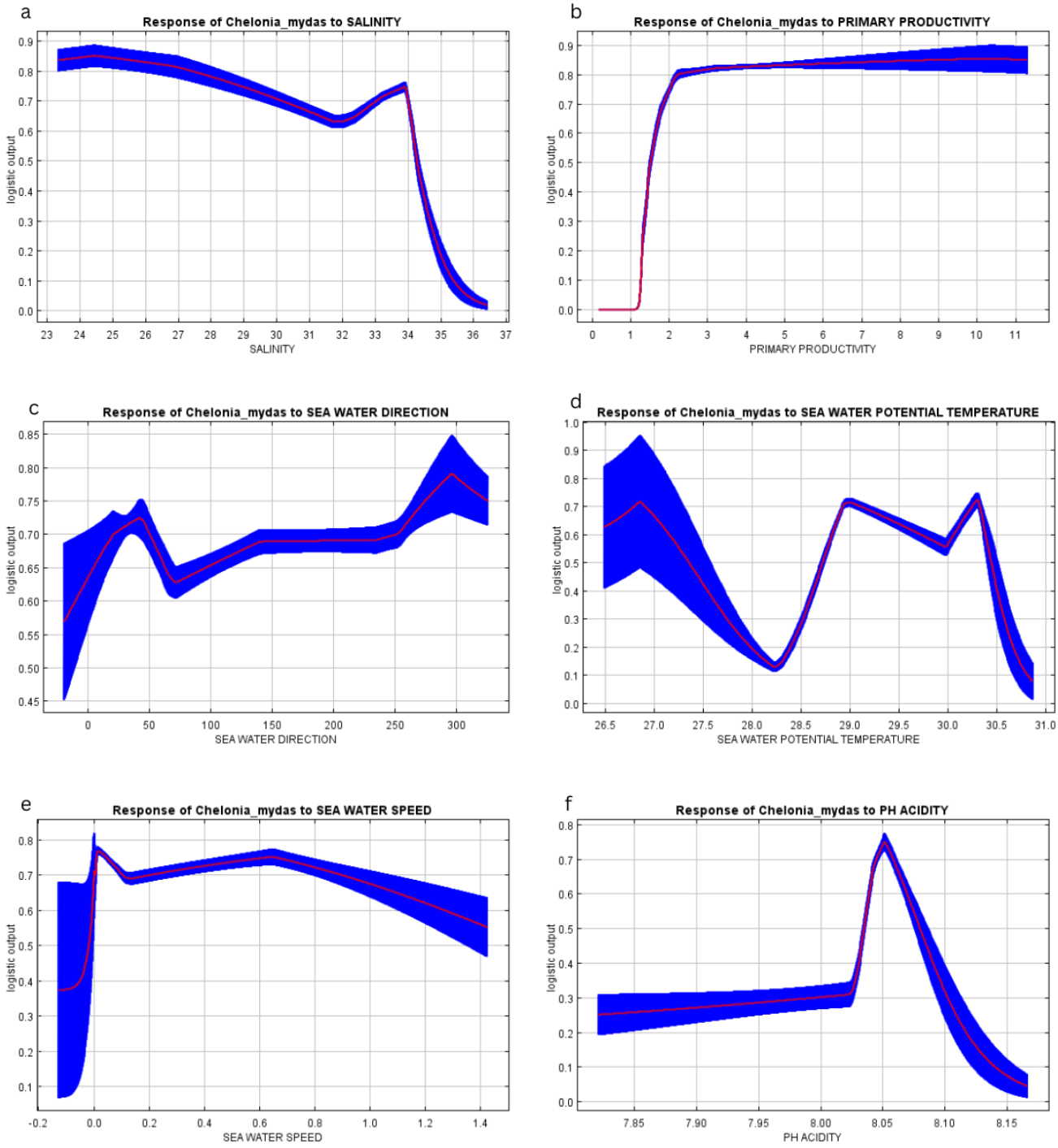


**Figure 4.** Marginal response curves showing the relationships between environmental variables and the predicted probability of occurrence (logistic output): (a) Salinity, (b) Primary Productivity, (c) Sea Water Direction, (d) Sea Water Potential Temperature, (e) Sea Water Speed, and (f) pH Acidity. The red lines represent the mean response of the replicate MaxEnt runs, while the blue shaded areas represent the standard deviation.

