Projected Climate Change Impacts on Philippine Marine Fish Distributions

Rollan C. Geronimo

With contributions from DA-BFAR, NFRDI, and U.S. NOAA PIFSC

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Front cover images:
(left) Map of mean sea surface temperatures from MODIS (2003 to 2016)
(right) Photos of fish species from M.D. Santos, N.C. Barut and AD Bayate (editors). 2017.
National Stock Assessment Program: The Philippine Capture Fisheries Atlas. Bureau of Fisheries and Aquatic Resources - National Fisheries Research and Development Institute. Quezon City, Philippines. 220 pages.

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Republic of the Philippines
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MESSAGE

Congratulations to all those who took part in the completion of this publication titled “Projected Climate Change Impacts on Philippine Marine Fish Distributions.”

A mandate of the Department of Agriculture, under the leadership of Secretary Emmanuel ‘Manny’ Piñol, is to ensure available and affordable food for the whole Filipino nation. Recognizing the threatening impacts of climate change to the fisheries and overall fish food production in the country, the Bureau of Fisheries and Aquatic Resources ensures the integration in its various policies and programs science-based disaster risk reduction management strategies as part of its climate change adaptation efforts.

This study is another valuable basis for policy development and reform as it provides clear data on climate change and its impacts to the habitat suitability of the country’s top fish commodities. Moreover, this presents us opportunity to counter the deep, continuing decline of these fisheries resources by serving as our powerful tool for generating climate change-responsive fisheries management strategies for the succeeding years.

We offer our sincere thanks to the United States Agency for International Development and the National Oceanic and Atmospheric Administration for their determined partnership with the DA-BFAR. We in the DA-BFAR really hope for our continued collaboration in attaining sustainable development and food security amidst natural adversities.

Thank you very much and mabuhay po kayo!

Commodore EDUARDO B GONGONA PCG (Ret)
Undersecretary for Fisheries and concurrent BFAR National Director

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The BFAR-National Fisheries Research and Development Institute's National Stock Assessment Program is indispensable to this study. Without the earlier contribution of each of the men and women behind the NSAP Program from the NFRDI down to the BFAR Regional NSAP Teams throughout the country, this work would not have been possible. Other regions also shared more than the regular NSAP monitoring data, particularly Dir. Remia Aparri and Sheryl Mesa from BFAR Region 6 and Dir. Fatma Idris and Jose Villanueva of BFAR Region 12. Undoubtedly, despite some shortcomings, the NSAP is one of the country's finest examples of long-term monitoring.

I deeply thank the leadership of BFAR, through both its former and concurrent National Director and UnderSecretary for Fisheries, Atty. Asis G. Perez and Commodore Eduardo B. Gongona, PCG (ret), and Assistant Director for Technical Services Drusila Esther Bayate, and their unwavering support to this undertaking to understand the impacts of climate change to our country's fisheries. I also thank all the BFAR Regional Directors who provided their inputs to the study. I am also indebted to the valuable assistance extended to me throughout the years by Rafael Ramiscal, Lainie Baraocor, Atty. Glady Mae Talan, Efren Hilario, Kima Karla Cedo, and other staff of BFAR and by Noel Barut, Dr. Mudjekeewis Santos, Francisco Torres, Jr., Val Manlulu, Ronnie Romero and other staff of the BFAR-NFRDI. May you find this work relevant as you continue to lead and provide technical assistance for the management of our Philippine fisheries.

This study also benefited from the work of the researchers of Aquamaps and FishBase, whose work was made accessible to me by Kathy Kesner-Reyes and Dr. Christine Casal of FIN, Inc. Likewise, I thank the developers of CT-ROMS for sharing their model results, particularly Dr. Joanie Kleypas, Dr. Enrique Curchister, and Dr. Frederic Castruccio.

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My work was also enriched by the consistent and encouraging guidance of my adviser from the University of Hawaii, Dr. Camilo Mora. Similarly, I am grateful to USAID/Philippines for the opportunity to do this work for our Philippine fisheries. I appreciate the crucial support and vision provided by Rebecca Guieb of the USAID Environment Office.

I could not have done this work without the love and understanding of my family, my parents and siblings. To Rhia, Luke, Amihan and Daniel, I dedicate this work for you.

EXECUTIVE SUMMARY

Global models project a decline of 9% to 24% in potential marine fisheries yield within the Philippines' exclusive economic zone (EEZ) by 2050 due to climate change, the range of estimates varying depending on the rate at which future global greenhouse gas emissions are reduced. These global models also project local species extirpations in tropical waters as environmental conditions such a sea surface temperature cross species-specific sensitivities and historical exposures, creating "novel environments" for marine life to cope with.

This study compared the potential changes in the distribution of 59 top commercial marine species by 2050s under two climate change scenarios. All 59 species will experience reductions in suitability of existing habitats and extent of suitable areas for growth and survival while eight of these species will encounter conditions beyond their current known occurrence range.

Being a tropical country, the Philippine seas are among the warmest in the world. Compared to 35 years ago, waters around the country are now warmer by ~0.7°C on average. As climate change is expected to accelerate the rates of these trends, Philippine seas in the next 35 years is projected to warm even more than 0.7°C, bringing marine life into contact with sea temperatures they have never previously been exposed to for prolonged periods.

This study evaluated how habitat suitability for 59 of the top commercially-exploited marine fish species in the Philippines could be affected by on-going and intensifying climate change, focusing on changes in the suitability of their environment for population growth. An ecological niche model was applied which (1) estimates environmental "preference" of species based on global occurrence data combined with local data from the Bureau of Fisheries and Aquatic Resources National Stock Assessment Program and (2) applies these preference thresholds or "environmental envelopes" to present and future climate change scenarios using high-resolution data from observations and models.

The key findings from this study are:

Historical Changes in Philippine Seas

- Seawater is warming since 1982 at an average rate of 0.20°C per decade or an average absolute increase of 0.65°C from 1982 to 2017.
- Coastal areas in western Luzon, the provinces of Aurora and Quezon, around Palawan, the Sulu Archipelago, Moro Gulf, and northwestern Mindanao are warming slower than the average rate.
- Offshore areas are warming faster than average.
- Chlorophyll-a and Primary Production changes from satellite observations from 2003 to 2016 vary across the country and most of the trends found were statistically non-significant.

Future Changes in Philippine Seas

- If global mitigation of greenhouse gases is implemented intensively by 2050s, the seas in the Philippines' exclusive economic zone will be warmer (by 0.77°C to 1.10°C), lower salinity (by

0.10 to 0.45 psu or 0.3% to 1.3% of present value), and have lower primary production (by 4 to 36 $mgC/m^2/day$ or 0.5% to 11.8% of present value).

- The worst case, and the likely scenario given the current rate of greenhouse gas emissions and assuming minimal mitigation, will lead to much warmer (by 0.2°C to 3.1°C) and lower salinity (0.3 to 2.1 psu or 1.0% to 6.7%) seas in the Philippines.

Effects on Distribution of Top Commercial Marine Species

- All 59 marine species will experience reductions in habitat suitability within the Philippines' EEZ with continued climate change but the magnitude of change varies across species.
- With the mild climate change future scenario (i.e., CMIP5; RCP4.5), most species will experience a 15% to 30% reduction in habitat suitability driven mainly by the projected increase in sea surface temperatures.
- Mackerel (*"alumahan"*) and large pelagic species will experience future ocean conditions beyond their current known environment, substantially reducing the areas in the Philippines where conditions are within their tolerance ranges.
- Climate change will substantially reduce the total area within the Philippines' EEZ that is suitable for growth for the following species (values in brackets represent percentage remaining suitable area by 2050s compared with the present; two future scenarios presented representing moderate and severe ocean changes in the future):

  - *Enhcrasicolina heteroloba* ("bolinaw") [13%; 0%]

  - *Scomber japonicus* ("tangigue") [17%, 0%]

  - *Trichiurus lepturus* ("espada") [18%, 0%]

  - *Rastrelliger kanagurta* ("alumahan") [19%, 0%]

  - *Elegatis bipinnulata* ("salmon") [27%, 2%]

  - *Gazza minuta* ("sapsap") [27%, 2%]

  - *Coryphaena hippurus* ("durado") [65%, 7%]

  - *Istiophorus platypterus* ("malasugi) [65%, 7%]
  - For these eight species, conditions in the Philippine seas by 2050s are predicted to exceed their current known environmental thresholds, possibly leading to local extinctions or massive reductions in abundance.
- The other species are projected to have only small reductions in the total area of suitable habitats but the suitability of existing areas could decline by as much as 70%, on average.

- Of the 59 species, *Katsuwonus pelamis* ("gulyasan")  and *Mene maculata*  ("hiwas") are projected to experience the smallest change in mean habitat suitability under both future scenarios for 2050s.

Gaps and Recommendations:

- Unfortunately, there is insufficient data to evaluate how these habitat suitability changes could translate to fish biomass changes and/or potential fisheries yields beyond what has already been done with global models. However, experiments and observations have shown that when fish is exposed to environmental conditions beyond their normal range, their fitness suffer.
- **Continued Vigilance and Updating of Plans & Actions.** Climate change is a continuing threat. Long-term climate projections of change are useful for long-term planning but these should be updated as new data become available.
- **Monitor Climate-Sensitive Species.** Being near the equator and having already some of the warmest waters in the world, further warming in Philippine seas bring with it great uncertainty on the possible responses of marine organisms to continued climate change in this region. The eight identified species vulnerable to local extirpation or extinction could be used as climate indicators given that these species could already be living near their thermal thresholds.
- **Collaborative Monitoring.** Expanding monitoring to include environmental variables and analyzing fish production versus climate variability will allow researchers to develop forecast models and anticipate climate shocks to fish production. This can be done collaboratively with other stakeholders and need not be the sole responsibility of BFAR or the government.
- **Improve Models and Incorporate Food Web Dynamics.** As an archipelagic country, the Philippines' oceanography is very complex. While global and regional models capture large-scale patterns, most of the Philippines' fisheries are confined to coastal waters and these are often not properly modelled. Moving from long-term projections to more operational short-term forecasting of fish productivity requires investing in oceanographic models that are parameterized with local data to capture the complex island topography, seascape bathymetry, monsoons, and currents in Philippine internal seas.
- **Complete the National NSAP Database.** The choice of using a simple method was driven by the limited available long-term trend data to run robust statistical analyses. Completing the collation of regional NSAP data into the national database and opening the data for scientific use would allow researchers to analyze these trends and provide better guidance for management.

Introduction

Wild caught marine fishes remain as one of the top affordable protein sources for the Philippines. It contributes half of the country's annual fish production. More than 1.7 million Filipinos also depend on marine fisheries for their livelihood and even more for daily subsistence and other fishing-related upstream and downstream industries. Canned tuna and sardines serve as important food relief in times of calamity.

The Philippines ranks among the most vulnerable countries in the world. A recently published scoring of climate risks for 67 countries identified the Philippines as the 3rd most vulnerable country to climate change, mainly driven by its high sensitivity to extreme events (Paun *et al.* 2018). Knowledge of the effects of climate variability and projected impacts of long-term climate change is more advance in agriculture than in fisheries. The Philippine government accounts climate variability (e.g., onset of El Niño or La Niña) into its crop production forecasts and design, also distributing climate-resilient crops. In the marine fisheries sector, researchers are only starting to uncover the mechanism behind climate variability and fish production/fisheries yield (Villanoy *et al.* 2011; Ferrera *et al.* 2017). Identifying appropriate adaptation measures require a good understanding of how local conditions would change along with global climate change.

Global studies have been done to project potential climate change effects on marine biodiversity (Cheung *et al.* 2009), fish distributions (Cheung *et al.* 2008), potential fisheries yield (Cheung *et al.* 2010; Stock *et al.* 2017) and economics (Sumaila *et al.* 2011). These studies, however, are often done at coarse spatial resolutions (e.g., usually 1° grids or ~111km x 111km grids along the equator) that and are not able to resolve coastal processes and also masks small islands. As an archipelagic country, the internal seas of the Philippines are often not simulated accurately in these global models. Also, these studies use mostly global database and, in the case of fisheries, rely on reports and data with the Food and Agriculture Organization which could miss the sub-national information available in-country.

Purpose of the Document

Combining information from a newly available high-resolution regional climate model for the Coral Triangle, global data on species occurrences, and local occurrence data gleaned from the Bureau of Fisheries and Aquatic Resources' National Fisheries Research and Development Institute's National Stock Assessment Program, this study evaluated the potential impacts of climate change on the distribution of suitable habitat for 59 of the top commercial marine fish species of the Philippines.

Limitations of the Study

Given the limitations of the available datasets, this study looked only at how the projected changes in the ocean environment compare with the present range of environmental conditions where the species are found globally and locally. Ideally, long-term fishery dependent and independent data are used to establish relationships between climate variability and fish production which is then extrapolated to future projected changes in ocean environments. As new data become available, these analyses should be revisited.

Other caveats of this study are:

- Treatment of primary production changes is limited by the lack of high-resolution models that include this variable for the Philippines.
- The habitat suitability maps represent only the potential of an area to maintain viable populations of a species.
- The suitability index (0 to 1) spatial patterns will not perfectly match with abundance distributions because a lot of other factors could affect abundance (e.g., fishing; larval dispersal).
- The method used does not account for potential adaptation of species. The method assumes that conditions that are beyond where species are currently found globally and locally are not viable for the species' survival.
- Larval environmental envelopes are often narrower than for adults. Accounting for these factors would most likely lead to more drastic changes in future distribution of species and continued viability of present spawning grounds.

Climate Change and Philippine Seas

Insights from Global Studies

There are already global studies of climate change impacts on fisheries at a country level or by large ecosystems. Here is a summary of findings extracted for the Philippines' Exclusive Economic Zone (EEZ):

- **Projected change in catch potential** (%) by 2050 relative to 2000 for the Philippines' EEZ is at -8% (under a strong mitigation scenario) to -24% (under a minimal or business-as-usual scenario) (Cheung *et al.* 2018). Below is an example of the projected catch potential change in the Philippines from the One Shared Ocean website (onesharedocean.org; **Figure 1**).

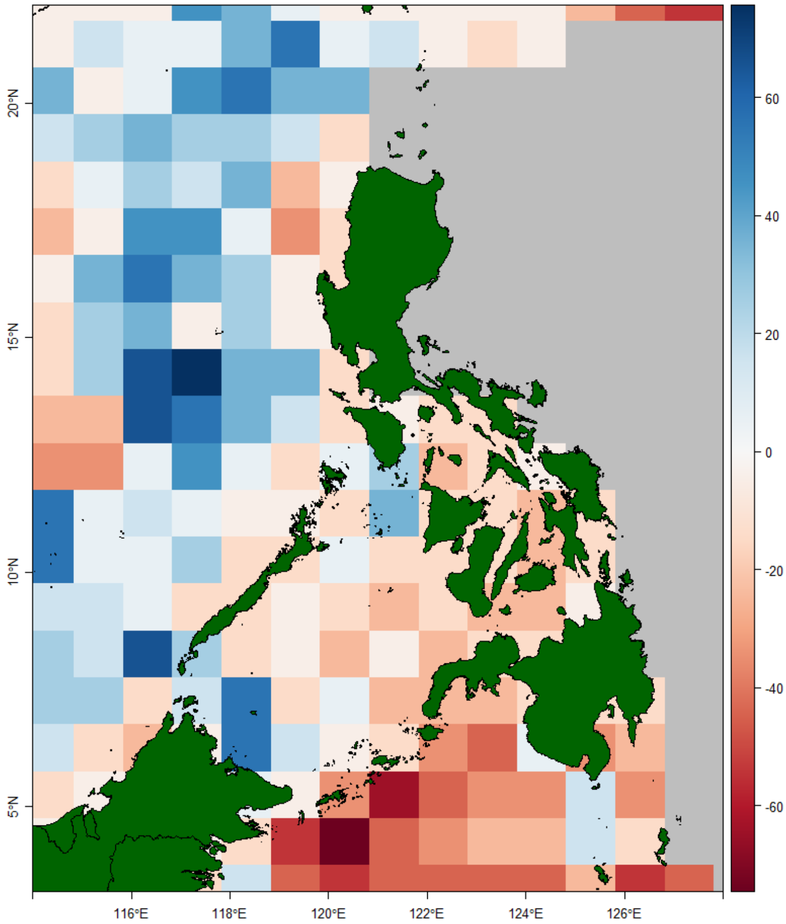


Figure 1. *Proportion of catch potential change in 2050 vs. 2000 (raw data source: http://onesharedocean.org; based also on Cheung et al. 2010). Grey colored area do not have data.*

- **Biodiversity.** Global models predict low species invasion risk with climate change in the seas surrounding the Philippines but relatively high extinction risks (Cheung *et al.* 2009; **Figure 2**).

- **Revenue.** Under a business-as-usual scenario (i.e., minimal global greenhouse gas mitigations), one model predicts the Philippines' maximum potential revenue from fisheries to decrease by as much as 50% by 2050 (Lam *et al.* 2016).

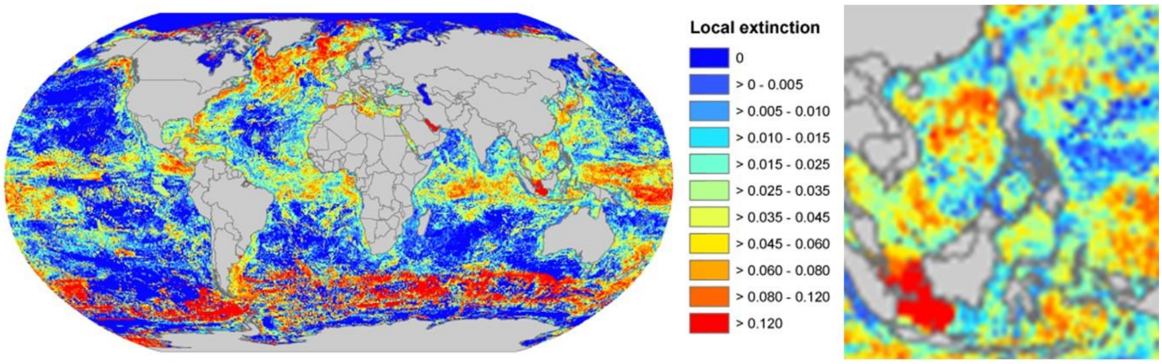


Figure 2. *Predicted distribution of biodiversity impact due to warming-induced range shifts for 1,066 species of fish and invertebrates by 2050. Values expressed as proportional to the initial (2001-2005) species richness.*

Changes in Philippine Seas Through Time

How have the marine waters in and around the Philippines changed over time, in the past from observations, and scenarios in the future from models?

Sea surface temperatures

Among different oceanographic parameters, sea surface temperature is probably the most commonly analyzed in relation to climate change. It is one of the easiest parameters to measure and have also been collected for a long time. It also has a big effect on physiological processes of marine organisms.

Previous studies have looked at trends in sea surface temperatures in and around the Philippines (Peñaflor *et al.* 2009; Khalil *et al.* 2016). From 1982 to 2017, based on NOAA's 1/4° annual-averaged Optimum Interpolation Sea Surface Temperature (OISST) data, seawater in the entire Philippine EEZ has been warming since 1982 at an average rate of 0.20°C per decade or an average absolute increase of 0.65°C up to 2017 (**Figure 3**). The warming rate varies across space with coastal areas in western Luzon, the provinces of Aurora and Quezon, around Palawan, the Sulu Archipelago, Moro Gulf, and northwestern Mindanao warming slower than the average rate. Offshore areas are warming faster than average, particularly in the Pacific Ocean, and also the waters off Antique and Ticao Pass to Samar Sea.

Using a longer (but coarser spatial resolution) time-series shows that this warming trend started only in the past half century (**Figure 4**; HadISST line). Earth System Models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) group show different trajectories of sea surface temperature trends within the Philippines' EEZ up to 2100 depending on how strongly global greenhouse gas emissions are mitigated ranging from 0.7°C to 3.1°C increase in mean sea surface temperature.

The Earth System Models from CMIP5 have very coarse resolutions at ~111km grids near the equator. More than 40 of CMIP5 models are available representing different ways that research institutions model global cycles and feedbacks. Many of these models incorporate trophic interactions and are able to project what will happen to nutrients, planktons and primary production. But their coarse spatial resolution means that the Philippines' internal seas and many islands are not modelled properly.

Downscaled models of sufficient resolution are critical to developing reliable and more robust projections of future changes that can be applied at local scales. Very few such models exist for Southeast Asia and most of the efforts are focused on terrestrial modeling. The Coral Triangle Regional Ocean Modeling System or CTROMS is a promising high-resolution model developed by the US National Center for Atmospheric Research and Rutgers University (Castruccio *et al.* 2013; Kleypas *et al.* 2015; Thompson *et al.* 2018; *www.ctroms.ucar.edu*). Using a 5km x 5km grid resolution with 50 depth levels encompassing the entire Coral Triangle and the Philippines' EEZ, the CTROMS has been run to simulate historical (1958 to 2008) and future (2040-2060 and 2080-2100) trends in sea temperature, salinity, and currents using the RCP8.5 scenario. CTROMS more accurately captures historical trends in sea surface temperature compared with the CMIP5 models (see **Figure 4**; blue versus red and orange lines). Based on the CTROMS, the Philippines seas is projected to warm by more than 3.5°C by 2100, higher than the CMIP5 estimates.

Chlorophyll-a and Primary Production

Data for chlorophyll-a and primary production come mainly from satellites. Unlike with SST, chlorophyll-a and primary production trends from 2003 to 2016 (MODIS; https://modis.gsfc.nasa.gov/data/dataprod/chlor_a.php) show varying directions with alternating increasing and decreasing trends coinciding with occurrence of fronts and eddies (**Figure 5**). Also, the trends for these variables are statistically significant in only a few areas.

CMIP5 models project declines in chlorophyll-a and primary production (by 4 to 36 mgC/m^2/day or 0.5% to 11.8% of present mean values) around the Philippines following the projected increases in sea surface temperature and shallowing of the mixed layer depth (**Figure 6**). CMIP5 models also project declines in dissolved oxygen and reduced pH levels in the Western Pacific. Together with the projected sea surface temperature changes in the future, these three factors combine to effect reductions in net primary production in the entire region by 2100.

CTROMS does not have a biogeochemistry and lower trophic level due to the high computation requirements to run the model at high resolution.

Changes used for the habitat suitability model

Figure 6 shows the present and future environmental change maps used for the suitable habitat analyses based on data sources in Table 1. Future scenarios are for 2050s (i.e., 2040-2060).