### *3.3. Species Occurrence and Current Habitat Suitability*

A total of green sea turtle (*Chelonia mydas*) occurrence records obtained from the Ocean Biodiversity Information System (OBIS) were successfully compiled and spatially filtered for the Indonesian Archipelago. The occurrence points were unevenly distributed across the study area, with higher concentrations observed along coastal regions of Java, Sumatra, Sulawesi, eastern Kalimantan, and parts of eastern Indonesia, particularly the Maluku and Papua regions (Figure 5). Offshore occurrences were comparatively sparse and scattered.

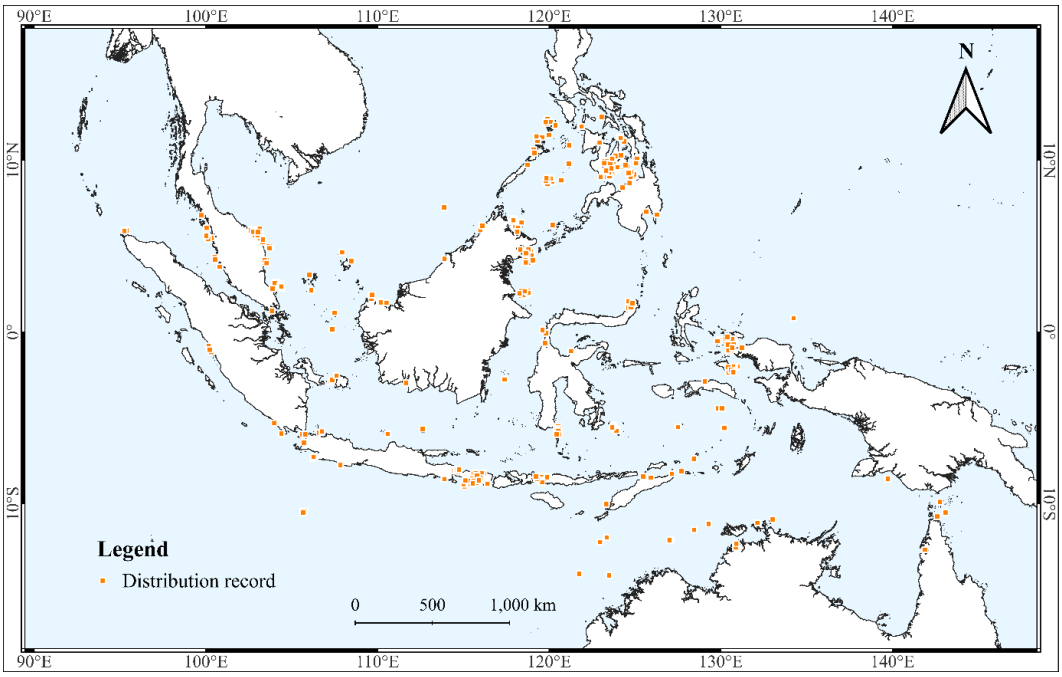


**Figure 5.** Spatial distribution of green sea turtle (*Chelonia mydas*) occurrence records across the Indonesian Archipelago compiled from the Ocean Biodiversity Information System (OBIS). Orange squares represent verified presence records used in the MaxEnt modeling.

The MaxEnt model produced a continuous habitat suitability index ranging from 0 to 1, which was subsequently classified into four suitability categories: unsuitable (≤ 0.2), poorly suitable (0.2–0.4), moderately suitable (0.4–0.6), and highly suitable (> 0.6). Under current environmental conditions, highly suitable habitats were predominantly distributed along shallow coastal waters, continental shelves, and nearshore areas throughout the Indonesian Archipelago (Figure 6). These areas were particularly prominent along the southern coast of Java, the eastern coast of Sumatra, the Makassar Strait, the Sulawesi Sea, and the Arafura Sea.