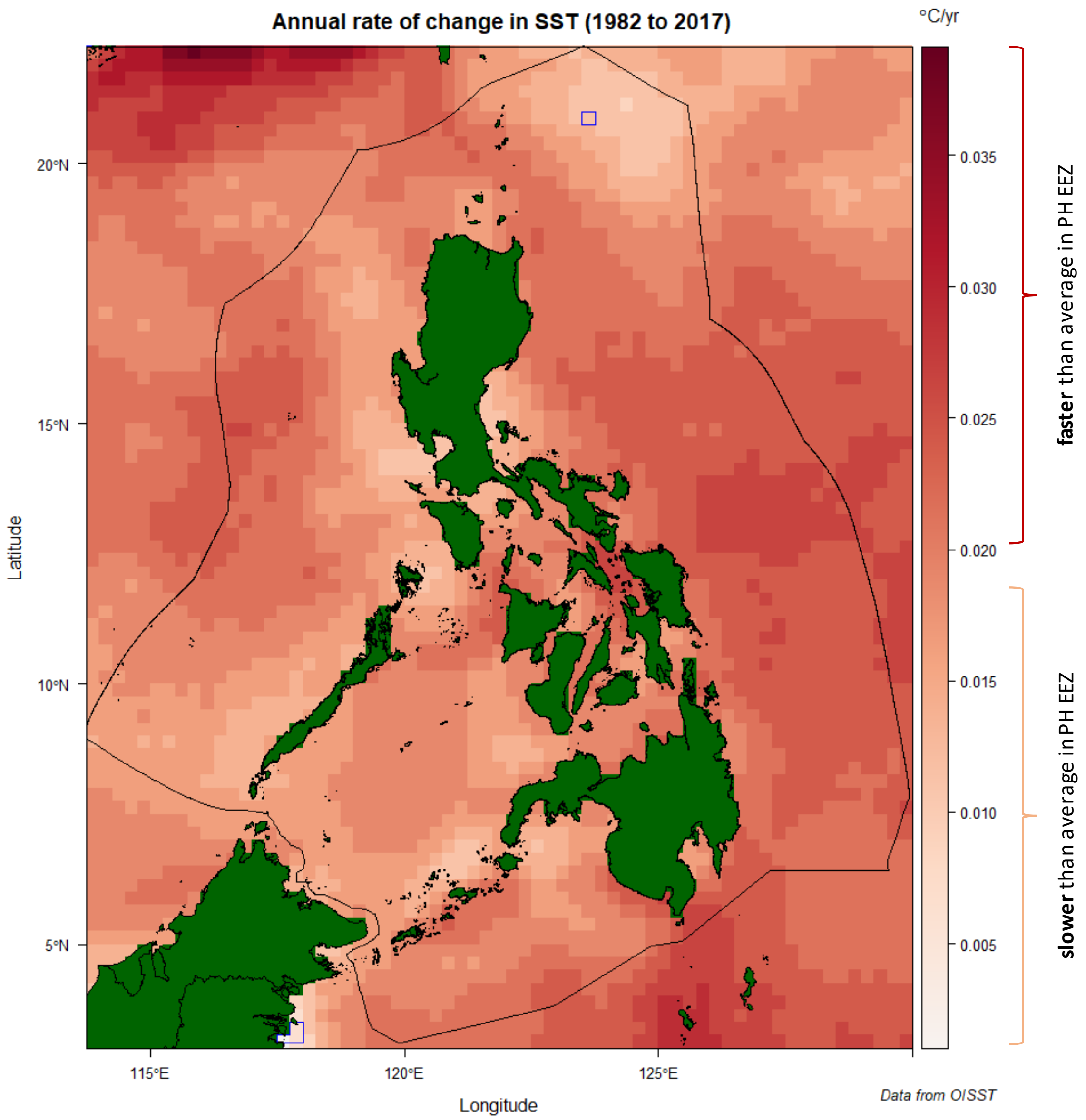


Figure 3. *Annual rate of change in Sea Surface Temperatures (SST) based on NOAA's Optimum Interpolation SST (OISST) data from 1982 to 2017 using a Theil-Sen estimator. Trends inside blue polygons are statistically non-significant (p>0.05) based on a mann-kendall test. The black line represents an unofficial exclusive economic zone delineation for the Philippines for illustrative purposes only (source: Claus S., De Hauwere N., Vanhoorne B., Souza Dias F., Oset García P., Schepers L., Hernandez F., and Mees J. (Flanders Marine Institute) (2015). MarineRegions.org. Accessed at http://www.marineregions.org on 2015-08-01.)*

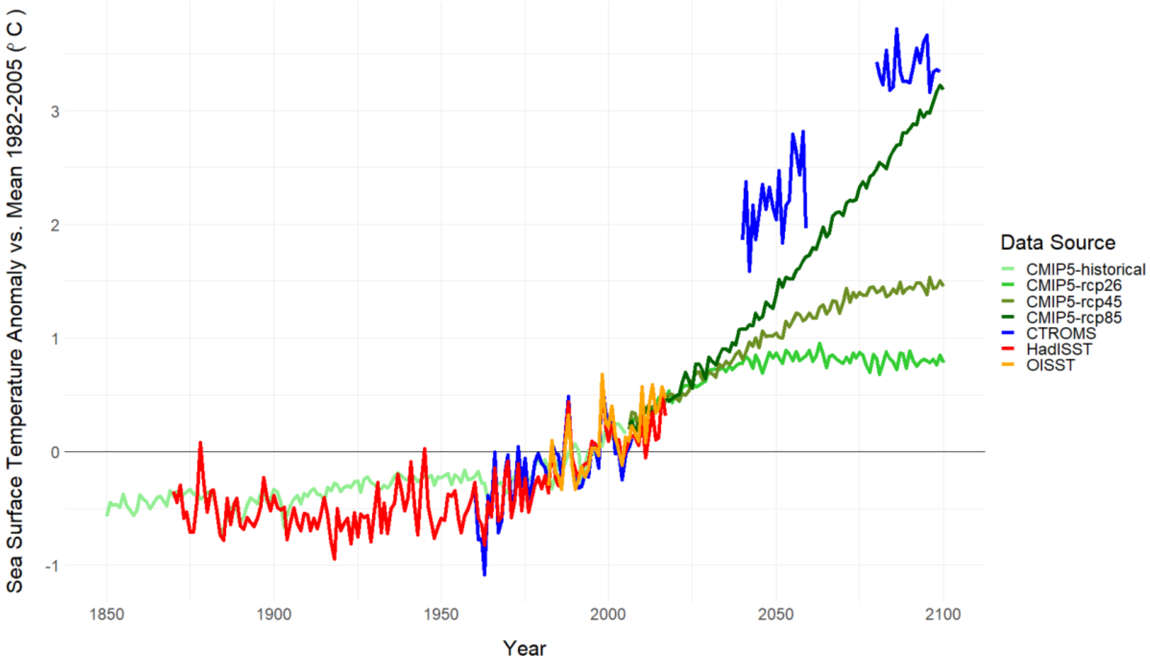


Figure 4. *Historical and projected changes in sea surface temperatures within the Philippines' EEZ based on observations (HadISST and OISST) and models (CTROMS, CMIP5-historical, CMIP5-rcp26, CMIP5-rcp45, and CMIP5-rcp85). The three CMIP5 future projections correspond to Representative Concentration Pathways representing drastic reductions in greenhouse gas emissions (RCP2.6), moderate reductions (RCP4.5), and business-as-usual or minimal reductions in global greenhouse gases (RCP8.5). The CTROMS model uses the RCP8.5 scenario.*

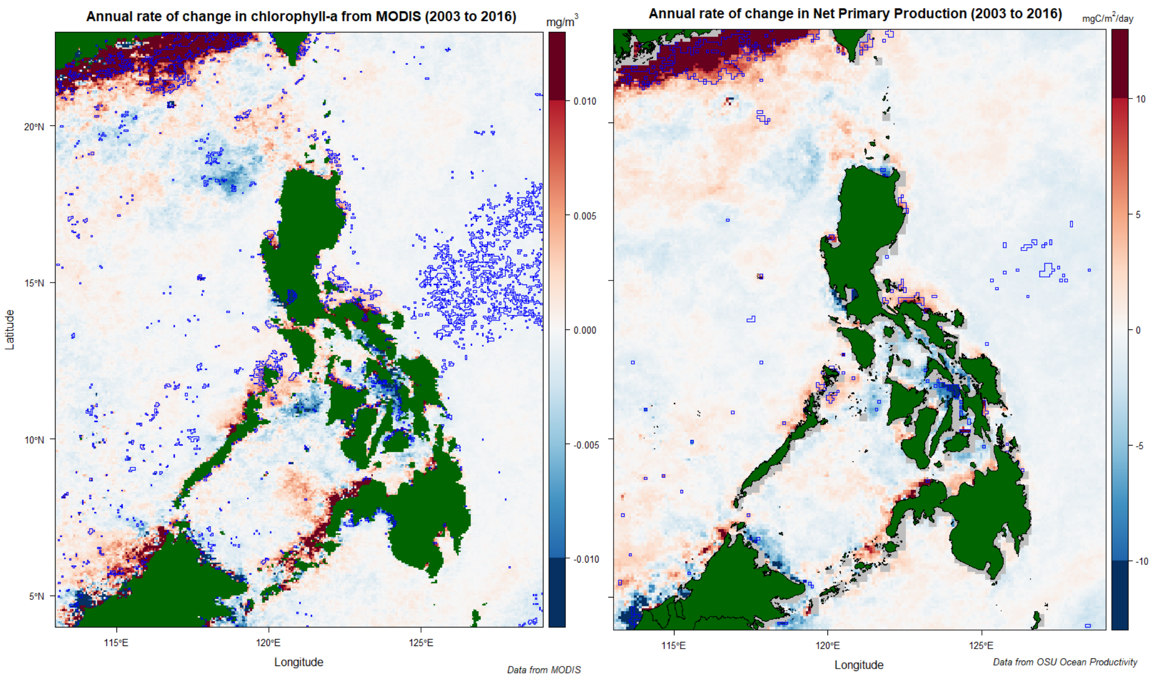


Figure 5. *Annual rate of change in chlorophyll-a (left) and net primary production (right) based on MODIS from 2003 to 2016 using a Theil-Sen estimator. Trends inside blue polygons are statistically significant ($p < 0.05$) based on a mann-kendall test.*

***Table 1.** Data used and sources for this study*

Variables	Data source	Description / Notes
Data used for the historical and projected changes analyses		
Sea surface temperature (SST)	1. US NOAA Optimum Interpolation Sea Surface Temperature[1] 2. Hadley Centre Sea Ice and Sea Surface Temperature data set[2]	- Global SSTat 1/4° resolution from 1982 to present - Global SST at 1° resolution extending back to 1871 from ship-based observations
Chlorophyll-a	Moderate Resolution Imaging Spectroradiometer (MODIS) [3]	Monthly chlorophyll-a maps from 2003 to 2017 at 4km resolution
Net Primary Production (NPP)	Oregon State University Standard VGPM (Behrenfeld & Falkowski 1997)[4]	Monthly NPP maps based on MODIS satellite data from 2003 to 2017
Environmental layer used for the suitable habitat analysis		
Sea surface temperature (SST)	<u>Present:</u> Bio-Oracle v2.0 (Assis *et al.* 2018)[3] Present Surface Temperature Mean (°C)[5] <u>Future</u> (CMIP5): Bio-Oracle v2.0 (Assis *et al.* 2018)[3] RCP4.5, 2040-2050 Surface Temperature Mean <u>Future</u> (CTROMS): CTROMS SST[6]	- 9km resolution climatology from Global Observed Ocean Physics Reprocessing - 9km resolution climatology from Global Observed Ocean Physics Reprocessing, - mean of monthly CTROMS SST from 2040 to 2059
Sea surface salinity (SSS)	<u>Present:</u> CTROMS mean SSS 1997 to 2007[6] <u>Future</u> (CMIP5): Bio-Oracle v2.0 RCP4.5, 2040-2050 Surface Salinity Mean[3] <u>Future</u> (CTROMS): CTROMS mean SSS 2040 to 2059	- mean SSS from 1997 to 2007 - used the difference between Bio-Oracle present and future surface salinity values and added these to the CTROMS mean SSS for 1997 to 2007 - mean SSS from CTROMS for 2040 to 2059
Primary production (PP)	<u>Present:</u> Oregon State University Standard VGPM (Behrenfeld & Falkowski 1997) [4] <u>Future</u> (Aquamaps): Primary production for 2050 from a CMIP5 model (Kaschner et al. 2016b)[7]	- Monthly NPP maps based on MODIS satellite data from 2003 to 2017 - Half-Degree Cells Authority File. Difference between Aquamaps PrimProd2050c and PrimProdMean added to the OSU mean NPP from 2003 to 2017

[1] https://www.ncdc.noaa.gov/oisst
[2] https://www.metoffice.gov.uk/hadobs/hadisst/
[3] https://modis.gsfc.nasa.gov/data/dataprod/chlor_a.php
[4] http://www.science.oregonstate.edu/ocean.productivity/index.php
[5] http://www.bio-oracle.org/
[6] http://www.ctroms.ucar.edu/
[7] https://www.aquamaps.org/download/main.php

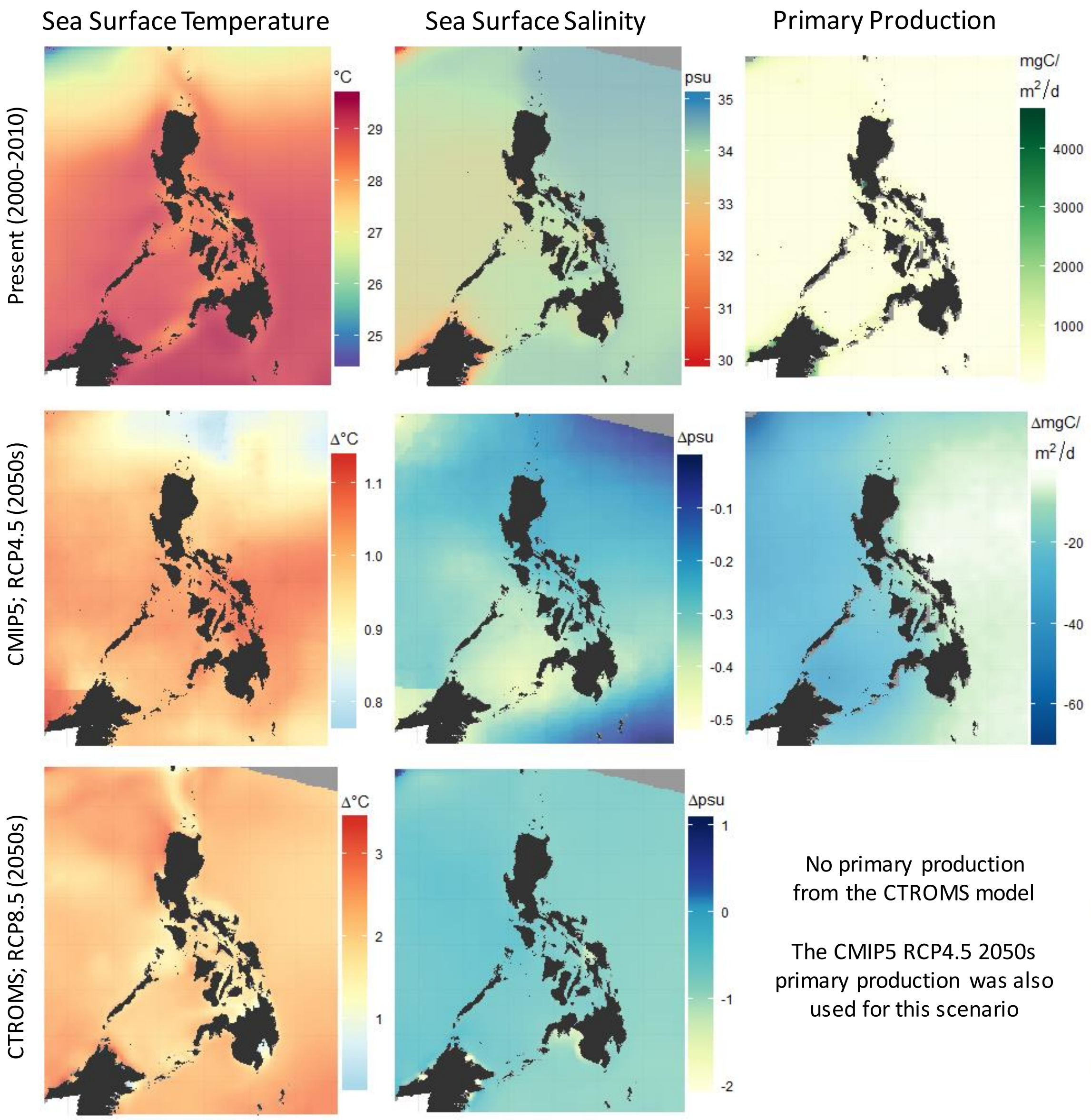


Figure 6. *Present mean conditions of sea surface temperature, sea surface salinity, and primary production for the Philippines (top row) and the projected changes from the CMIP5 models (middle row) and the CTROMS model (bottom row).*

Mapping Suitable Habitats

Taxonomic Coverage

Fifty-nine (59) marine capture fisheries species were selected for this analyses from the compiled list of top 10 marine capture fish species per region from BFAR/NFRDI's National Stock Assessment Program's Philippine Atlas of Capture Fisheries (Santos *et al.* 2017) and a species ranking of landed catches by volume from the February 2018 version of the NSAP National Database (NFRDI, unpublished data).[1]

The species covered in this study include anchovies (5), sardines (7), scads (10), tuna (8), squids (3), and other demersal (11), small pelagic (6), and large pelagic (4) fish species. Together, the taxonomic groups that these species represent account for ~80% of the total commercial and municipal marine capture fisheries production based on the Philippine Statistics Authority data.

Combining Global Information with Local Data and Regional Climate Models

One way of projecting the potential impacts of climate change on species is through ecological niche modeling. Ecological niche models predict the distribution of species by correlating their known occurrences with environmental conditions in these areas and applying the derived relationship to other areas. This results into a metric of habitat suitability for the given species, usually a value from 0 to 1, with areas having similar combinations of environmental conditions to where the species have been found to thrive receiving the highest habitat suitability score (i.e., 1).

Various methods are available to generate relationships between species occurrence and environmental conditions. A global resource of species distribution maps is currently available. The *Aquamaps* website contains standardized distribution maps at 0.5 x 0.5 degree grid resolution for over 25,000 species of fishes, marine mammals, and invertebrates (Kaschner *et al.* 2016a). The Aquamaps method estimates environmental thresholds, called "envelopes", for each species per environmental variable based on global occurrence data and corresponding environmental conditions in these occurrence locations.[2] These *envelopes* are used to convert environmental variable values to *probability of occurrence* index (0 to 1). The *probability of occurrence* per environmental variable are combined to give a habitat suitability index per area.

Aquamaps are computer-generated predictions of natural occurrence of marine species, based on the environmental tolerance of a given species with respect to depth, salinity, temperature, primary productivity, and its association with sea ice or coastal areas. These 'environmental envelopes' are matched against an authority file which contains respective information for the Oceans of the World. Independent knowledge such as distribution by FAO areas or bounding boxes are used to avoid mapping species in areas that contain suitable habitat, but are not occupied by the species. Maps show the color-coded likelihood of a species to occur in a half-degree cell, with about 50 km side length near the equator. Experts are able to review, modify and approve maps.

Source: *https://www.aquamaps.org/main/home.php*

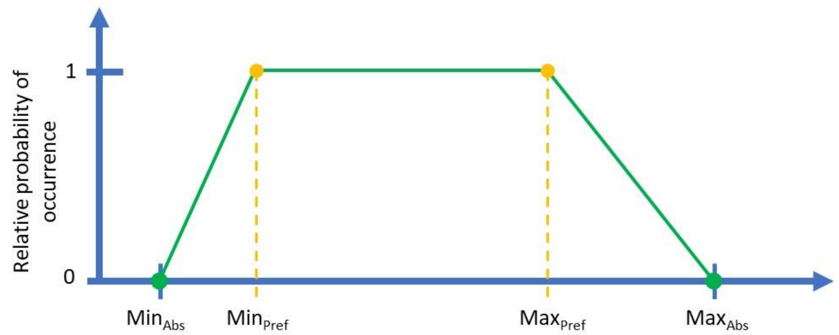
[1] The data was provided by NFRDI thru Dr. Mudjekeewis Santos and Val Manlulu after a formal request for data access was submitted to BFAR Director and Undersecretary Eduardo Gongona and Assistant Director for Technical Services Drusila Bayate.

[2] For more details on the Aquamaps method, readers are directed to the aquamaps web page (www.aquamaps.org) and accompanying method summaries (e.g., https://www.aquamaps.org/main/AquaMaps_Algorithm_and_Data_Sources.pdf)

The basic Aquamaps approach was modified to incorporate (a) local occurrence information from BFAR NFRDI's National Stock Assessment Program and (b) use higher resolution (~9km grids) oceanographic data and regional climate projection models. The major steps to produce the habitat suitability maps were: (1) generate "environmental envelopes" using higher resolution environmental data, local occurrence information from the NFRDI NSAP national database, and existing environmental envelopes from the Aquamaps website; (2) apply these environmental envelopes to present (years 2000-2010) and projected (years 2040-2060) changes in environmental conditions.

The following modifications were made to the Aquamaps approach:

1. Used only sea surface temperature, sea surface salinity, and primary productivity as the environmental variables. Depth was not included as a limiting factor since the other parameters should be able to constrain the distribution sufficiently.
2. Used BioOracle v2.0 basemaps at 1/12° resolution for sea surface temperature and sea surface salinity (Assis *et al.* 2018; http://www.bio-oracle.org/) and Net Primary Productivity from the Oregon State University Ocean Productivity website (Behrenfeld & Falkowski, 1997; http://www.science.oregonstate.edu/ocean.productivity/index.php).
3. Re-calculated environmental envelopes absolute and preferred minimum and maximum values per variable per species using occurrence records from GBIF and OBIS database and fishing grounds from the NSAP national database (**Figure 7**). The recalculated envelope thresholds were compared with those available from Aquamaps and the values that gave the lowest absolute minimum and highest absolute maximum thresholds were used.
4. Suitable habitat computed as the product of probability of occurrences for temperature, salinity, and primary productivity.



Min_{Abs} (Absolute minimum) 25th percentile - 1.5 x interquartile or absolute minimum in extracted data (whichever is lesser)

Min_{Pref} (Preferred minimum) 10th percentile of observed variation in environmental parameter.

Max_{Pref} (Preferred maximum) 90th percentile of observed variation in environmental parameter

Max_{Abs} (Absolute minimum) 75th percentile + 1.5 x interquartile or absolute maximum in extracted data (whichever is greatest)

Based on Aquamaps documentation (https://www.aquamaps.org/main/AquaMaps_Algorithm_and_Data_Sources.pdf)

Figure 7. *Aquamap's definition of an environmental envelope. Additional rules were added (see text) to integrate local occurrence data from the Philippines' BFAR/NFRDI National Stock Assessment Program and the use of finer-resolution sea surface temperature and sea surface salinity layers.*

Interpretation of Probability of Occurrence and Habitat Suitability Maps

The **Probability of Occurrence** and **Habitat Suitability** maps represent how environmental variables in a given site compare with the environmental envelop (**Figure 7**) thresholds for the species. The color scale in both types of maps range from 0 to 1.

Consider sea surface temperature (SST). For the Probability of Occurrence in a given area a value of:

1: indicates that the mean SST in the area is within the Preferred Minimum and Preferred Maximum values for the species' SST envelope.

0: means that the SST in the area is beyond the Absolute Minimum or Absolute Maximum values for the species' SST envelope.

Between 0 and 1: The SST in the area is beyond either the Preferred Minimum (or Maximum) SST but still greater (or lesser) than the Absolute Minimum (or Absolute Maximum) SST envelope. The smaller the value, the closer the SST of the given area to either the Absolute Minimum or Absolute Maximum SST.

The Habitat Suitability is interpreted the same way but represents the product of the three probabilities of occurrences (temperature, salinity, and primary production). The difference is that a value of 0 means that at least one or more probability of occurrence is beyond the species' envelope or absolute thresholds.

Future scenarios. Two future scenarios are modelled representing a less severe climate change brought about by reductions in future greenhouse gas emissions (CMIP5; RCP 4.5) and another from a regionally-calibrated climate model following a business-as-usual (or minimal mitigation) scenario of future greenhouse gas emissions (CTROMS; RCP8.5):

1. CMIP5; RCP4.5[3]: BioOracle v2.0 RCP4.5 for 2040 to 2050 (www.bio-oracle.org) from 3 CMIP5 models, namely CCSM4, HadGEM2-ES, and MIROC5. Environmental layers have been downscaled to a 1/12° or ~9km resolution
2. CTROMS; RCP8.5: High-resolution model calibrated for the Coral Triangle region using an RCP8.5 or a business-as-usual scenario of global greenhouse gas emissions.

In each species page, the top collection of nine (9) maps represents the probability of occurrences for each of the three environmental variables and the present and two future scenarios. The bottom three maps are the habitat suitability change maps, combining the three probabilities of occurrences for the present and two future climate change scenarios.

Summary of Habitat Suitability Changes

- Present distributions of marine species are limited primarily by primary production while future changes could be driven more by the projected rapid rate of sea warming.
- All 59 marine species will experience reductions in habitat suitability within the Philippines' EEZ with continued climate change but the magnitude of change in suitability varies across groups and species (**Figure 8**). Projected changes in habitat suitability is clearly species-specific and no consistent patterns can be seen when comparing groups.
- At the mild climate change future scenario (i.e., CMIP5; RCP4.5), most species will experience a 15% to 30% reduction in habitat suitability driven mainly by the projected increase in sea surface temperatures.
- Future conditions in Philippines' EEZ will exceed estimated environmental envelopes for eight (8) species (**Figure 9**), namely: shorthead anchovy (*bolinaw)*, chub mackerel (*tangigue*),

[3] CMIP5: Coupled Model Intercomparison Project Phase 5 is a modeling framework followed by more than 40 different global climate projection models. Models under the CMIP5 are complex, modeling both physico-chemical changes in ocean and land conditions and various lower trophic level variables (e.g., planktons). The trade-off for this complexity is the coarse resolution of these models, usually at 1° resolution or ~111km grids along the equator. At this scale, many small island features, bathymetry, and topography, are not modeled accurately.

larghead hairtail (*espada*), Indian mackerel (*alumahan*), rainbow runner (*salmon*), toothpony (*sapsap*), common dolphinfish (*durado*), and Indo-Pacific sailfish (*malasugi*). The area considered as potentially suitable for these species (i.e., with habitat suitability index > 0) could decrease to less than 70% of current extent or even result in local extinction with the more sever climate change scenarios.

- Skipjack tuna (*gulyasan*) and moonfish (*hiwas*) are projected to experience the smallest change in mean habitat suitability under both future scenarios for 2050s.
- Climate change impact in terms of reductions in habitat suitability and area of suitable habitats is greatest offshore and smallest in coastal waters (**Figure 10** and **Figure 11**).