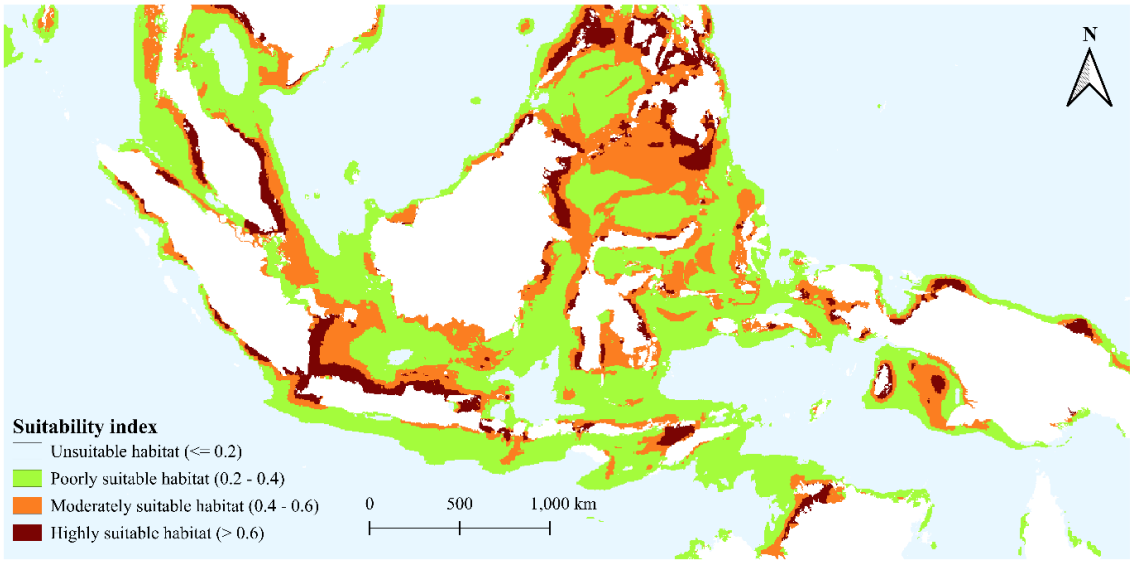


**Figure 6.** Current habitat suitability of green sea turtle (*Chelonia mydas*) in the Indonesian Archipelago predicted using the MaxEnt model. Habitat suitability is expressed as a continuous index and classified into four categories: unsuitable (≤ 0.2), poorly suitable (0.2–0.4), moderately suitable (0.4–0.6), and highly suitable (> 0.6).

Moderately suitable habitats extended beyond coastal zones into adjacent offshore waters, forming transitional areas surrounding highly suitable regions. Poorly suitable habitats were mainly found in deeper offshore waters, while unsuitable habitats dominated the open ocean regions. Overall, the spatial pattern

of habitat suitability showed strong coastal affinity, reflecting the ecological preference of *C. mydas* for neritic environments.

### *3.4. Projected Changes in Habitat Suitability under Future Climate Scenarios*

Projected habitat suitability under future climate conditions revealed substantial spatial changes across all Shared Socioeconomic Pathway (SSP) scenarios and time horizons (Figure 7). Across scenarios, changes were expressed as habitat gain, loss, or stability relative to current conditions.

Under the SSP1-1.9 scenario, which represents a low-emission and sustainable development pathway, projected changes in habitat suitability were relatively moderate. In both 2045 and 2065 projections, large portions of currently suitable habitats remained stable, particularly in eastern Indonesia and parts of the southern Java and Arafura regions. Habitat loss was observed mainly in localized coastal areas, while habitat gains were limited and spatially fragmented.