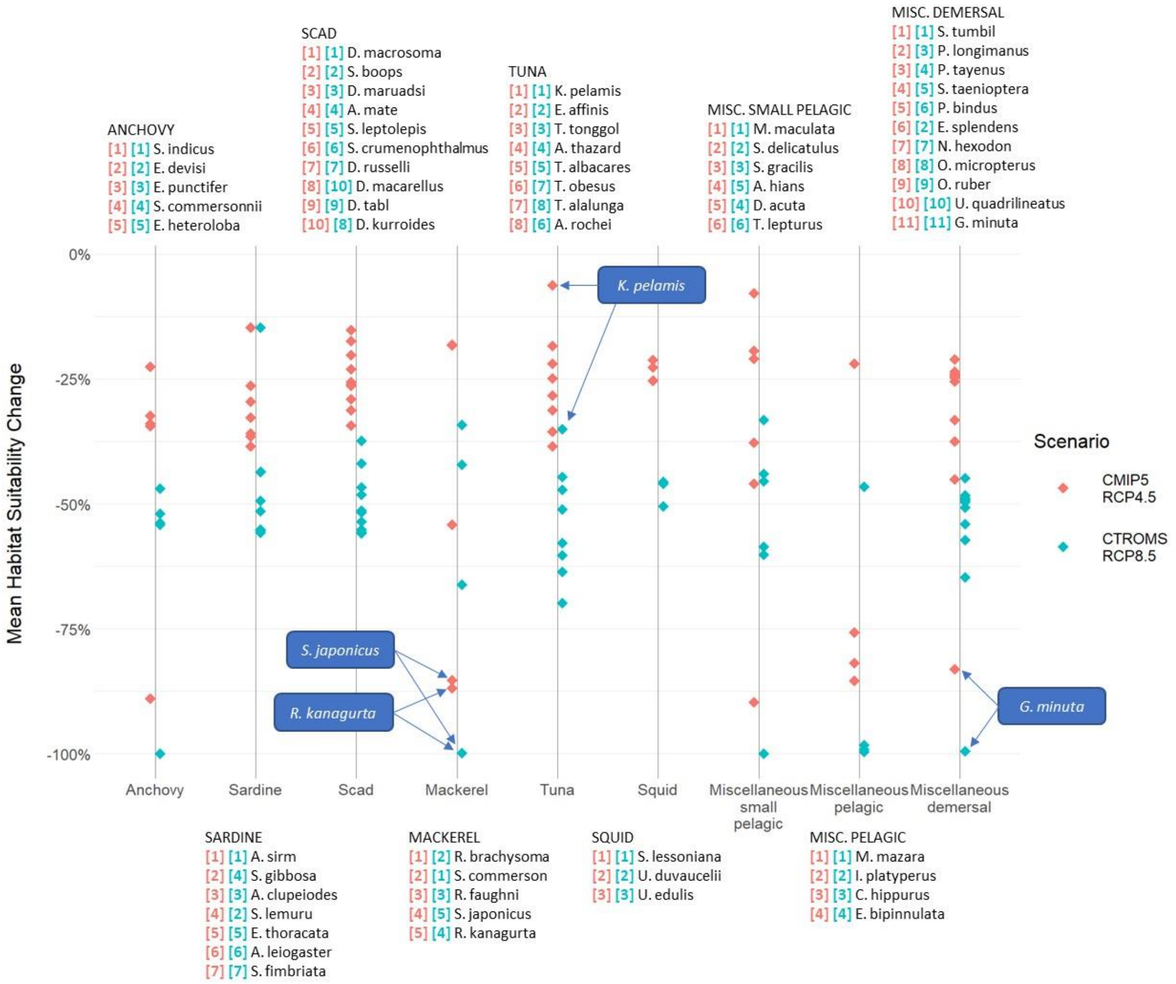


Figure 8. *Mean changes in habitat suitability per species using the CMIP5 RCP4.5 (red) and CTROMS RCP8.5 (blue) projections for 2050 versus values in 2000. The numbers beside the list of species corresponds with the vertical order of points in the graph for each species group following the same color legend as the points.*

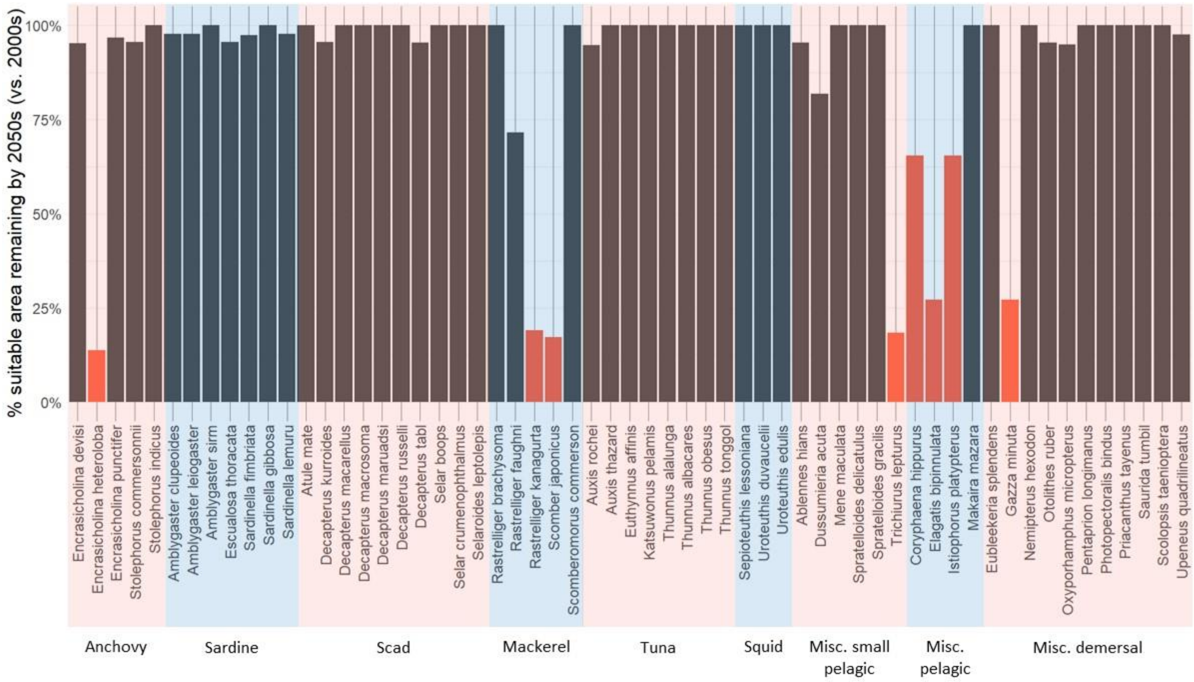


Figure 9. *Percentage of suitable habitat remaining by 2050s versus present under the CMIP5, RCP4.5 scenario. Red bars highlight species projected to have less than 70% suitable area left within the Philippines' EEZ by 2050s. An area is counted as suitable if its habitat suitability score is greater than 0. The figure for the CTROMS, RCP8.5 scenario shows a similar pattern per species but with much lower values of suitable area left for the highlighted species.*

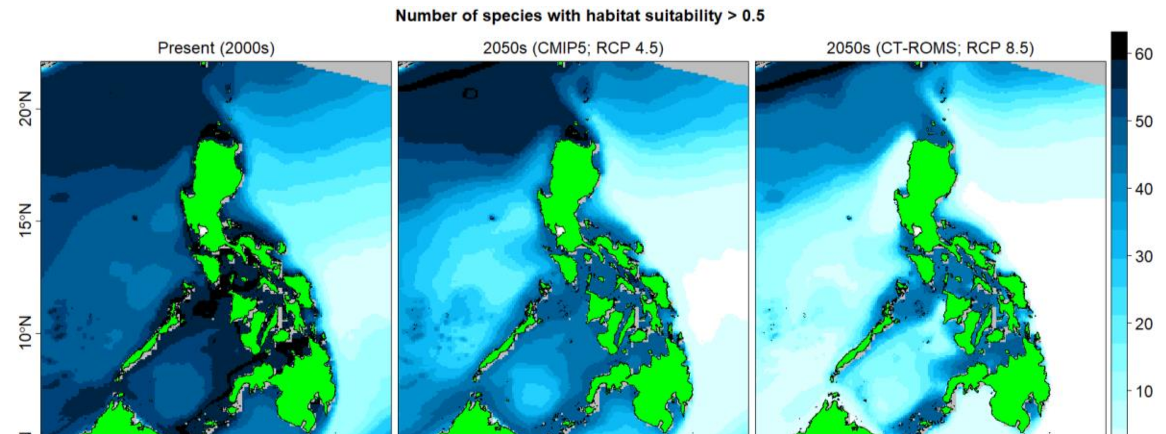


Figure 10. *Number of species with habitat suitability score of greater than 0.5 for present and the two future climate change scenarios.*

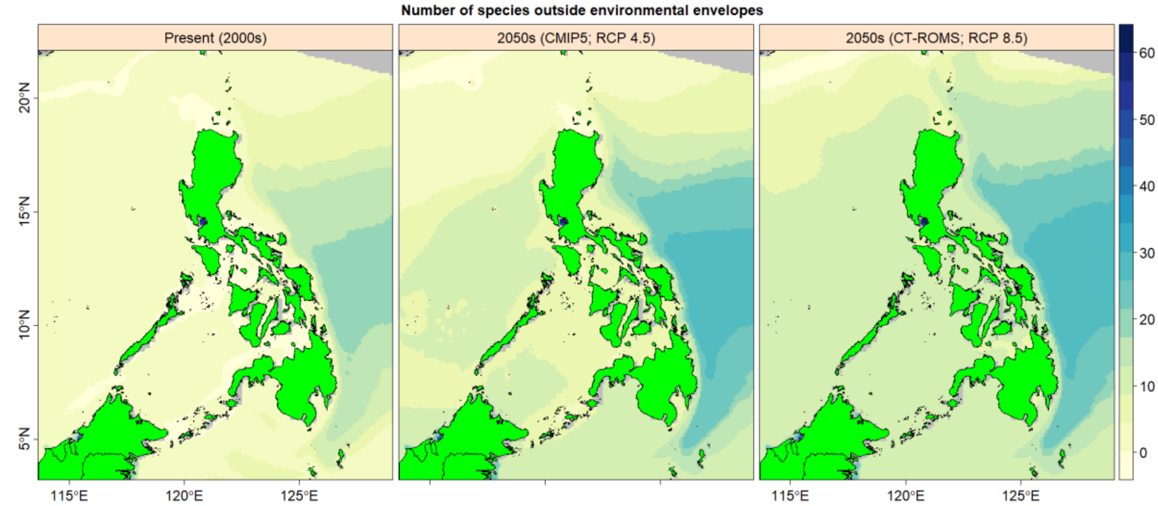


Figure 11. *Number of species where the environmental conditions exceed absolute thresholds based on environmental envelopes.*

Species List

Anchovy
1. *Encrasicholina devisi*
2. *Encrasicholina heteroloba*
3. *Encrasicholina punctifer*
4. *Stolephorus commersonnii*
5. *Stolephorus indicus*

Mackerel
6. *Rastrelliger brachysoma*
7. *Rastrelliger faughni*
8. *Rastrelliger kanagurta*
9. *Scomber japonicus*
10. *Scomberomorus commerson*

Sardine
11. *Amblygaster clupeoides*
12. *Amblygaster leiogaster*
13. *Amblygaster sirm*
14. *Escualosa thoracata*
15. *Sardinella fimbriata*
16. *Sardinella gibbosa*
17. *Sardinella lemuru*

Scad
18. *Atule mate*
19. *Decapterus kurroides*
20. *Decapterus macarellus*
21. *Decapterus macrosoma*
22. *Decapterus maruadsi*
23. *Decapterus russelli*
24. *Decapterus tabl*
25. *Selar boops*
26. *Selar crumenophthalmus*
27. *Selaroides leptolepis*

Tuna
28. *Auxis rochei*
29. *Auxis thazard*
30. *Euthynnus affinis*
31. *Katsuwonus pelamis*
32. *Thunnus alalunga*
33. *Thunnus albacares*
34. *Thunnus obesus*
35. *Thunnus tonggol*

Squid
36. *Sepioteuthis lessoniana*
37. *Uroteuthis duvaucelii*
38. *Uroteuthis edulis*

Miscellaneous small pelagic
39. *Ablennes hians*
40. *Dussumieria acuta*
41. *Mene maculata*
42. *Spratelloides delicatulus*
43. *Spratelloides gracilis*
44. *Trichiurus lepturus*

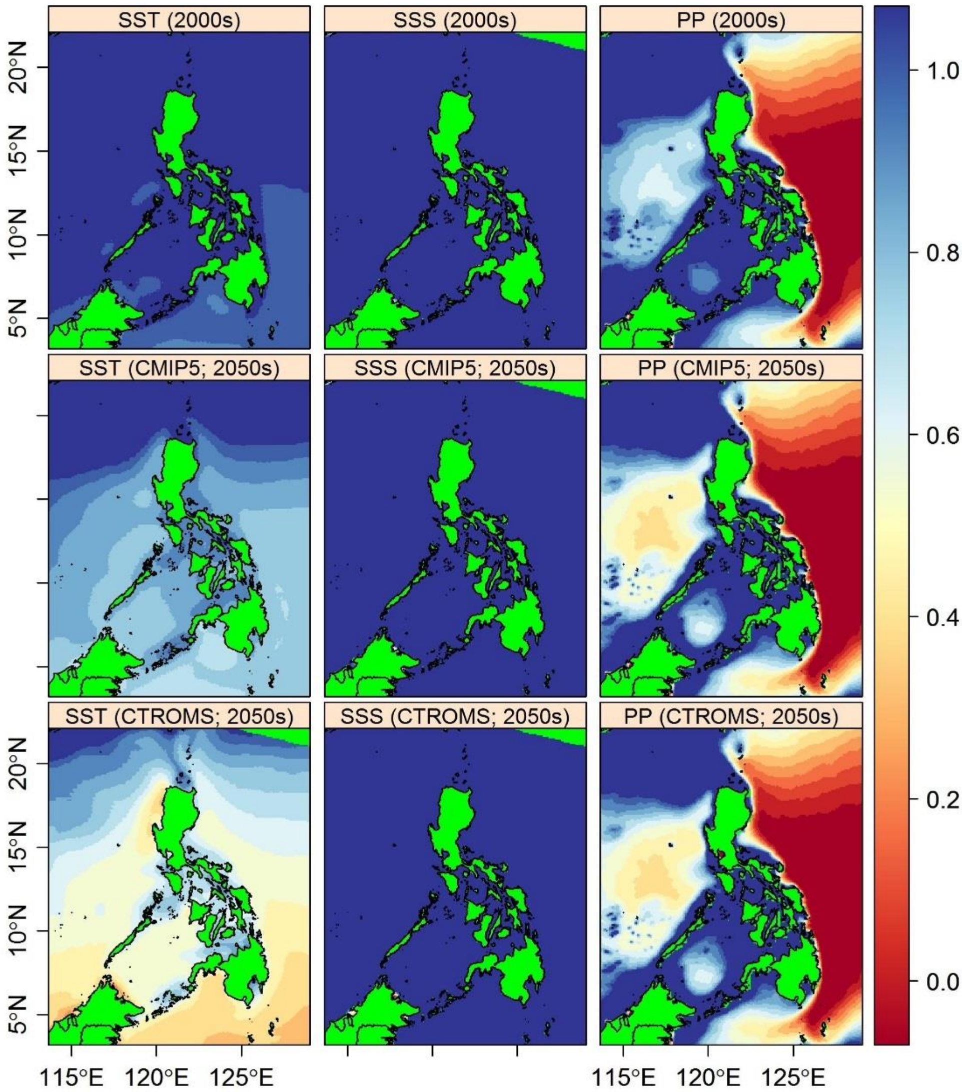
Miscellaneous pelagic
45. *Coryphaena hippurus*
46. *Elagatis bipinnulata*
47. *Istiophorus platypterus*
48. *Makaira mazara*

Miscellaneous demersal
49. *Eubleekeria splendens*
50. *Gazza minuta*
51. *Nemipterus hexodon*
52. *Otolithes ruber*
53. *Oxyporhamphus micropterus*
54. *Pentaprion longimanus*
55. *Photopectoralis bindus*
56. *Priacanthus tayenus*
57. *Saurida tumbil*
58. *Scolopsis taeniopterа*
59. *Upeneus quadrilineatus*

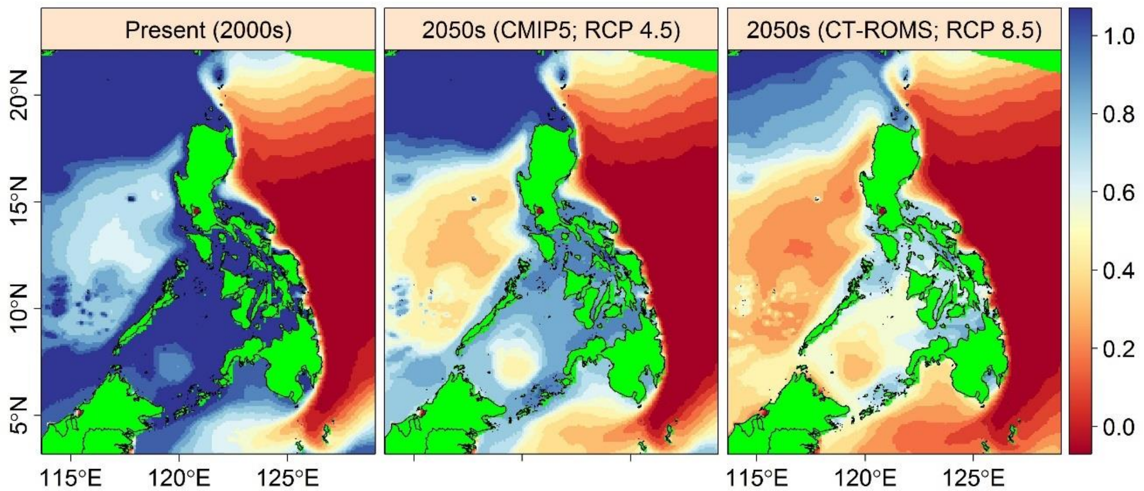
Encrasicholina devisi

Devil's anchovy (*"Dilis"*)

Probability of occurrence for *Encrasicholina devisi* by variable



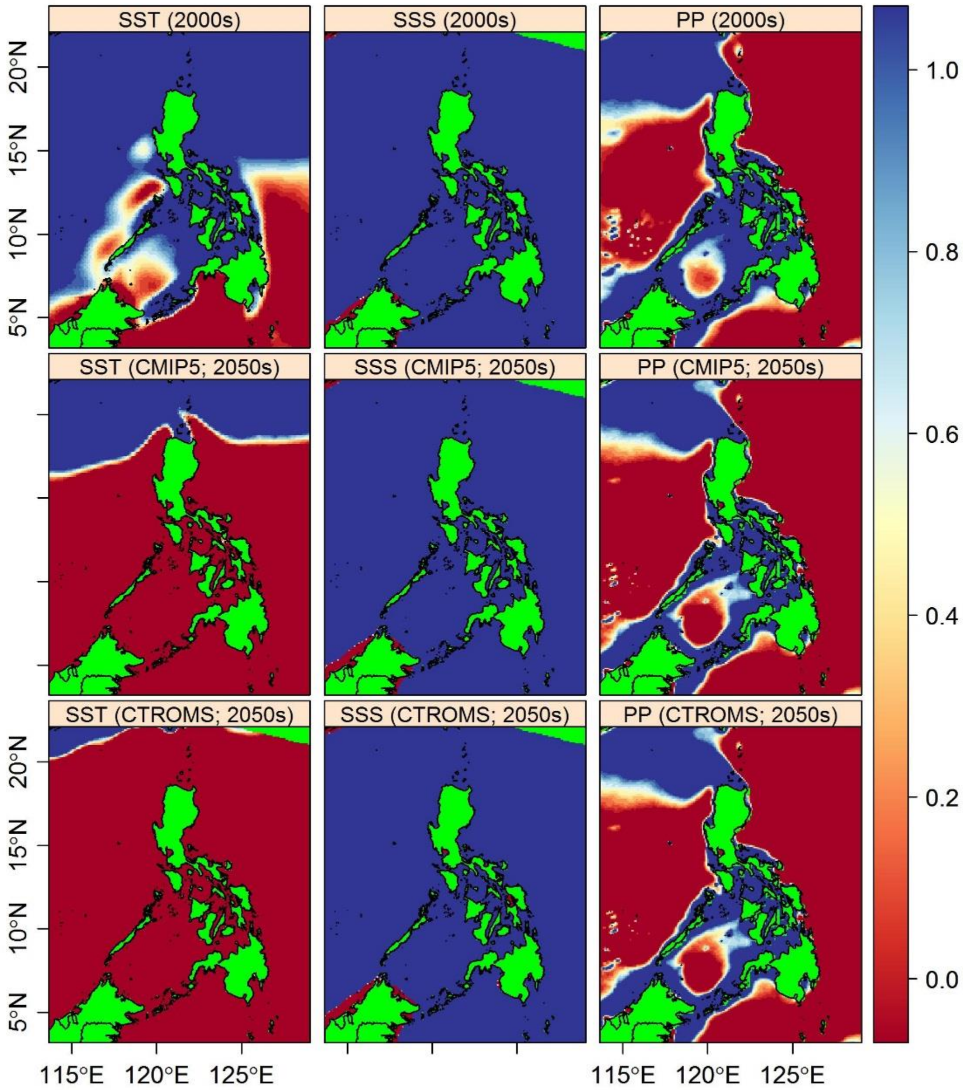
Projected Suitable Habitat for *Encrasicholina devisi*



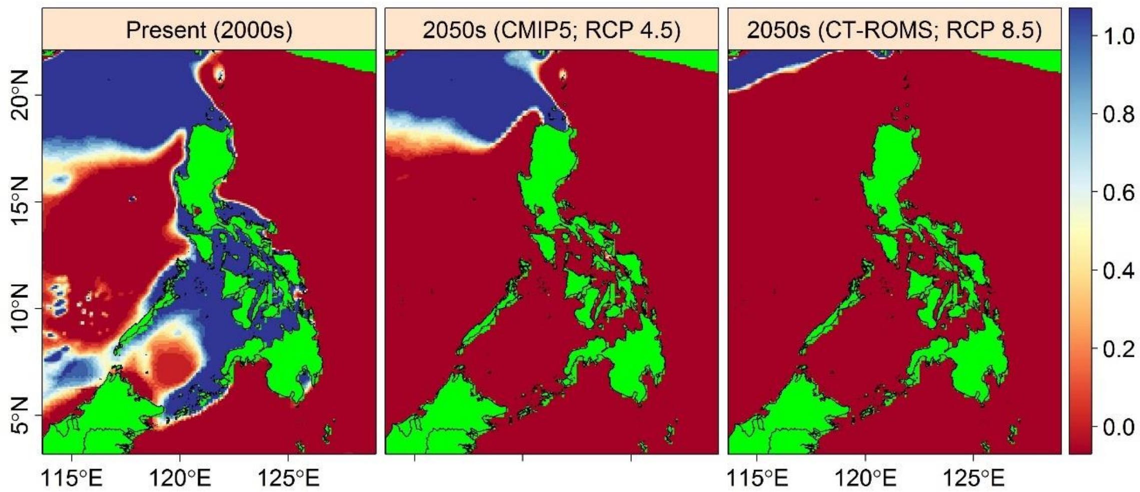
Encrasicholina heteroloba

Shorthead anchovy (*"Bolinaw"*)