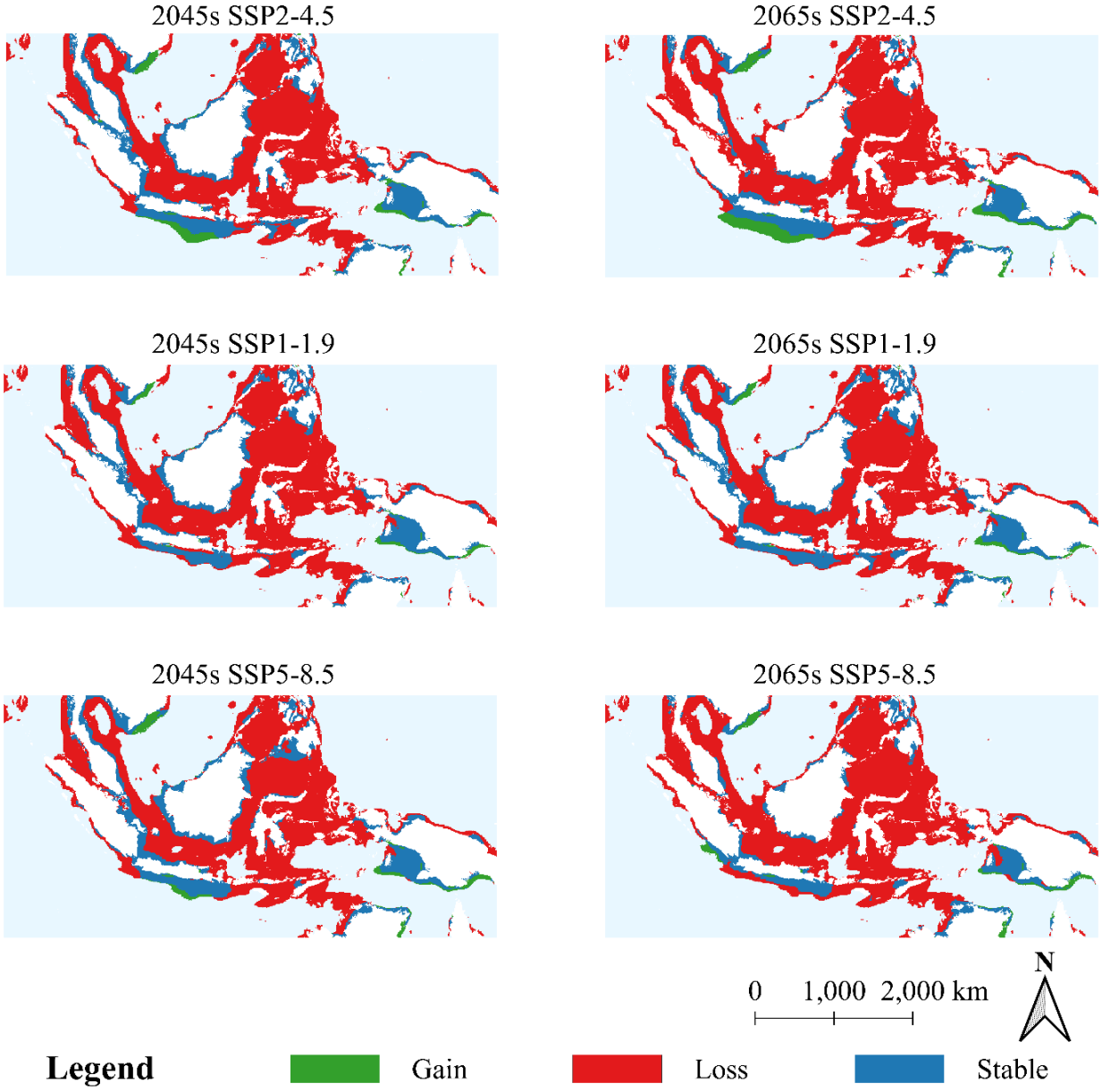


**Figure 7.** Projected changes in habitat suitability of green sea turtle (*Chelonia mydas*) across the Indonesian Archipelago under CMIP6 climate scenarios. Habitat dynamics are shown for two time horizons (2045 and 2065) under SSP1-1.9, SSP2-4.5, and SSP5-8.5, and classified into habitat gain, loss, and stability relative to current conditions

In contrast, the SSP2-4.5 scenario showed a more pronounced redistribution of suitable habitats. By 2045, several coastal regions exhibited notable habitat loss, particularly along densely distributed coastal zones. However, limited habitat gains were observed in selected areas, suggesting partial shifts rather than uniform contraction. By 2065, habitat loss became more extensive, with stability zones shrinking and gains remaining spatially restricted.

The SSP5-8.5 scenario resulted in the most substantial changes in habitat suitability. Under this high-emission scenario, widespread habitat loss was evident across much of the Indonesian Archipelago as early as 2045. Coastal and nearshore areas that were previously classified as highly suitable experienced significant reductions in suitability. By 2065, habitat loss dominated the study area, while stable habitats were confined to narrow coastal strips and isolated regions. Habitat gains under SSP5-8.5 were minimal and highly localized, indicating limited compensatory expansion of suitable environments.