Probability of occurrence for *Encrasicholina heteroloba* by variable



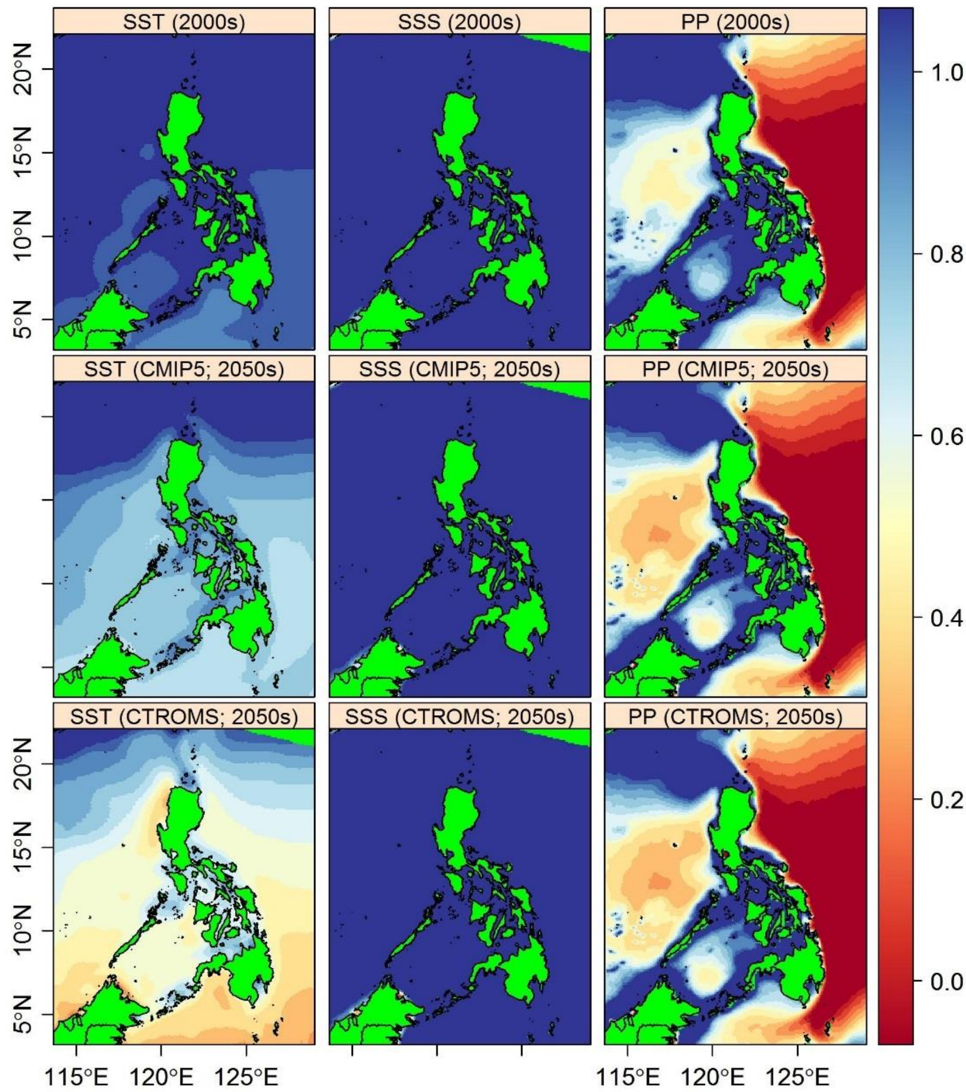
Projected Suitable Habitat for *Encrasicholina heteroloba*



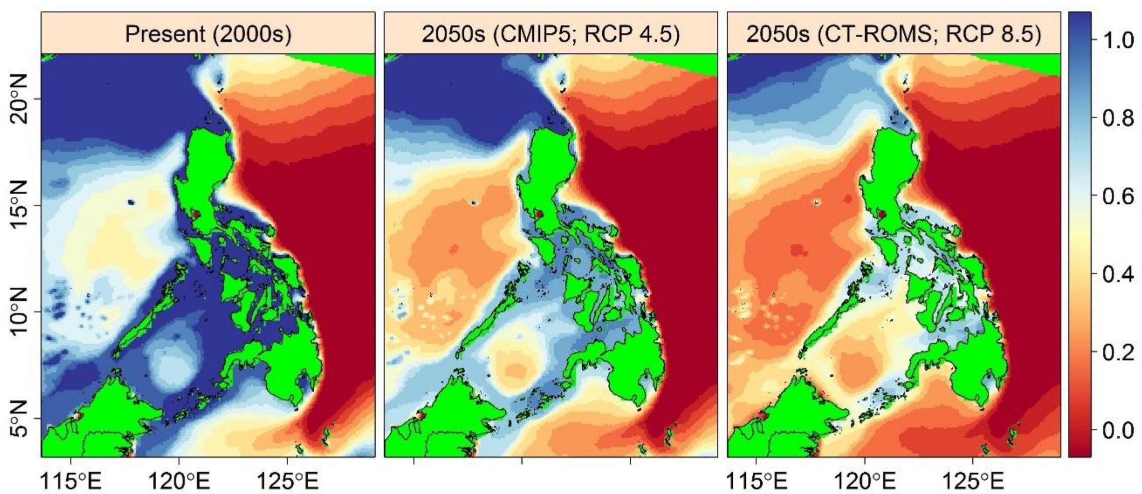
Encrasicholina punctifer

Buccaneer anchovy (*"Taburkit"*)

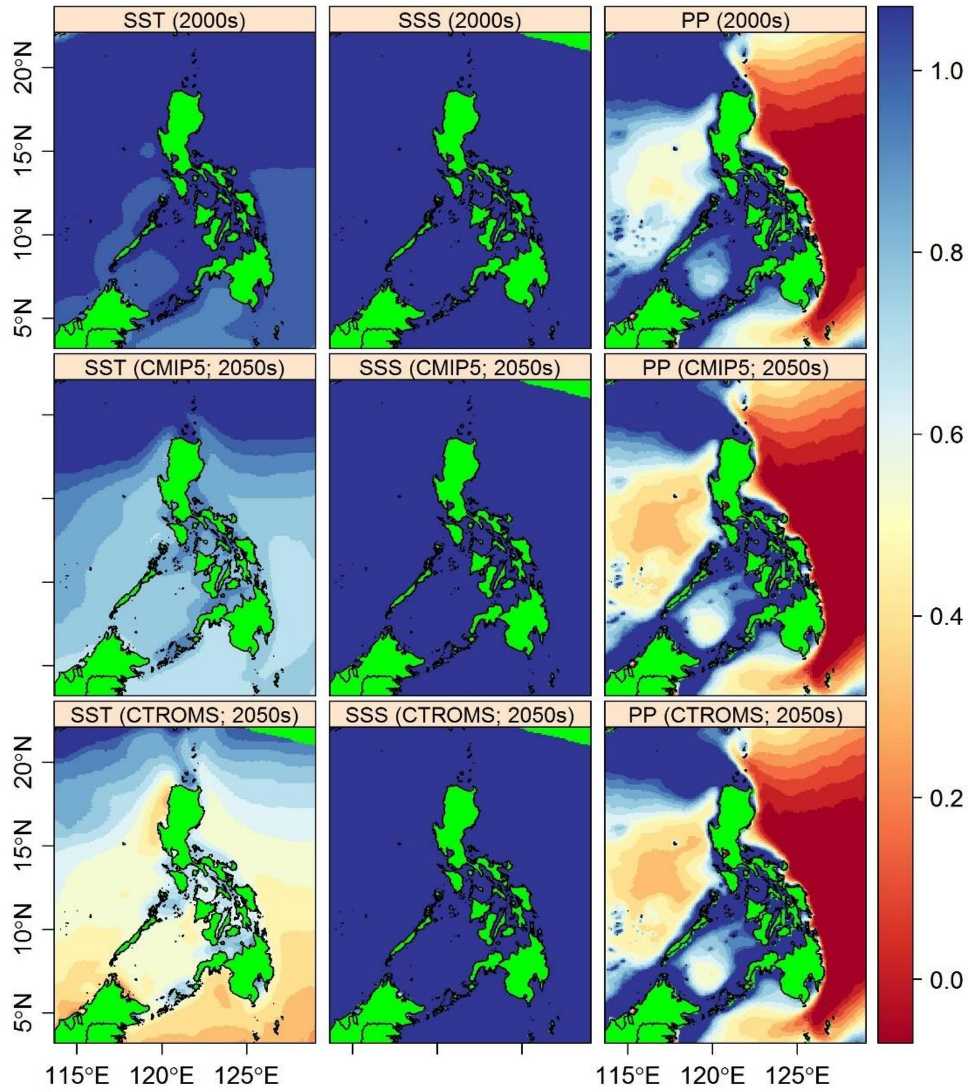
Probability of occurrence for *Encrasicholina punctifer* by variable



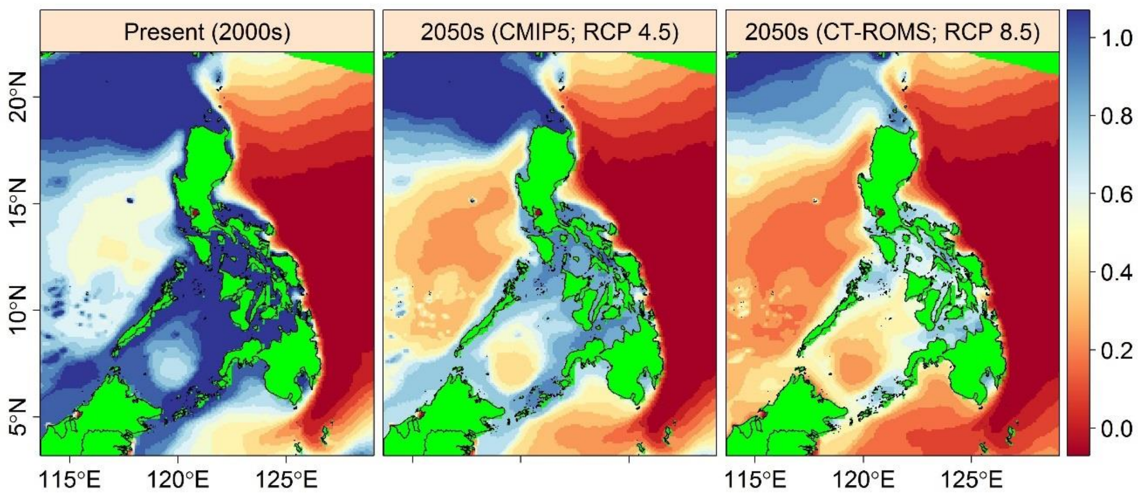
Projected Suitable Habitat for *Encrasicholina punctifer*



Probability of occurrence for *Stolephorus commersonnii* by variable



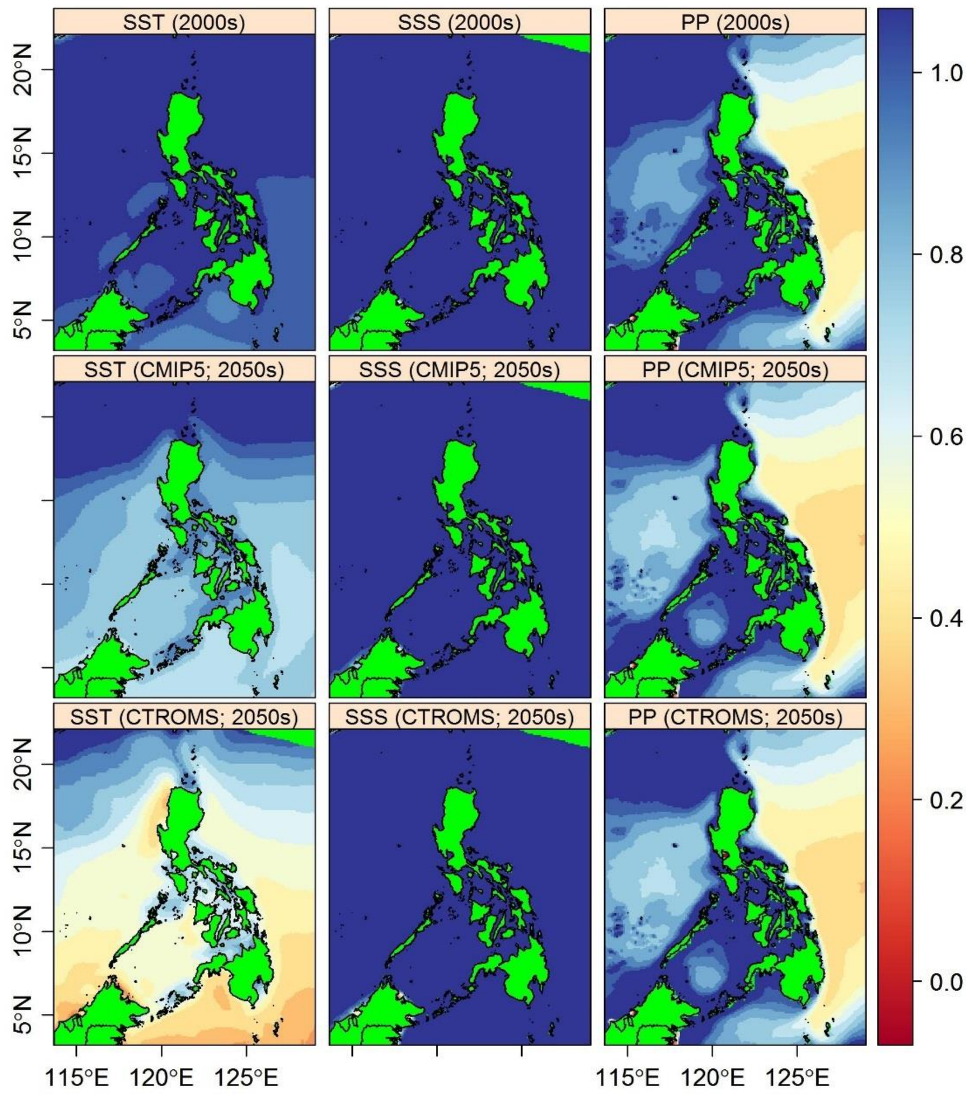
Projected Suitable Habitat for *Stolephorus commersonnii*



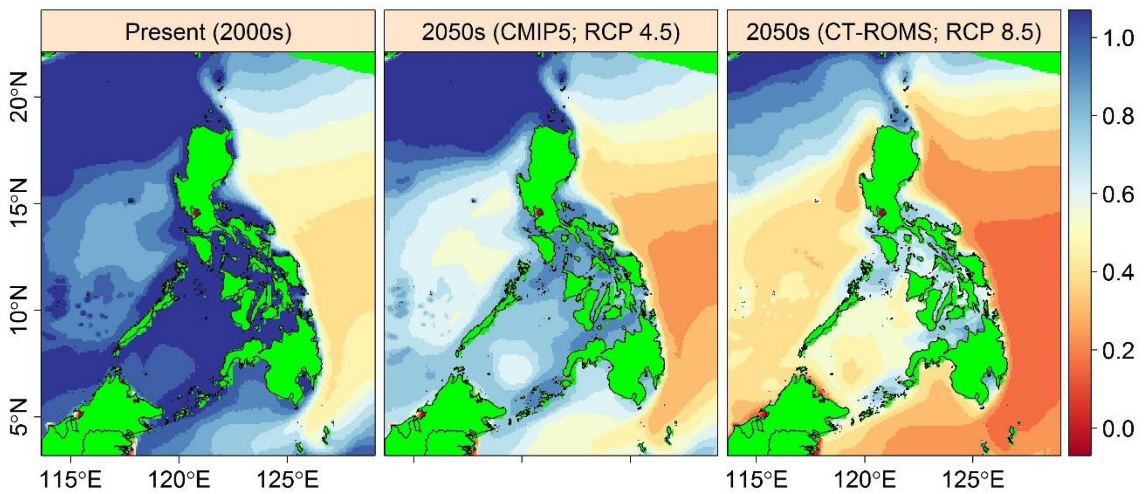
Stolephorus indicus

Indian anchovy (*"Dilis"*)

Probability of occurrence for *Stolephorus indicus* by variable

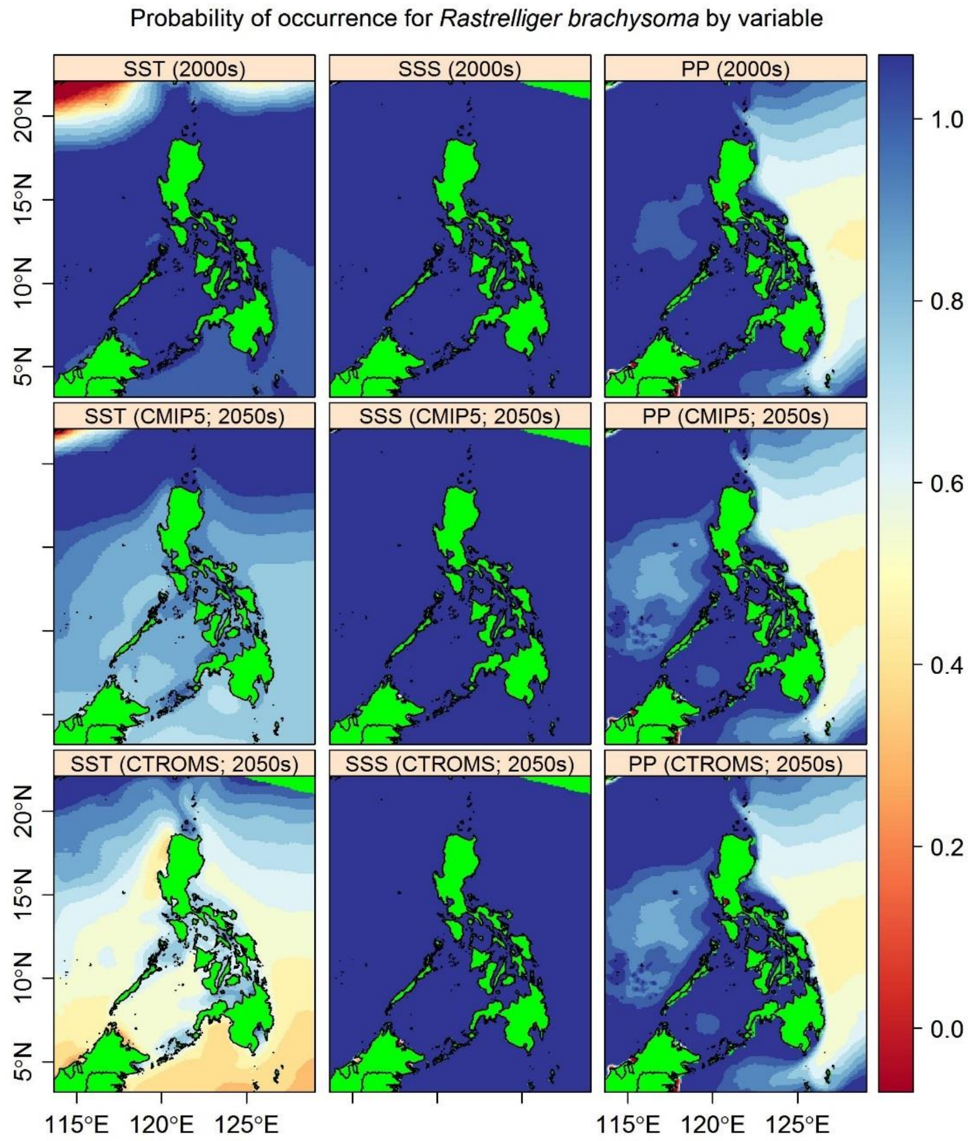


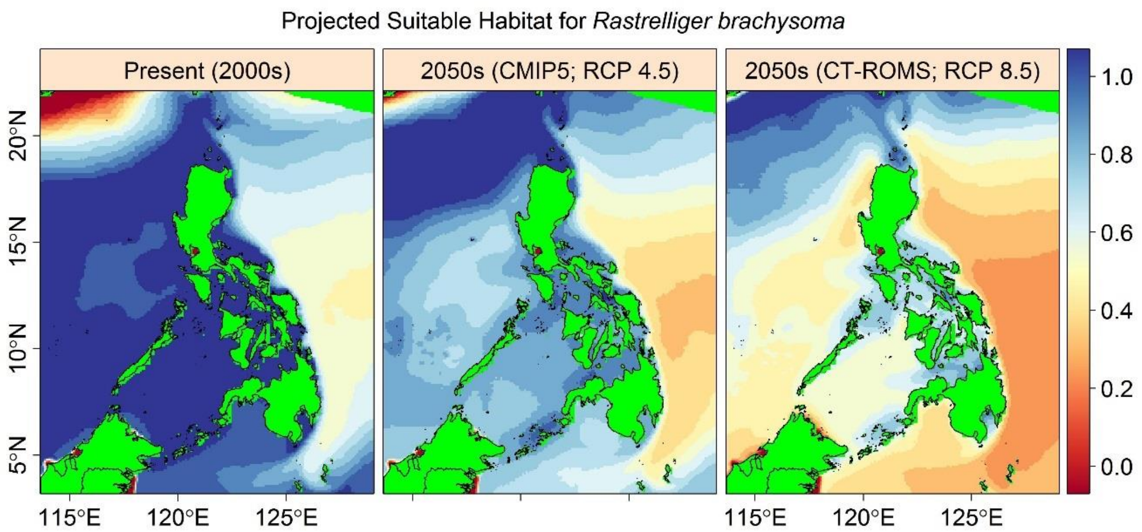
Projected Suitable Habitat for *Stolephorus indicus*



Rastrelliger brachysoma

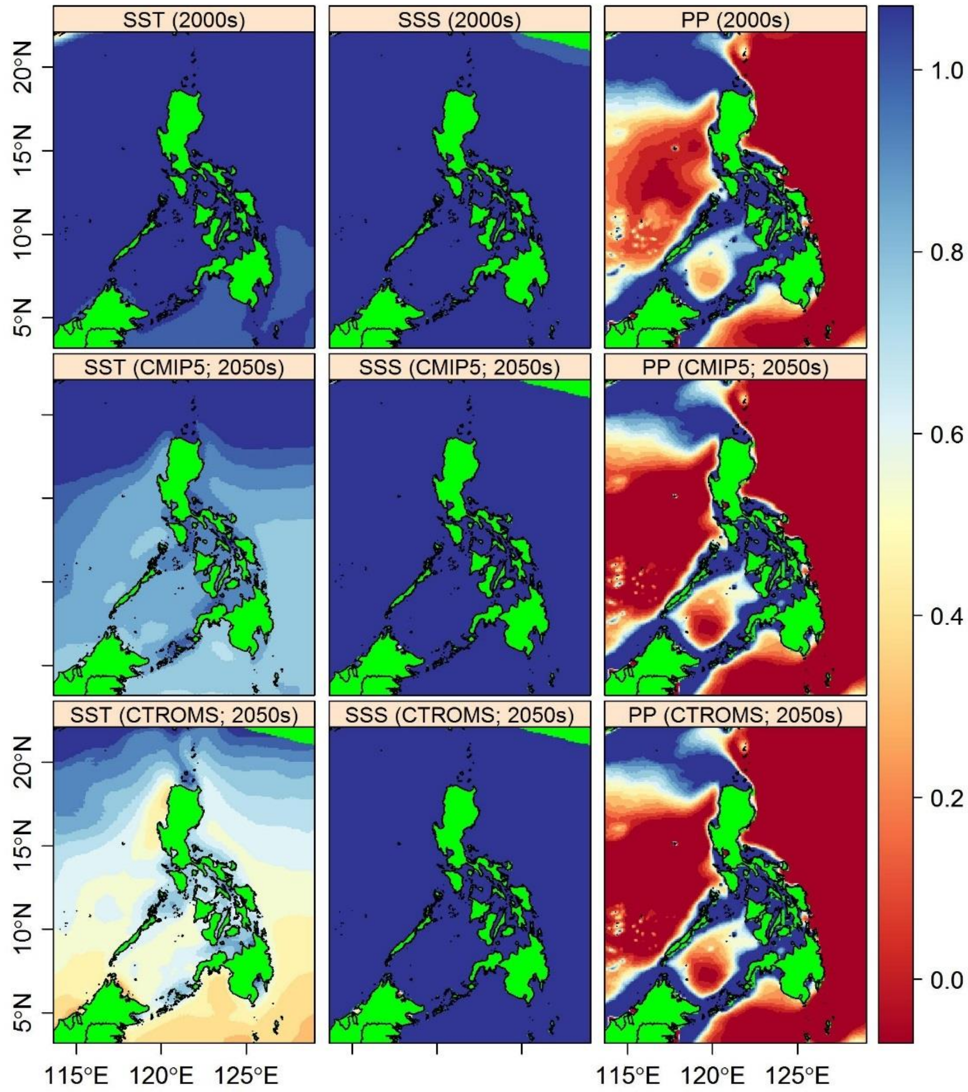
Short mackerel (*"Buraw"*)



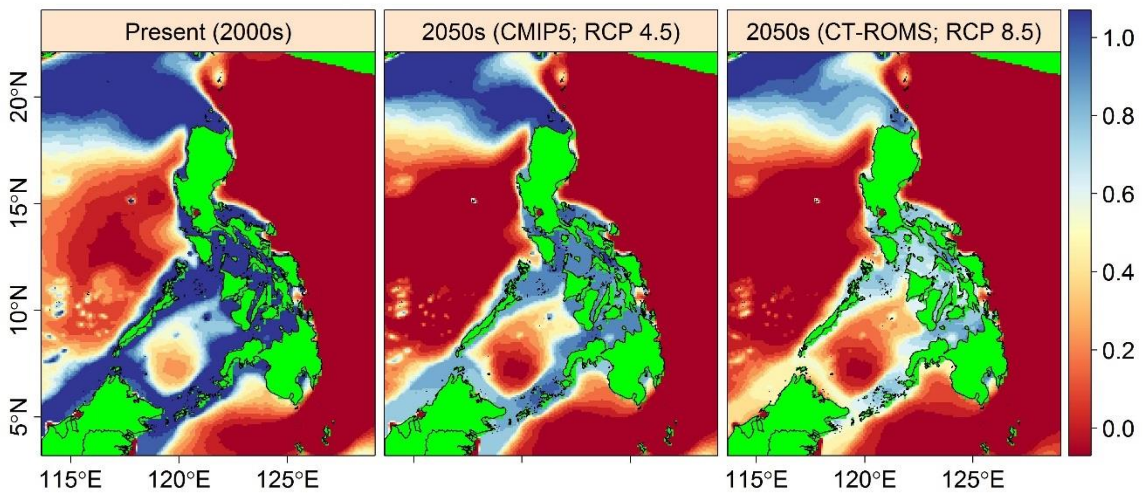


Rastrelliger faughni
Island mackerel (*"Buraw"*)

Probability of occurrence for *Rastrelliger faughni* by variable



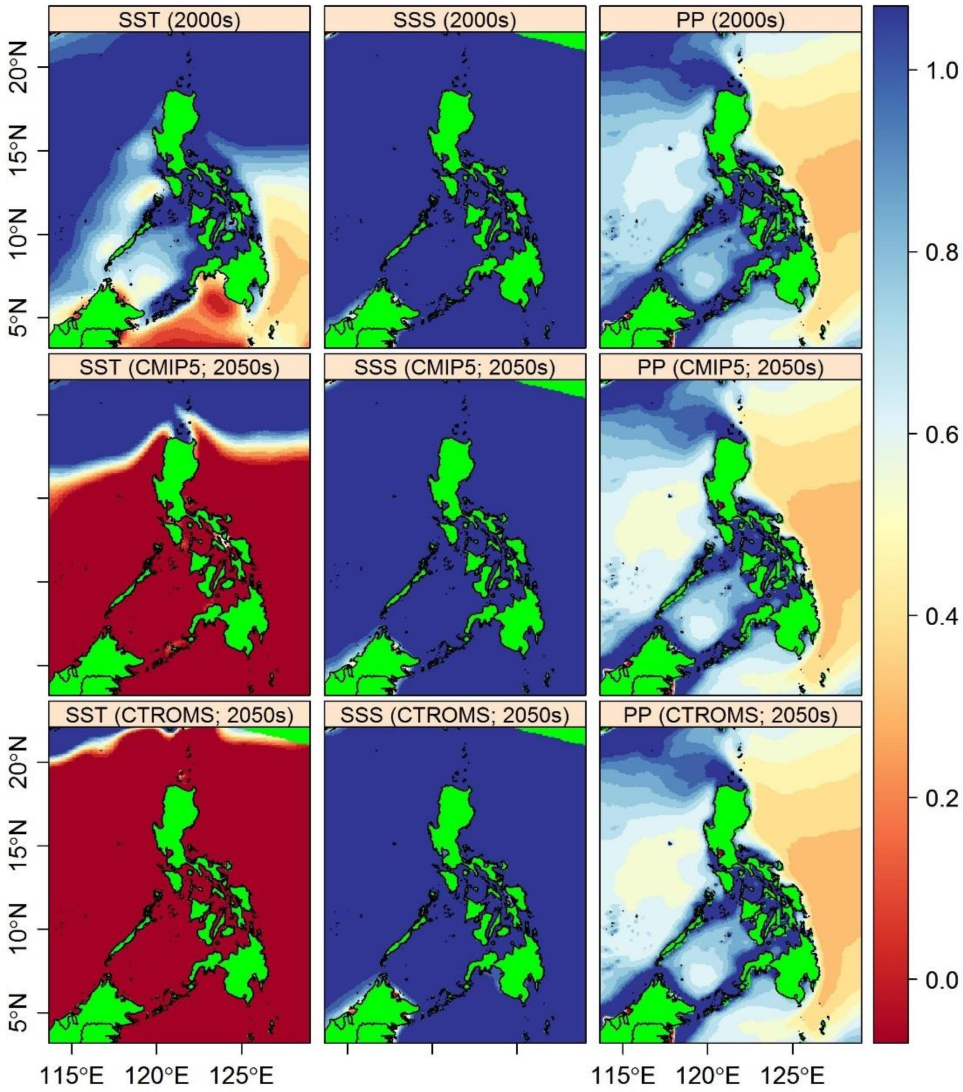
Projected Suitable Habitat for *Rastrelliger faughni*



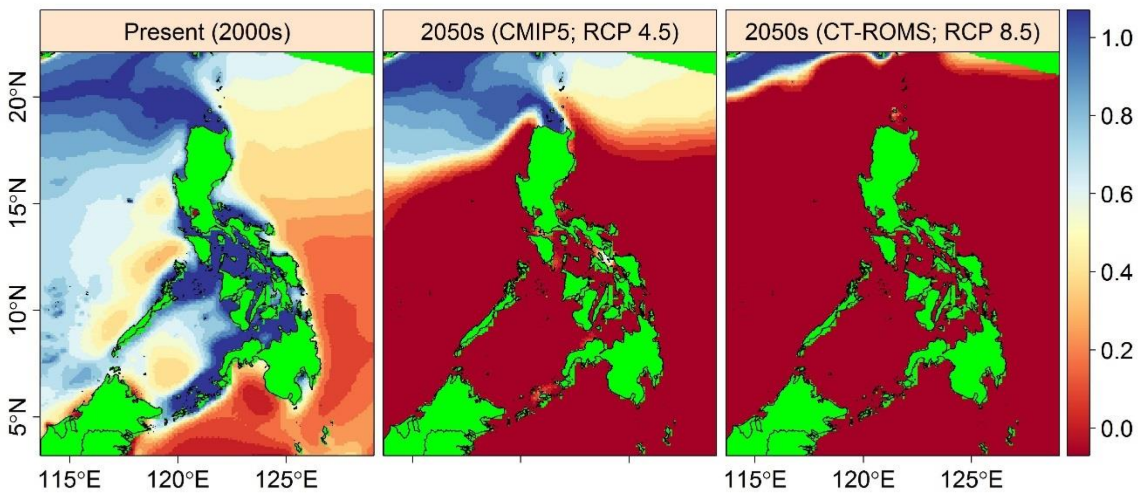
Rastrelliger kanagurta

Indian mackerel (*"Alumahan"*)

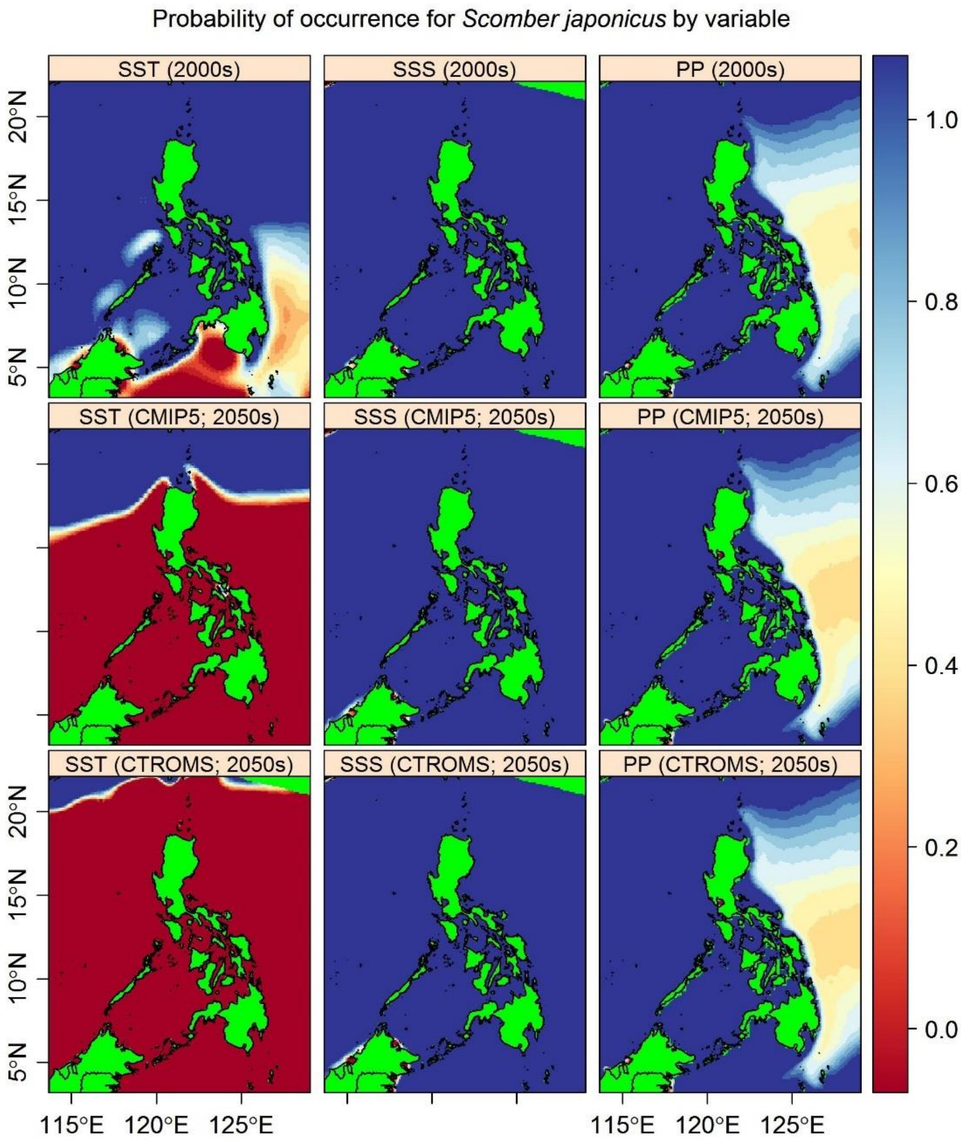
Probability of occurrence for *Rastrelliger kanagurta* by variable

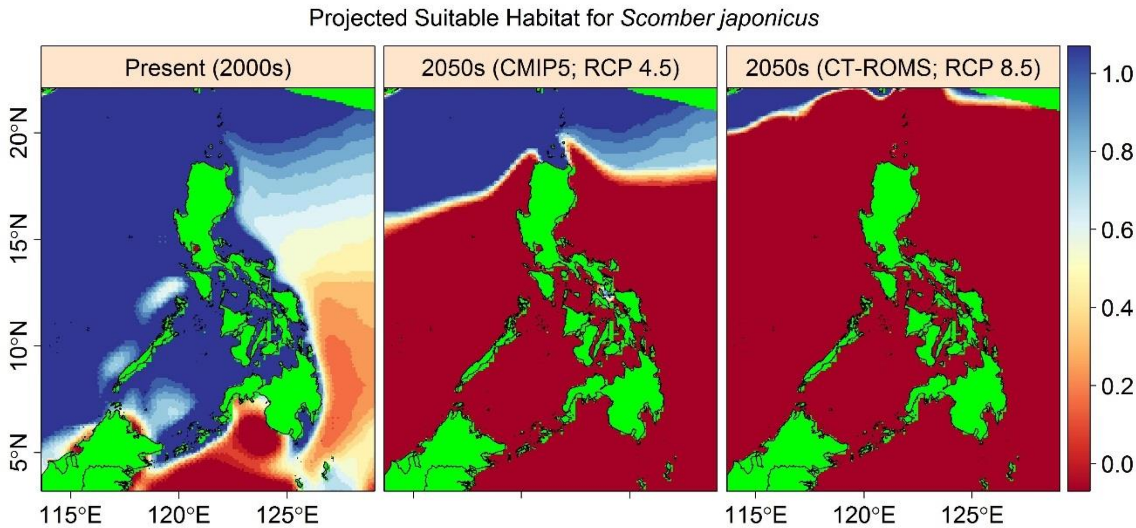


Projected Suitable Habitat for *Rastrelliger kanagurta*

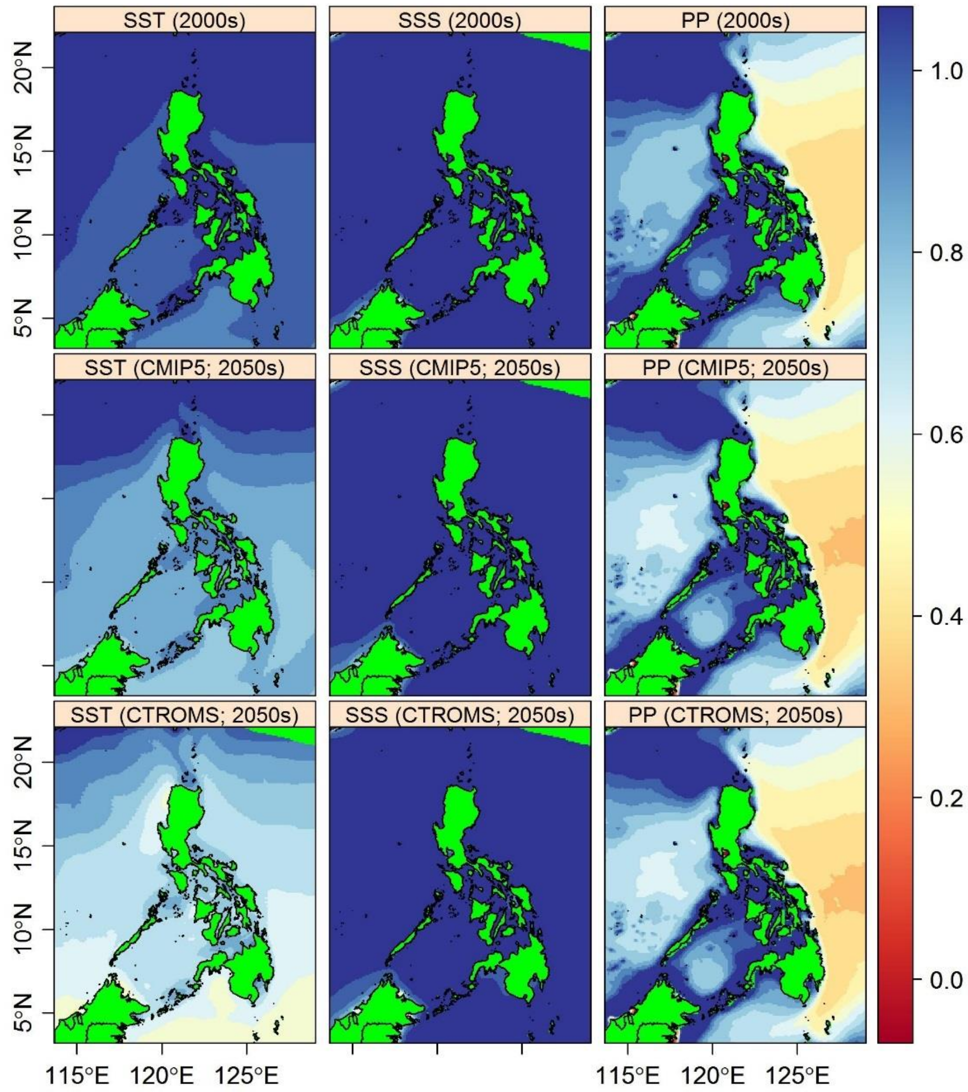


Scomber japonicus
Chub mackerel (*"Tangigue"*)

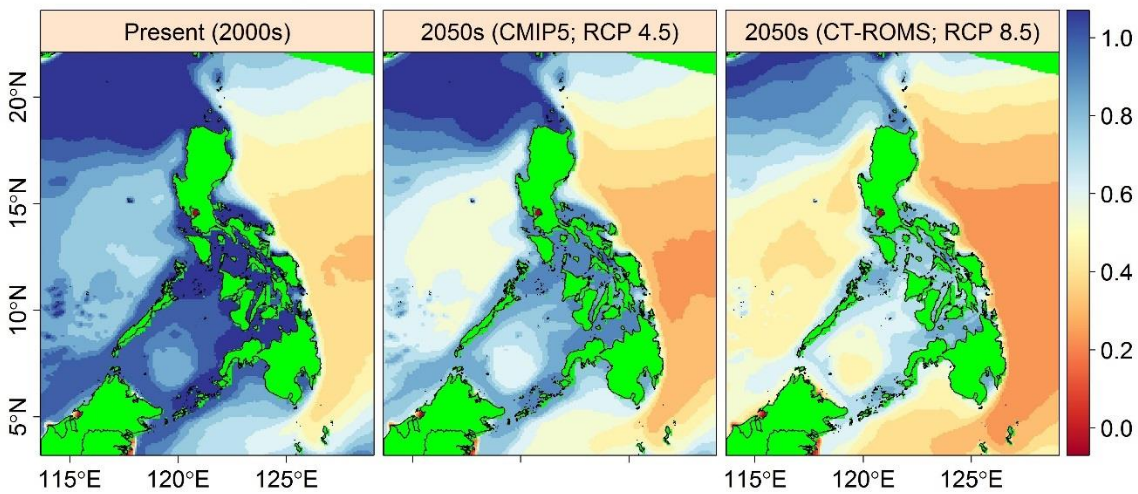




Probability of occurrence for *Scomberomorus commerson* by variable



Projected Suitable Habitat for *Scomberomorus commerson*

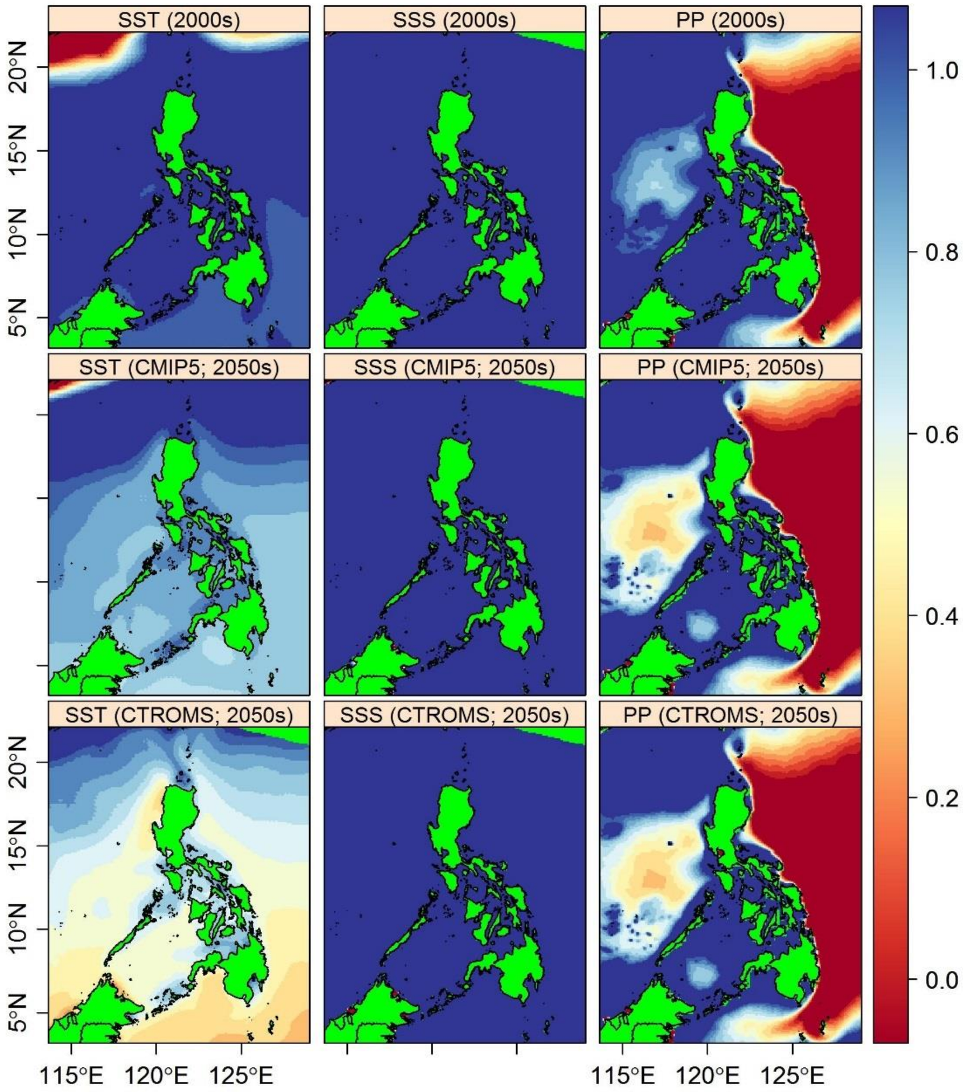


Amblygaster clupeoides

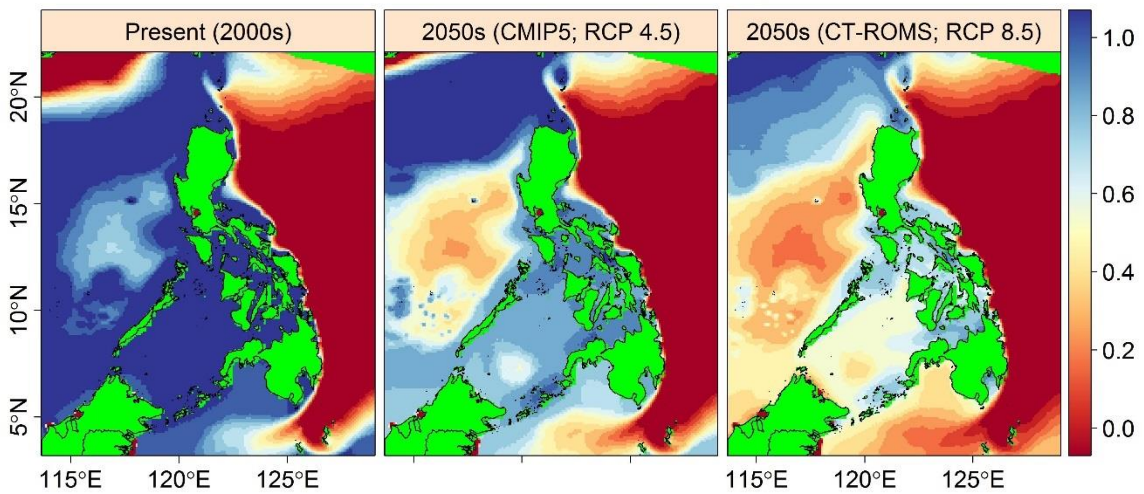
Bleeker smoothbelly sardinella (*"Turay"*)

SARDINES

Probability of occurrence for *Amblygaster clupeoides* by variable



Projected Suitable Habitat for *Amblygaster clupeoides*

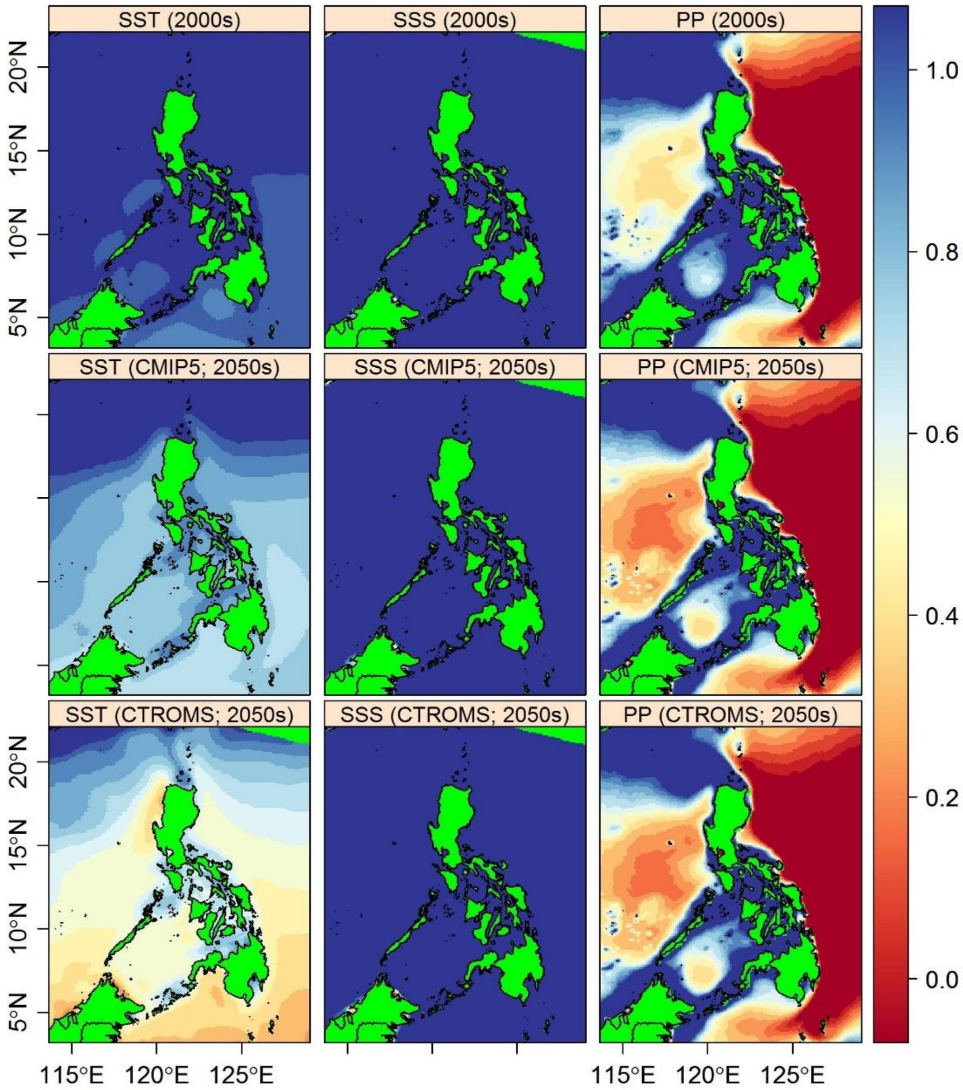


Amblygaster leiogaster

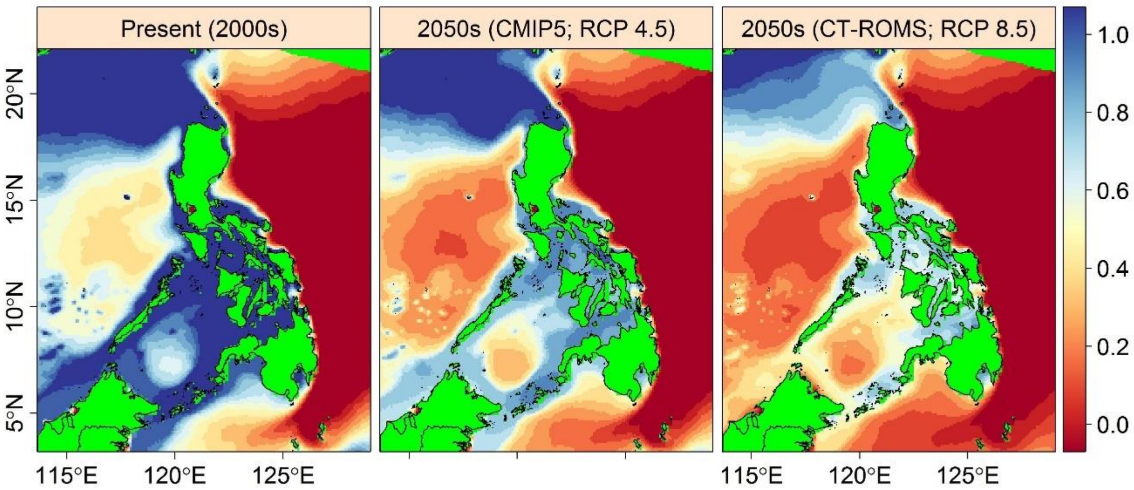
Smoothbelly sardinella (*"Tamban"*)