Comparison between mid-century (2045) and later-century (2065) projections across all SSP scenarios indicated a consistent temporal trend of increasing habitat loss and decreasing habitat stability. This trend was most pronounced under SSP5-8.5, followed by SSP2-4.5, while SSP1-1.9 showed the least severe changes. Across scenarios, habitat gains did not proportionally offset habitat losses, suggesting an overall contraction of suitable habitats for *C. mydas* in Indonesian waters under future climate conditions.

### *3.5. Future Projections of Habitat Suitability*

The projected changes in suitable habitat area for *Chelonia mydas* under various Shared Socioeconomic Pathways (SSPs) for the 2045s and 2065s are summarized in Table 1. The model predicts a significant and consistent contraction of suitable habitats across all tested climate scenarios. For the 2045s period, the total proportion of habitat change ranges from -70.50% under SSP2-4.5 to a more severe reduction of -76.01% under the SSP1-1.9 scenario. During this period, although a small fraction of the habitat remains stable (ranging from 22.45% to 25.45%), the area of habitat loss significantly outweighs the minimal gains, which do not exceed 4.05% of the total area.

**Table 1.** Summary of projected habitat changes for *Chelonia mydas* under Shared Socioeconomic Pathways (SSP1-1.9, SSP2-4.5, and SSP5-5.8) for the 2045s and 2065s periods. The table displays the area (x$10^4$ km²) and proportion (%) of stable, gained, and lost habitats, along with the total net change relative to current conditions.

| Period | Area/x$10^4$ km² | | | Total change | Proportion/% | | | Total change |
|---|---|---|---|---|---|---|---|---|
| | Stable | Gain | Loss | | Stable | Gain | Loss | |
| **2045s SSP2-4.5** | 116.87 | 18.61 | 342.42 | -323.81 | 25.45 | 4.05 | 74.55 | -70.50 |
| **2045s SSP1-1.9** | 103.11 | 7.07 | 356.18 | -349.11 | 22.45 | 1.54 | 77.55 | -76.01 |
| **2045s SSP5-5.8** | 115.71 | 15.09 | 343.59 | -328.50 | 25.19 | 3.28 | 74.81 | -71.52 |
| **2065s SSP2-4.5** | 87.92 | 30.39 | 371.37 | -340.99 | 19.14 | 6.62 | 80.86 | -74.24 |
| **2065s SSP1-1.9** | 114.12 | 9.36 | 345.16 | -335.80 | 24.85 | 2.04 | 75.15 | -73.11 |
| **2065s SSP5-5.8** | 72.56 | 12.10 | 386.73 | -374.63 | 15.80 | 2.63 | 84.20 | -81.57 |

By the 2065s, the degradation of suitable habitats is projected to intensify further. The most critical outcome is observed under the high-emission SSP5-5.8 scenario, which results in a total negative change of -81.57%, representing a loss of approximately 386.73 × $10^4$ km². While the SSP2-4.5 scenario in the 2065s shows the highest potential for habitat gain at 6.62%, it is still insufficient to offset the massive predicted loss of 80.86%. Overall, these findings indicate that under all future climate trajectories, *C. mydas* will face a drastic reduction in its ecological niche, with the vast majority of currently suitable areas becoming unfavorable by the mid-to-late 21st century.

## 4. Discussion

The distribution of the green sea turtle (*Chelonia mydas*) within the Indonesian Archipelago is driven by a complex interplay of oceanographic dynamism and biological productivity, a relationship clearly delineated by the high predictive performance of our MaxEnt model (AUC = 0.883). The dominance of Primary Productivity as the most influential environmental predictor fundamentally underscores the nutritional dependency of this species on specific benthic habitats. Unlike other marine turtle species that may exhibit more opportunistic omnivory, *C. mydas* in its post-pelagic stages functions primarily as a mega-herbivore, showing high fidelity to seagrass meadows and algal beds (Bjorndal, 1997; Christianen et al., 2014). The model's identification of a productivity threshold above 1.2 $mg.m^{-3}$ aligns with the ecological requirement for dense foraging grounds, suggesting that the species' distribution in Indonesia is constrained 'bottom-up' by the carrying capacity of these shallow, productive ecosystems. This trophic reliance makes the population exceptionally vulnerable to coastal eutrophication and sedimentation, which can degrade seagrass quality through light attenuation (Orth et al., 2006).