SARDINES

Probability of occurrence for *Amblygaster leiogaster* by variable



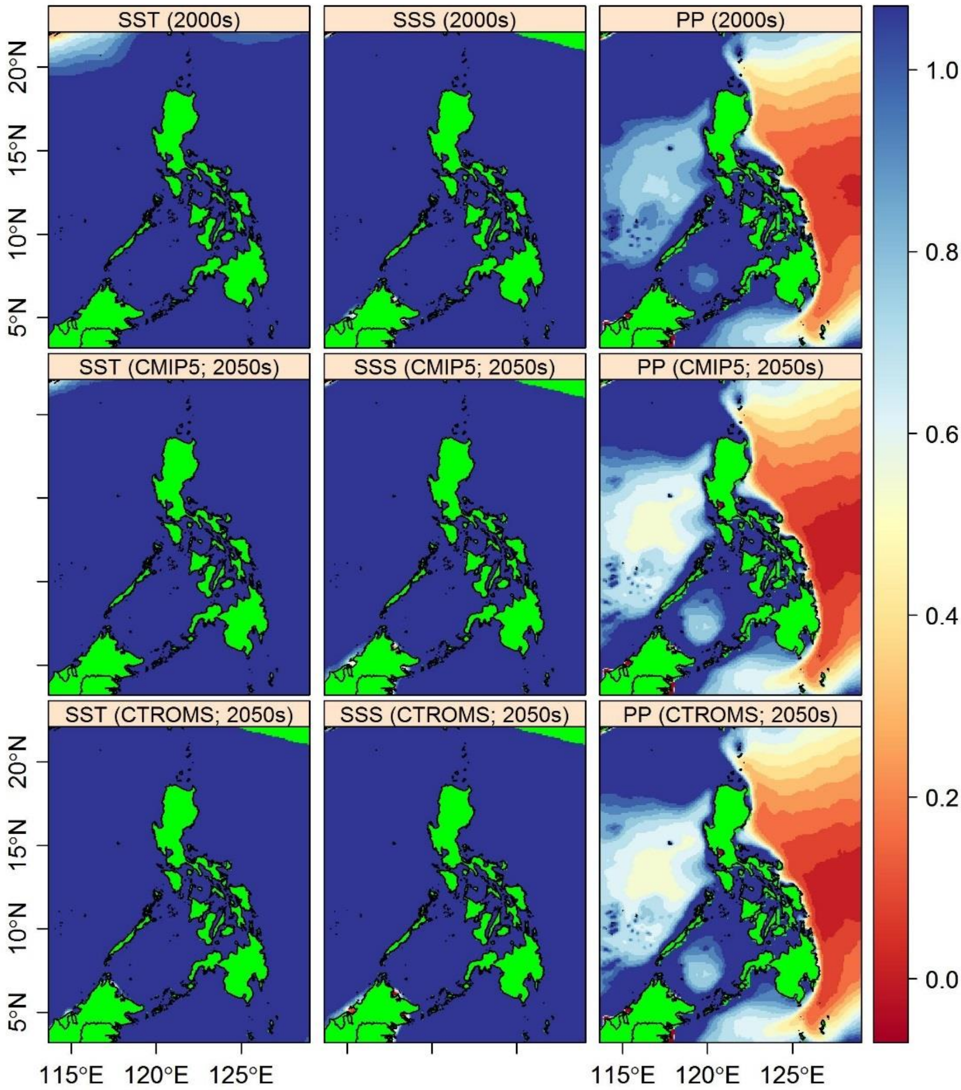
Projected Suitable Habitat for *Amblygaster leiogaster*



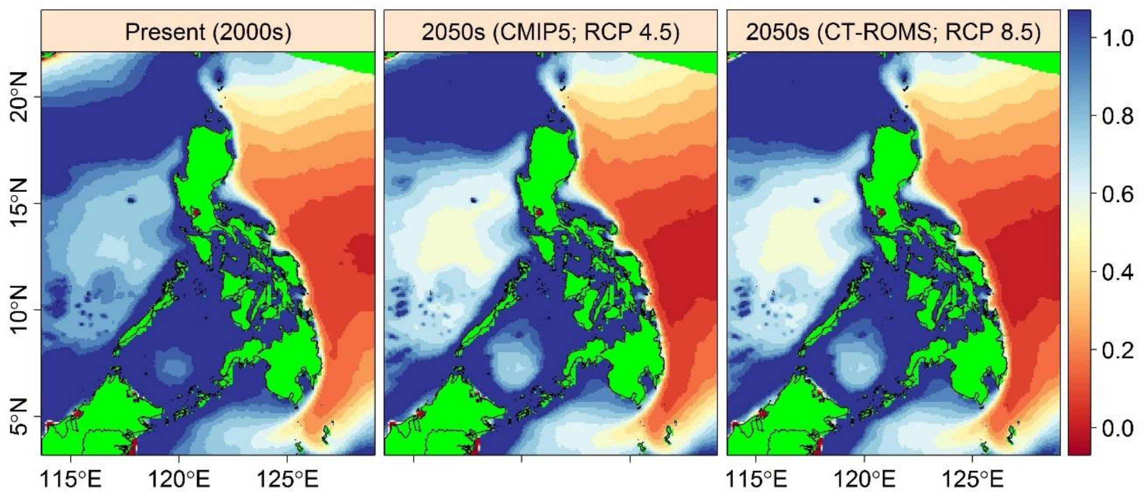
Amblygaster sirm

Spotted sardinella (*"Tamban"*)

Probability of occurrence for *Amblygaster sirm* by variable



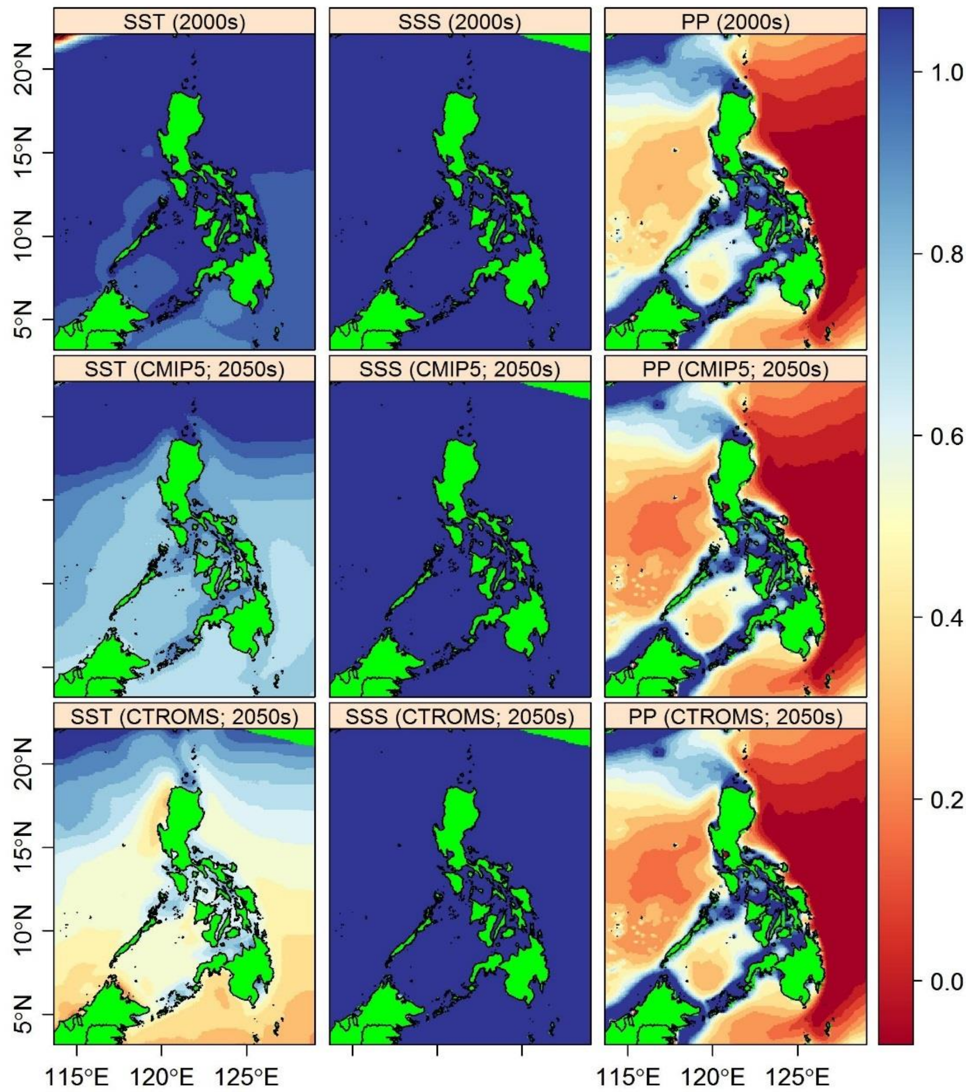
Projected Suitable Habitat for *Amblygaster sirm*



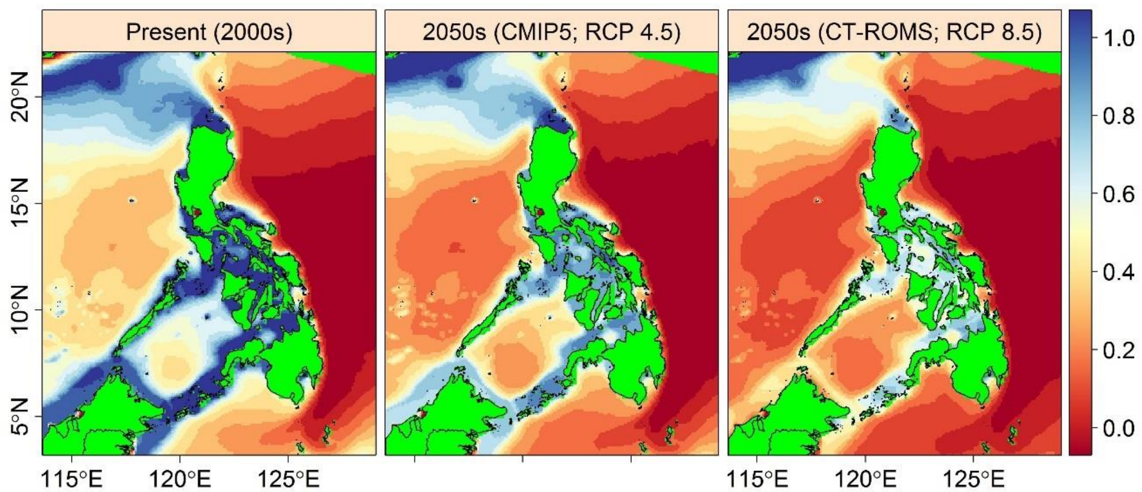
Escualosa thoracata

White sardine (*"Silag"*)

Probability of occurrence for *Escualosa thoracata* by variable

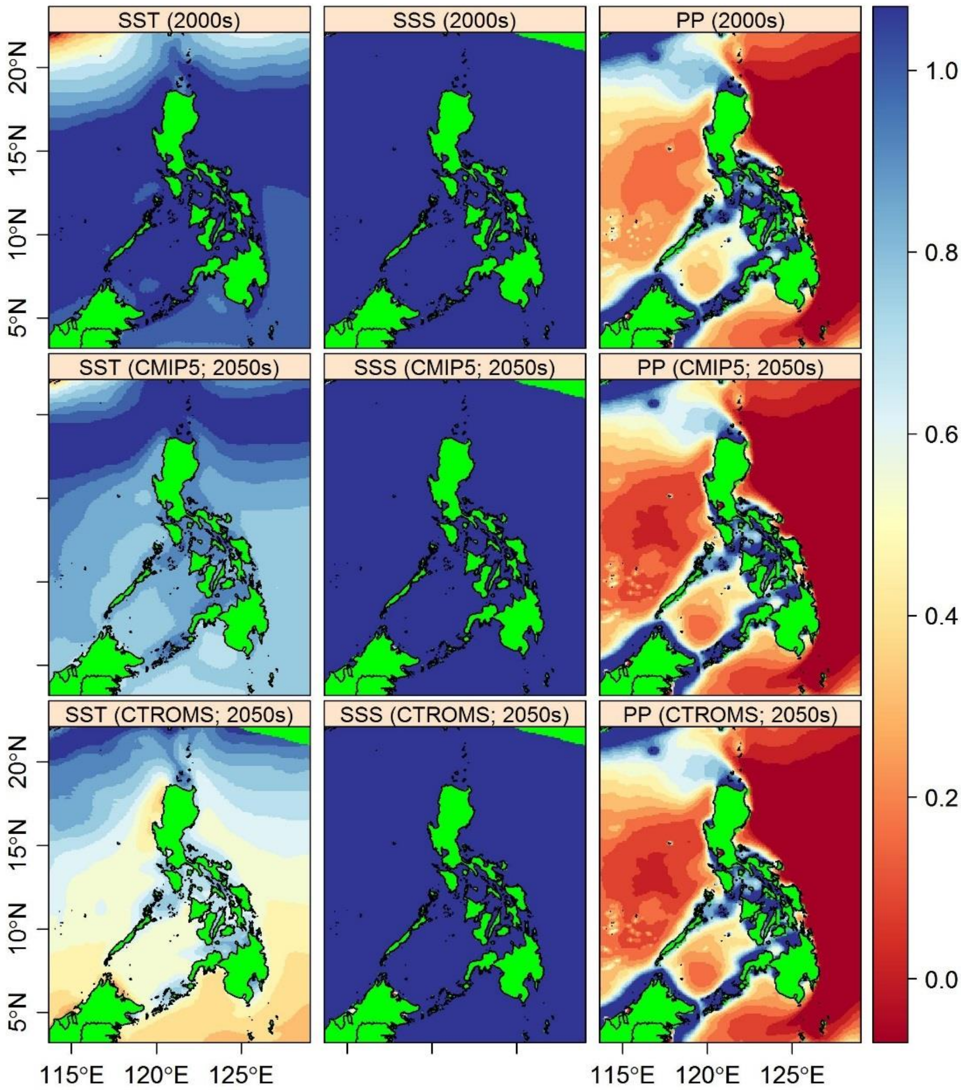


Projected Suitable Habitat for *Escualosa thoracata*

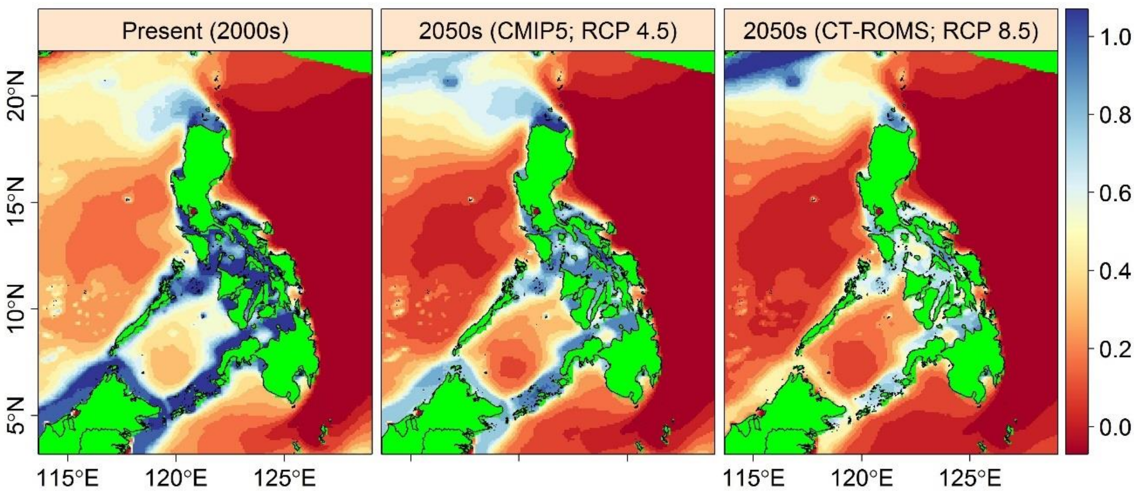


Sardinella fimbriata
Fingerscale sardinella (*"Tamban"*)

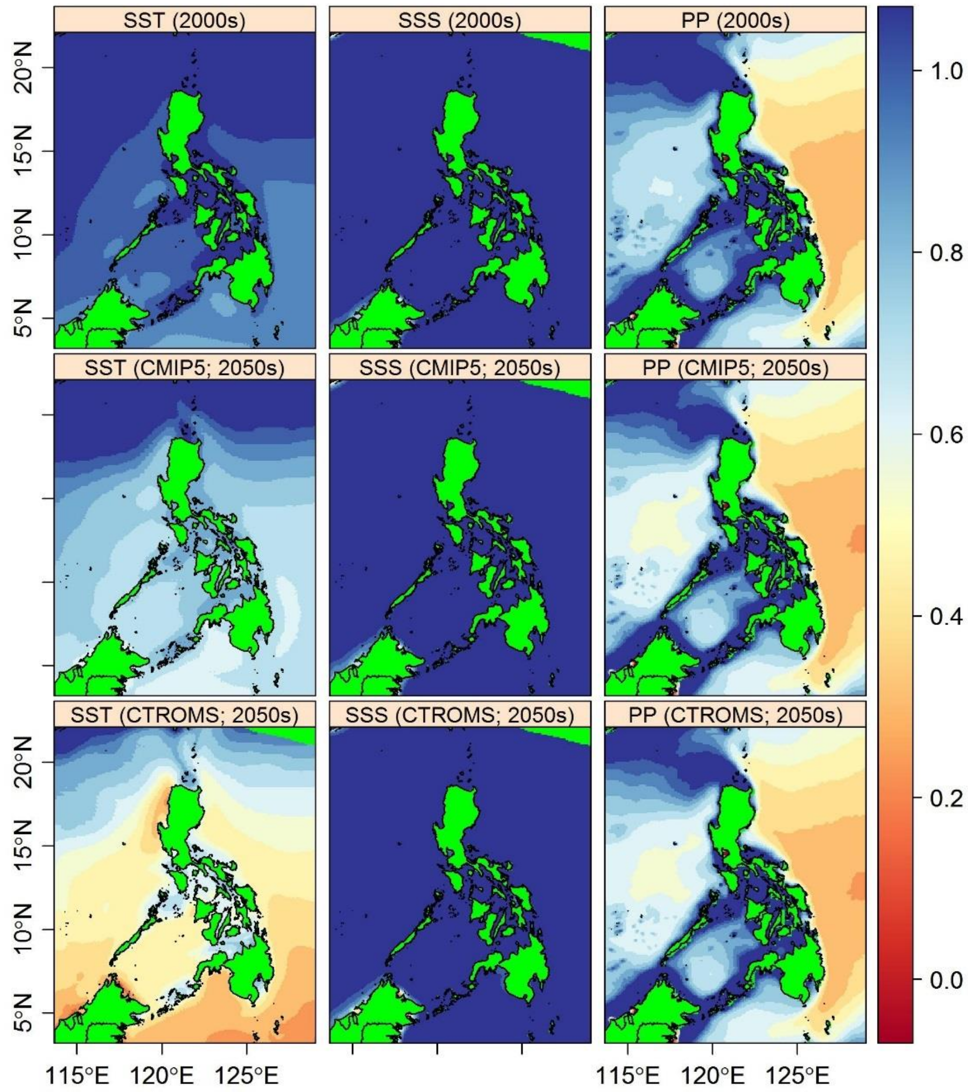
Probability of occurrence for *Sardinella fimbriata* by variable



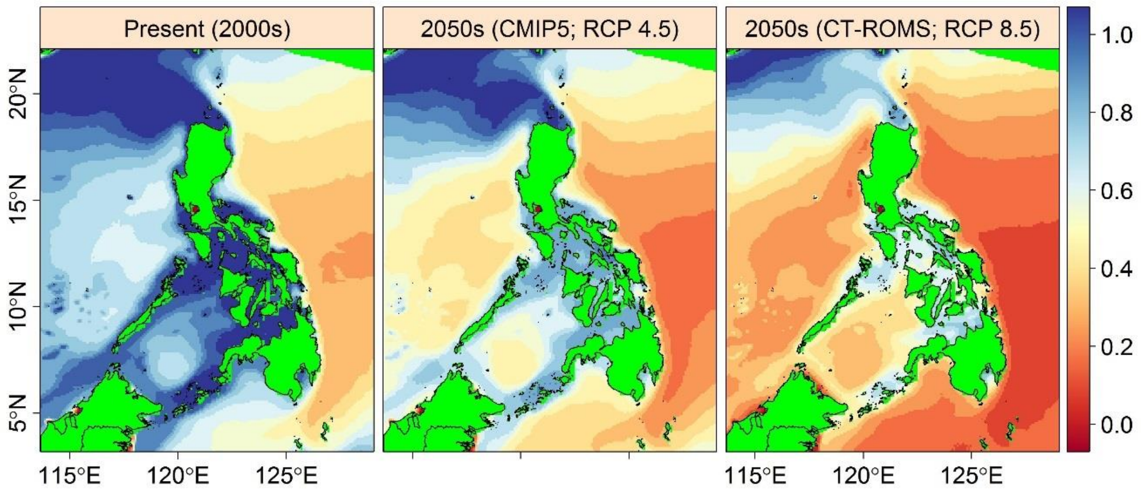
Projected Suitable Habitat for *Sardinella fimbriata*



Probability of occurrence for *Sardinella gibbosa* by variable



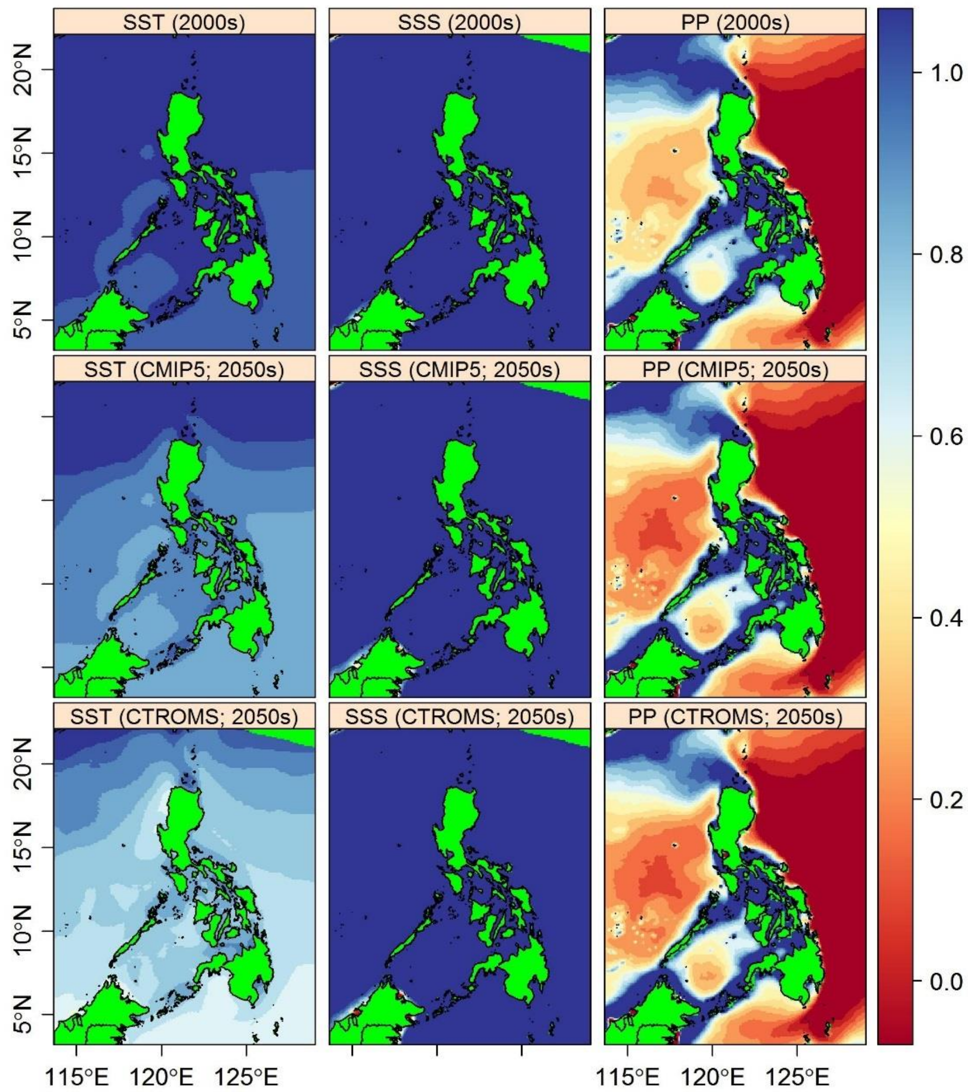
Projected Suitable Habitat for *Sardinella gibbosa*



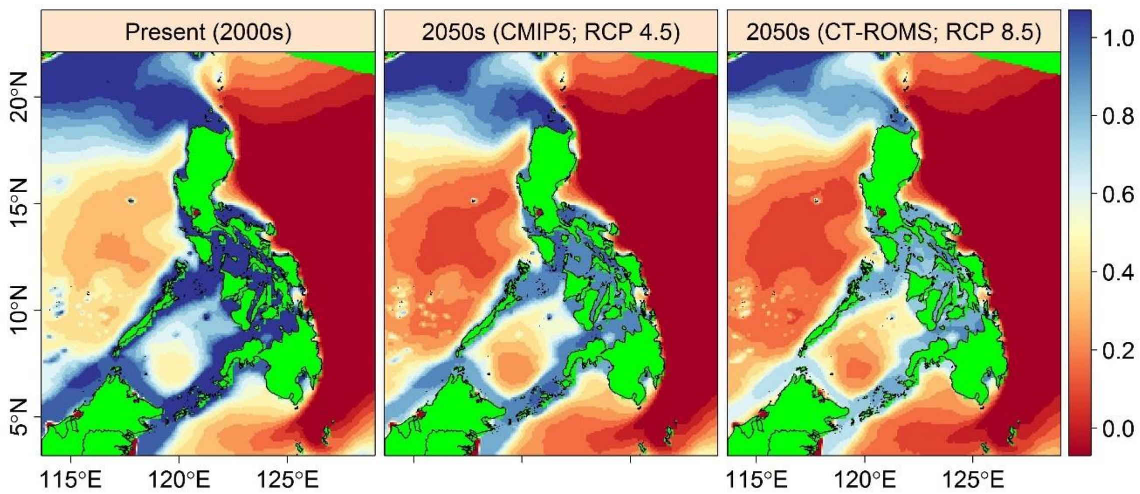
Sardinella lemuru
Bali sardinella (*"Tamban"*)

SARDINES

Probability of occurrence for *Sardinella lemuru* by variable

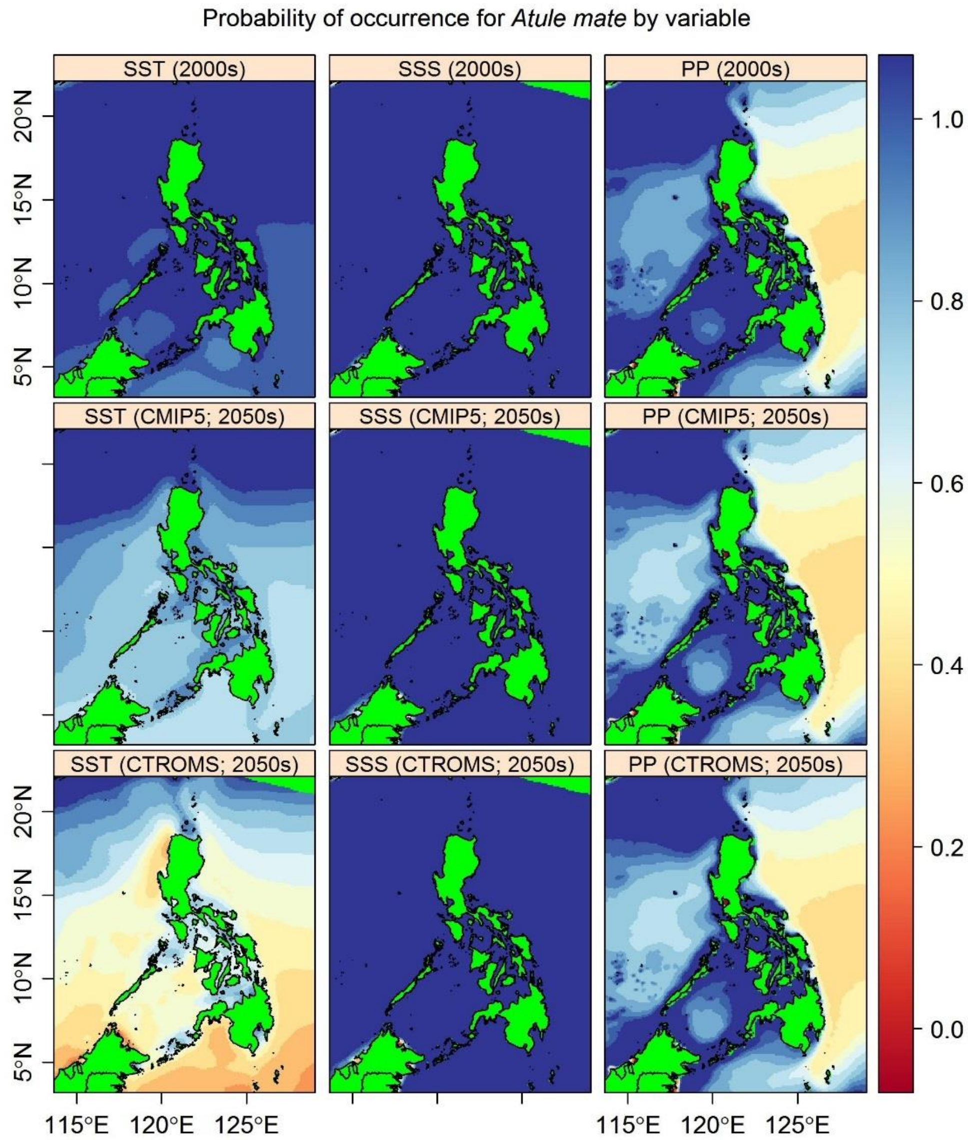


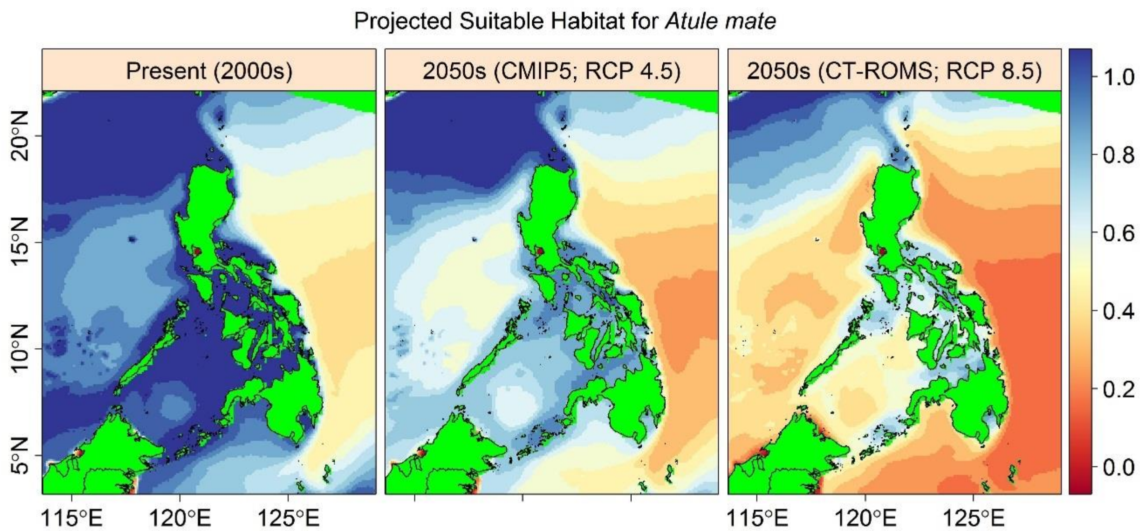
Projected Suitable Habitat for *Sardinella lemuru*



Atule mate

Yellowtail scad (*"Gutob"*)

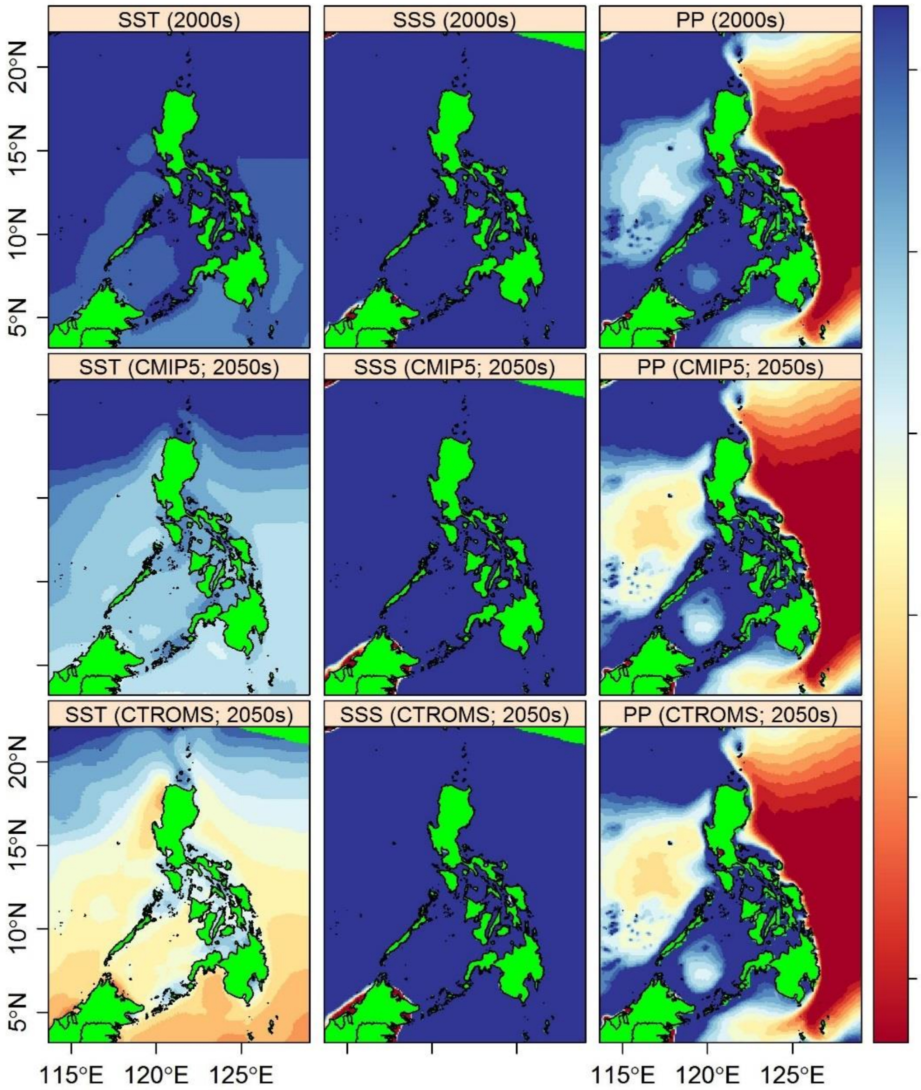




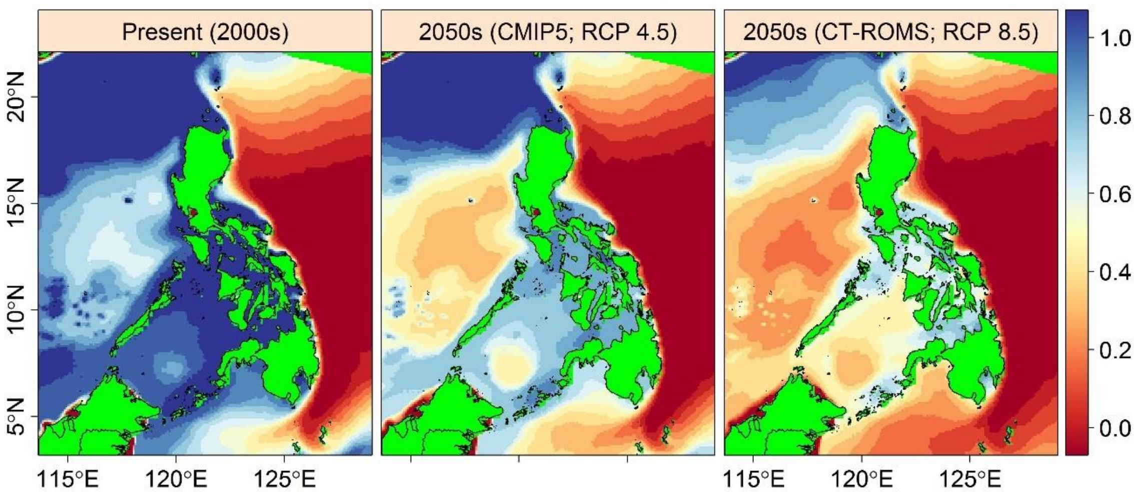
Decapterus kurroides

Redtail scad (*"Galunggong"*)

Probability of occurrence for *Decapterus kurroides* by variable



Projected Suitable Habitat for *Decapterus kurroides*

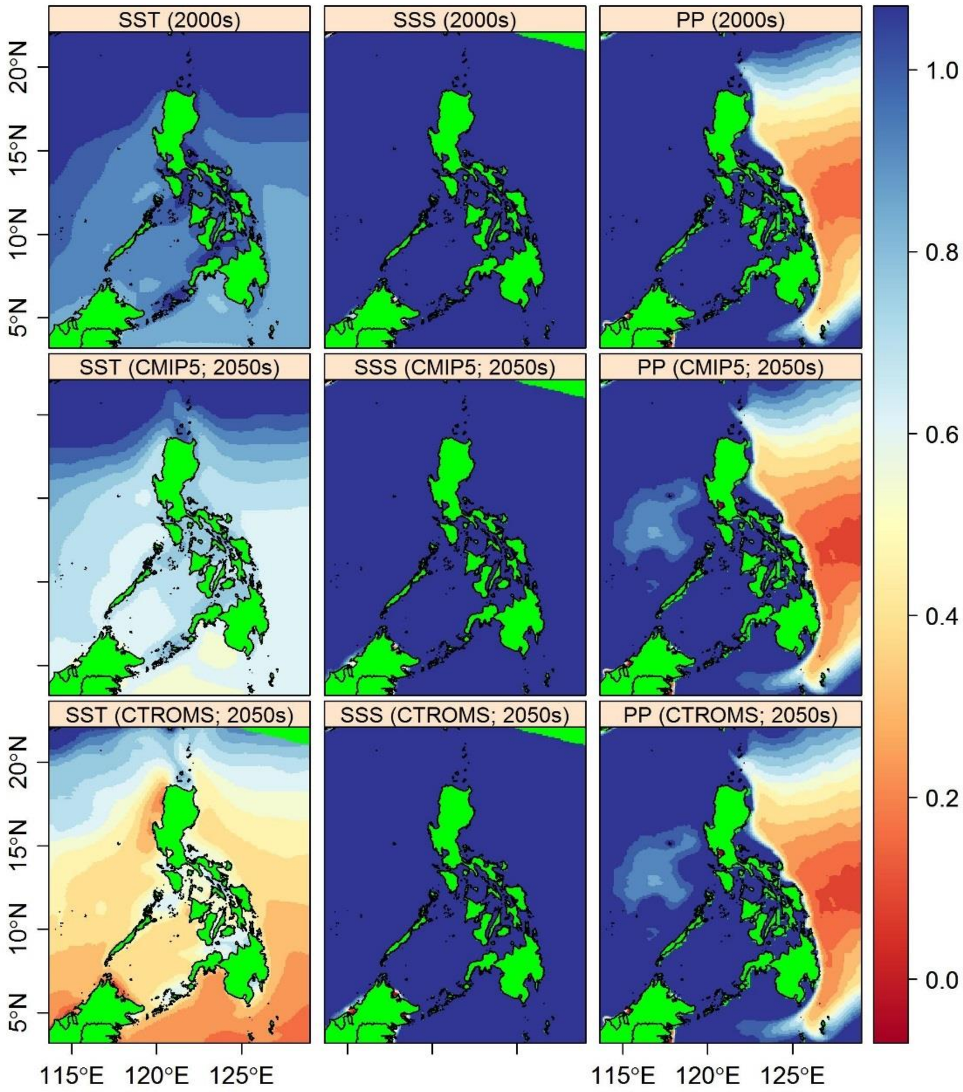


Decapterus macarellus

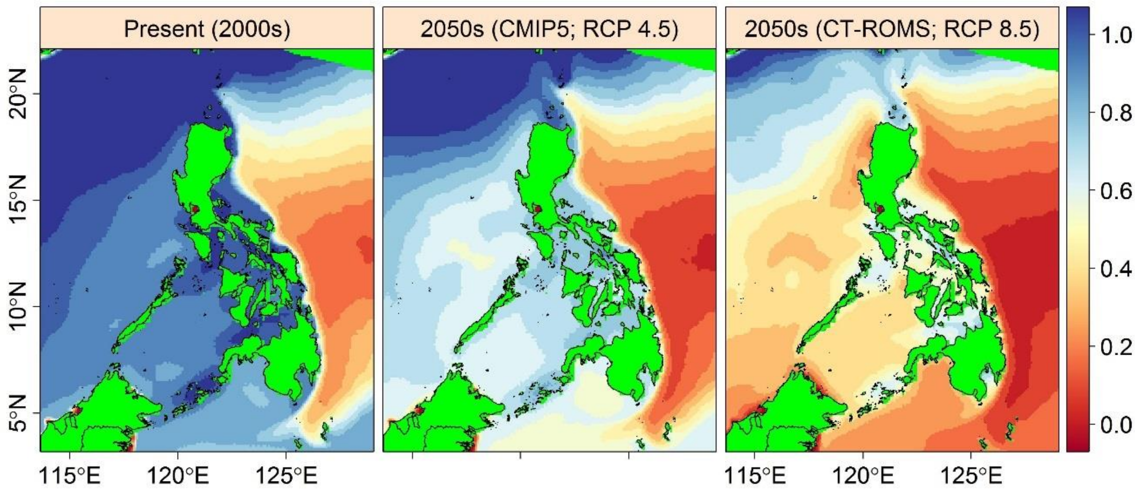
Mackerel scad (*"Galunggong"*)

SCADS

Probability of occurrence for *Decapterus macarellus* by variable



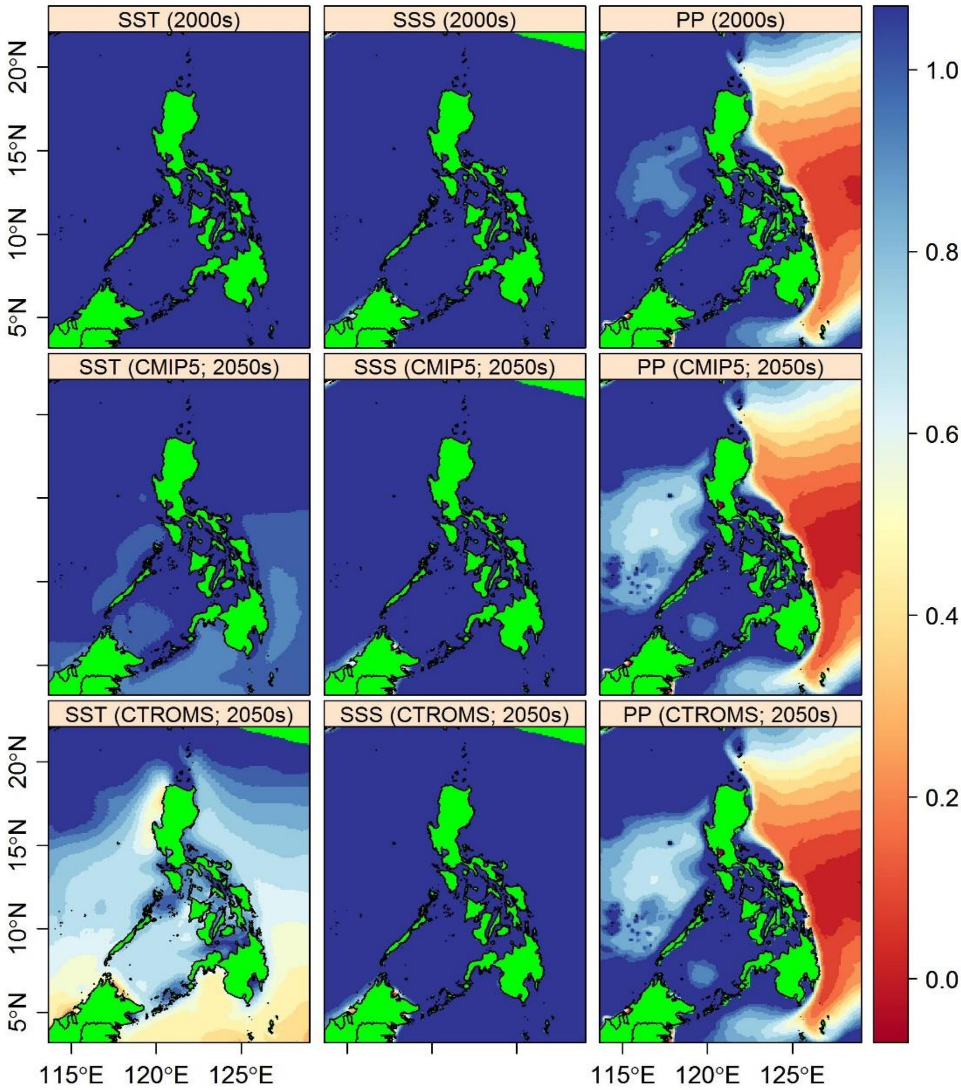
Projected Suitable Habitat for *Decapterus macarellus*



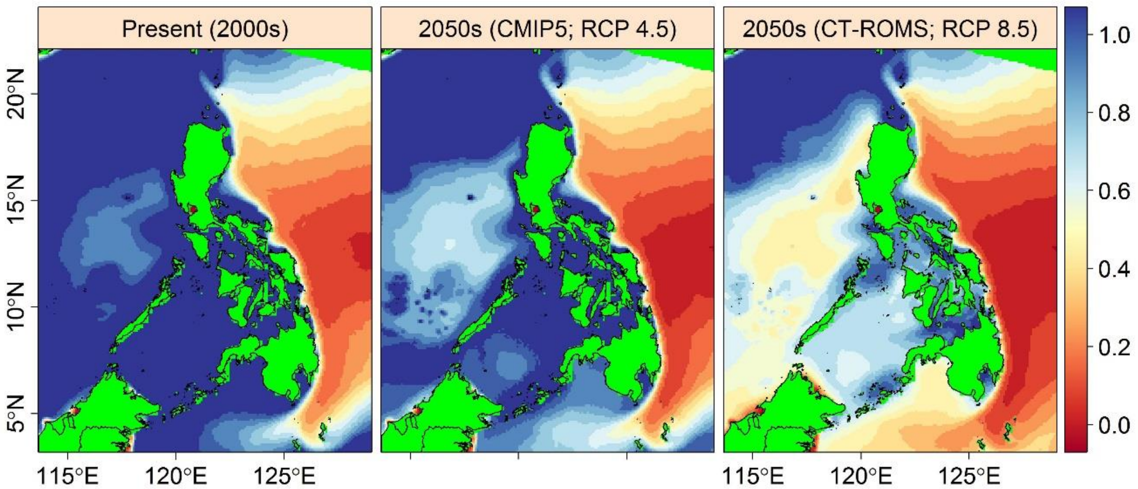
Decapterus macrosoma

Shortfin scad (*"Galunggong"*)