Beyond trophic factors, the model reveals that *C. mydas* occupies a specific physiological niche defined by salinity and ocean chemistry. The bimodal response to Salinity is peaking at brackish levels (24–25 PSU) and typical marine levels (~34 PSU), likely reflects the species's utilization of two distinct critical habitats, riverine plumes for developmental foraging and coral reefs for adult residency. The lower salinity peak corresponds to estuarine interfaces where nutrient runoff fuels high macroalgal growth, habitats known to be favored by juvenile green turtles for rapid somatic growth (Seminoff et al., 2002; Howell et al., 2016). Conversely, the sharp decline in habitat suitability at salinities exceeding 35 PSU and the narrow preference for a specific pH range highlight the species's sensitivity to hyper-saline and chemically unstable environments. This environmental specificity suggests that the projected ocean acidification and alterations in freshwater flux due to changing precipitation patterns in the tropics could mechanically shrink the realized niche of *C. mydas*, independent of temperature rise (Poloczanska et al., 2009).

The influence of hydrodynamic variables, particularly Sea Water Potential Temperature and Sea Water Direction, further refines our understanding of the species's spatial ecology. The multi-peaked thermal preference (26.8 $^{o}$C to 30.3 $^{o}$C) indicates a thermal window that balances metabolic efficiency with avoidance of thermal stress. However, the upper limit of this suitability is precariously close to the projected sea surface temperatures (SST) for the region. The specific preference for northwestward currents (300$^{o}$) likely correlates with the prevailing Indonesian Throughflow (ITF) and seasonal monsoonal gyres that facilitate hatchling dispersal and adult migration corridors between nesting beaches in places like Berau and foraging grounds in the Sulu-Sulawesi Large Marine Ecosystem (Dethmers et al., 2006). Disruption to these currents, coupled with rising SSTs, threatens to decouple nesting phenology from optimal foraging conditions.

Most alarmingly, the future projections under CMIP6 scenarios present a dire prognosis for the persistence of *C. mydas* habitats in the Indonesian Archipelago. The model predicts a catastrophic contraction of suitable habitat ranging from 70% to over 81% by the mid-to-late 21st century, regardless of the emission pathway. The extensive loss observed even under the sustainability-focused SSP1-1.9 scenario suggests that the inertia of the climate system may have already locked in environmental changes that exceed the species' ecological thresholds in the tropics. This phenomenon is likely driven by the synergistic effects of thermal exclusion where waters become too hot for physiological homeostasis and the degradation of biogenic habitats like seagrass and coral reefs, which are sensitive to the combined stressors of warming and acidification (Fuentes et al., 2013; Kwiatkowski et al., 2020). The limited "Gains" in habitat area (maximum 6.62%) are insufficient to offset these losses, indicating a lack of poleward refugia within the archipelago's geographical boundaries.

## 5. Conclusions

This study provides a critical assessment of the spatial vulnerability of the green sea turtle (*Chelonia mydas*) in the Indonesian Archipelago, identifying primary productivity as the preeminent driver of its current distribution. The findings confirm that the species relies on a specific, narrow environmental envelope characterized by mesotrophic productivity, estuarine-marine salinity gradients, and stable pH levels, rendering

it highly sensitive to environmental perturbation. The future outlook for *C. mydas* in this region is precarious; under all modeled CMIP6 climate scenarios, the species faces an existential threat from a massive contraction of suitable habitat that could exceed 80% by the 2060s. This projected loss is not merely a shift in distribution but a substantial reduction in the carrying capacity of the marine environment in the Coral Triangle. Consequently, conservation strategies must urgently pivot from static, area-based protection to dynamic management approaches that prioritize the preservation of identified climate refugia and the mitigation of local non-climate stressors to enhance the resilience of remaining populations against the inevitable pressures of a warming ocean.

**Supplementary Materials:** This journal does not provide hosting for supplementary materials on its website.

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

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