Probability of occurrence for *Decapterus macrosoma* by variable



Projected Suitable Habitat for *Decapterus macrosoma*

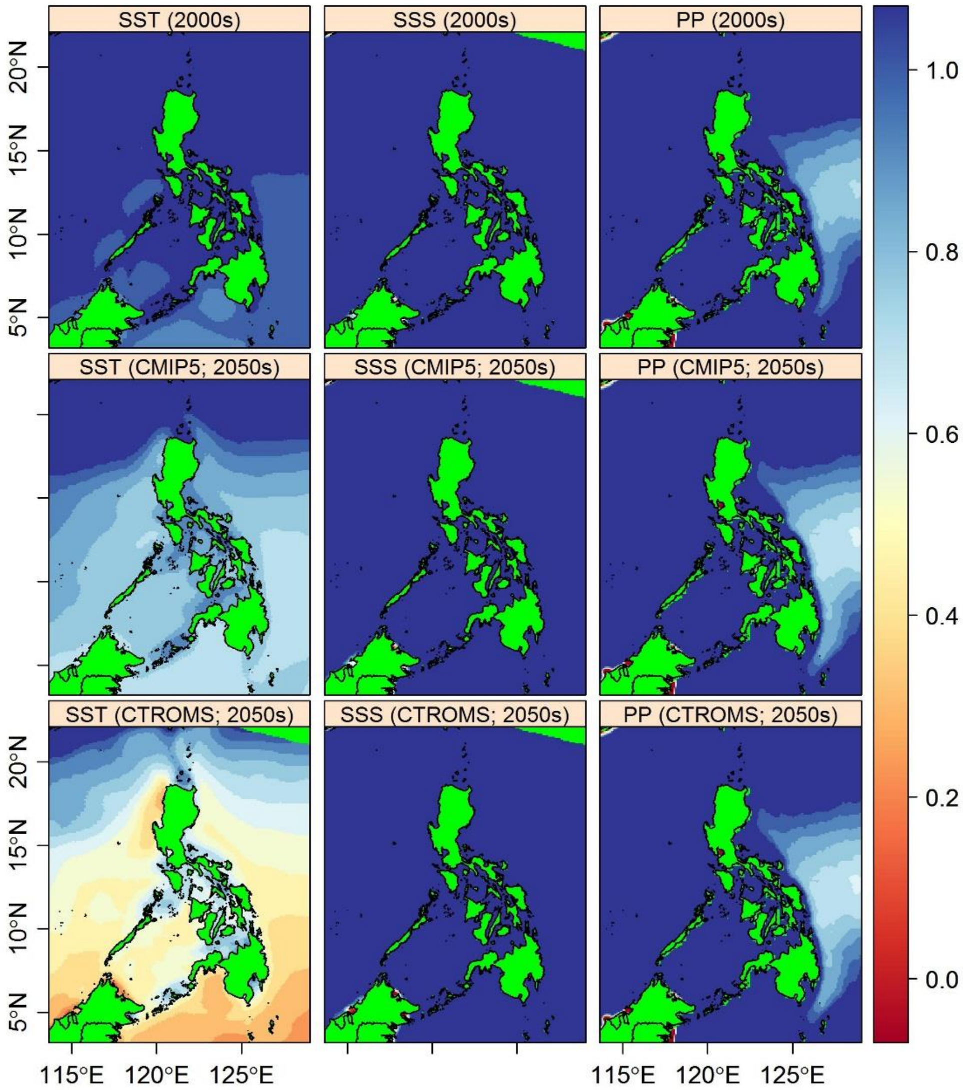


Decapterus maruadsi

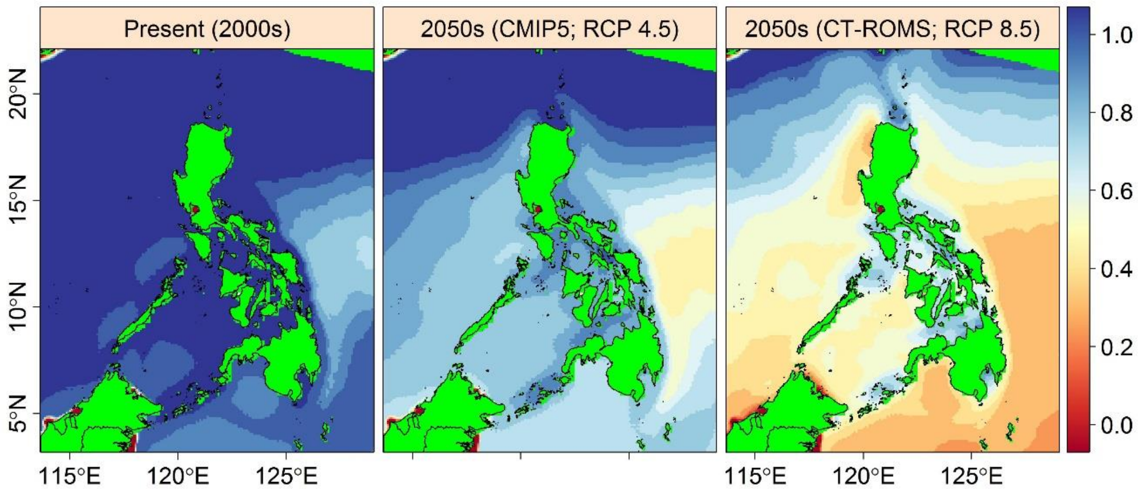
Japanese scad (*"Galunggong"*)

SCADS

Probability of occurrence for *Decapterus maruadsi* by variable

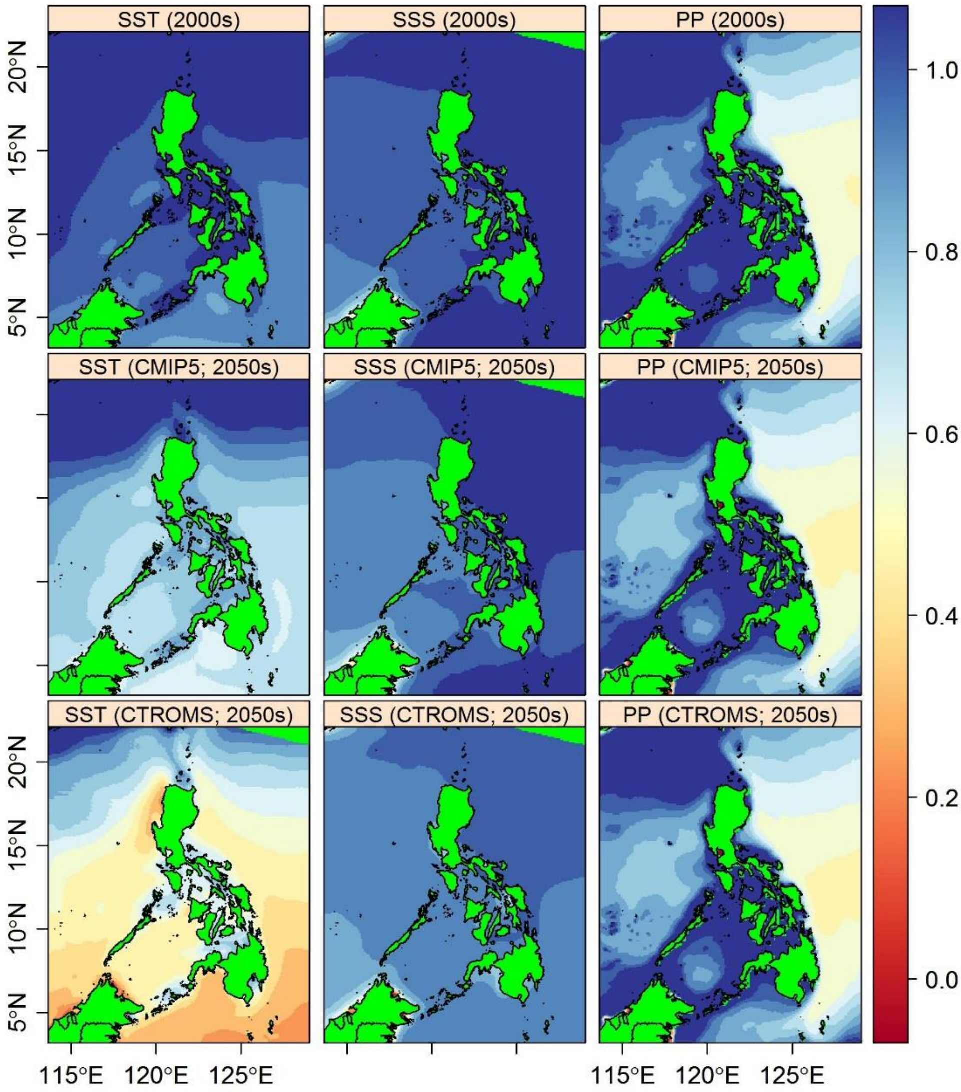


Projected Suitable Habitat for *Decapterus maruadsi*

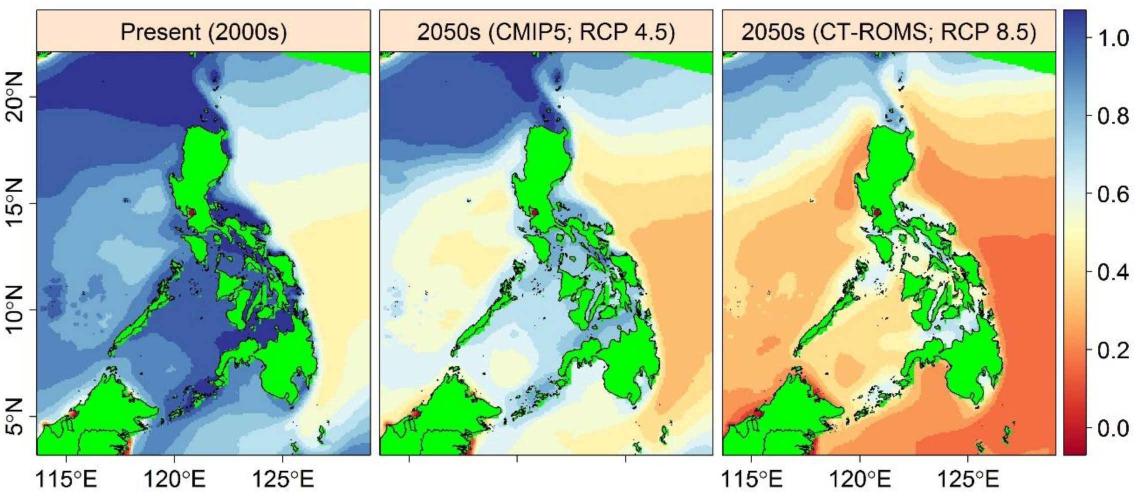


Decapterus russelli
Indian scad (*"Galunggong"*)

Probability of occurrence for *Decapterus russelli* by variable



Projected Suitable Habitat for *Decapterus russelli*

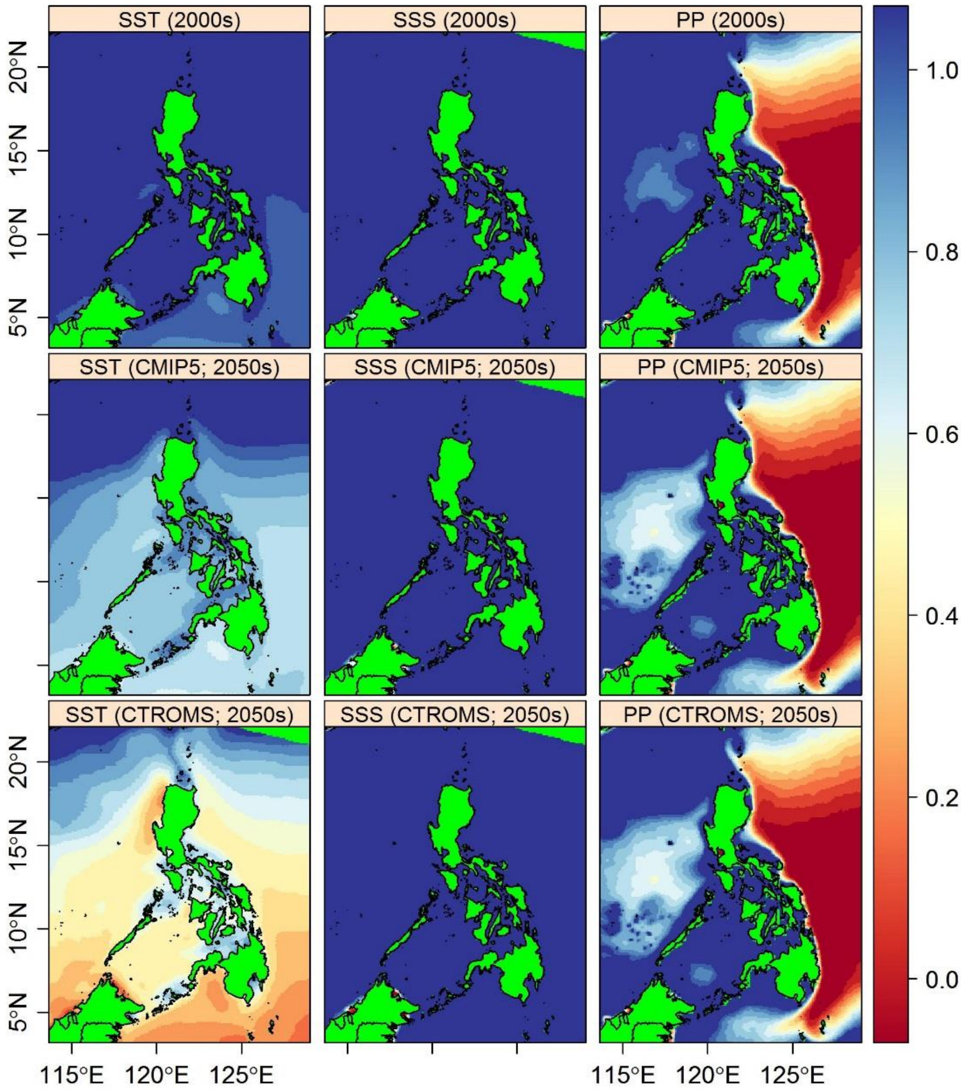


Decapterus tabl

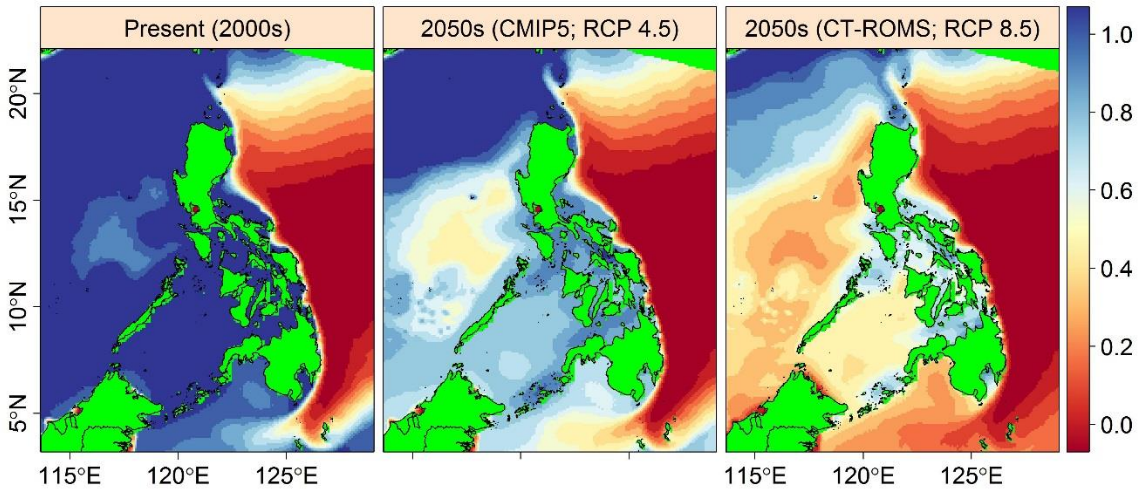
Roughear scad (*"Galunggong"*)

SCADS

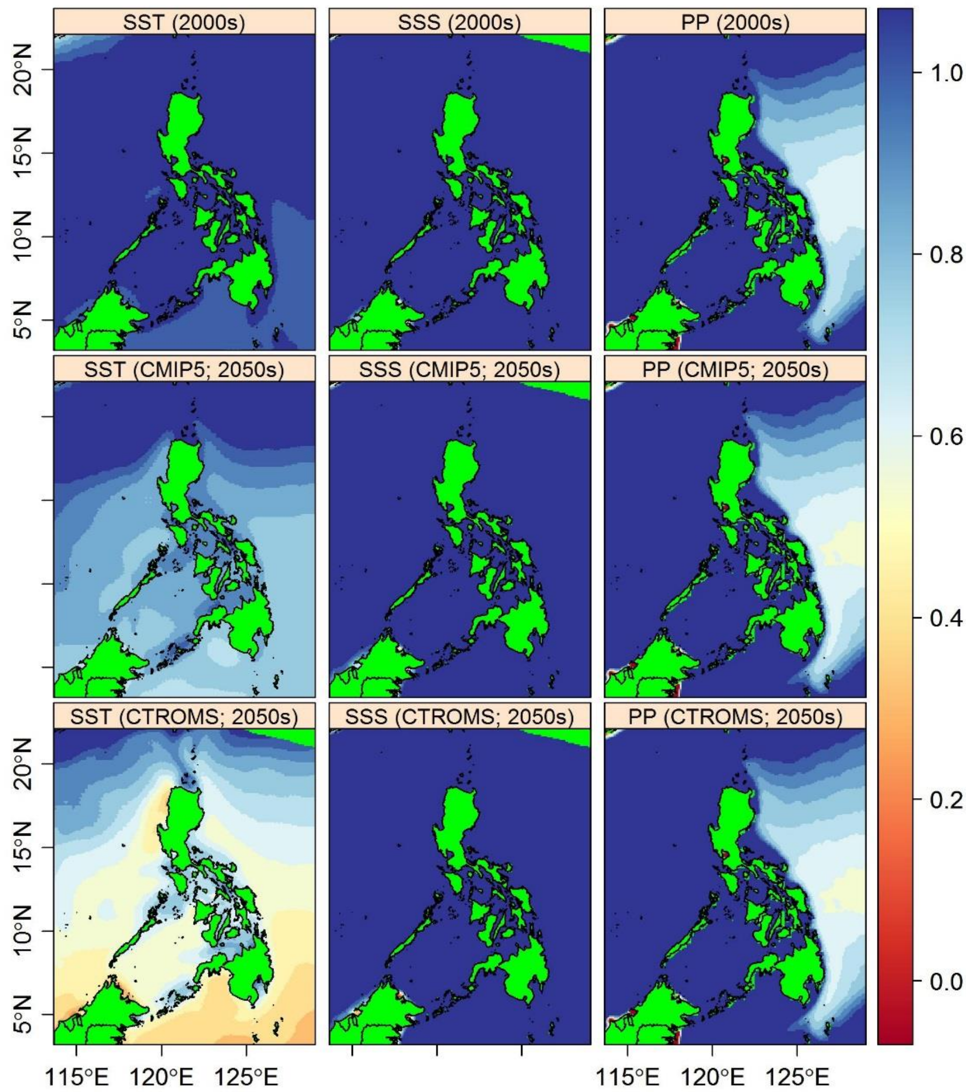
Probability of occurrence for *Decapterus tabl* by variable



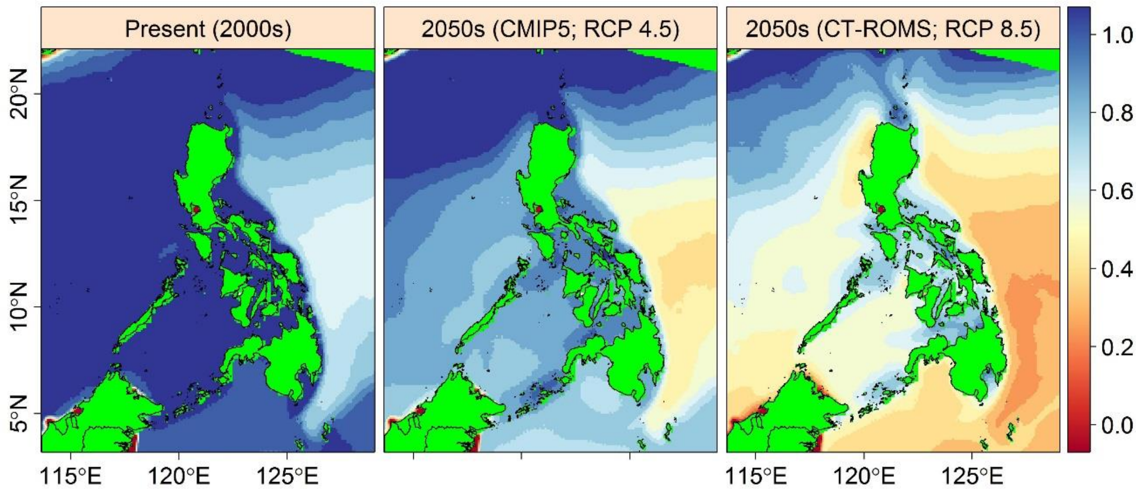
Projected Suitable Habitat for *Decapterus tabl*



Probability of occurrence for *Selar boops* by variable



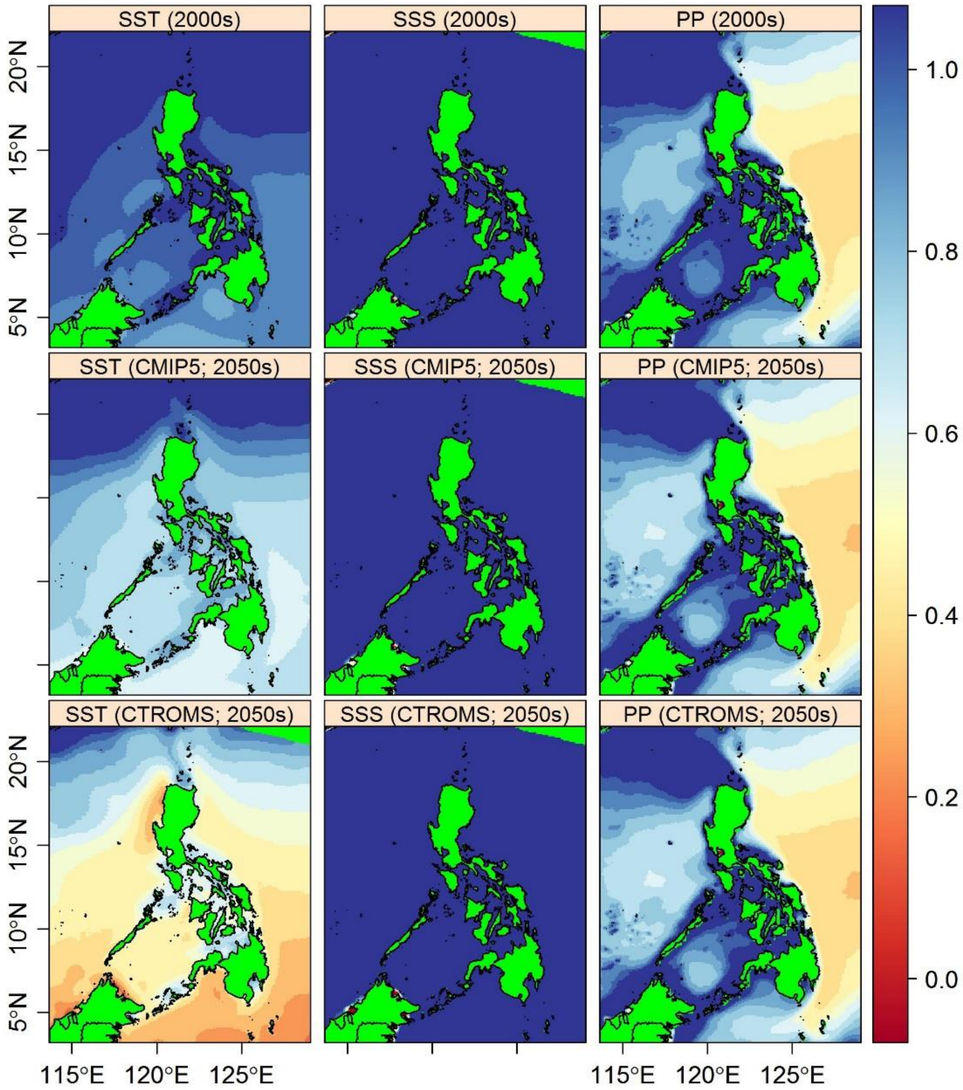
Projected Suitable Habitat for *Selar boops*



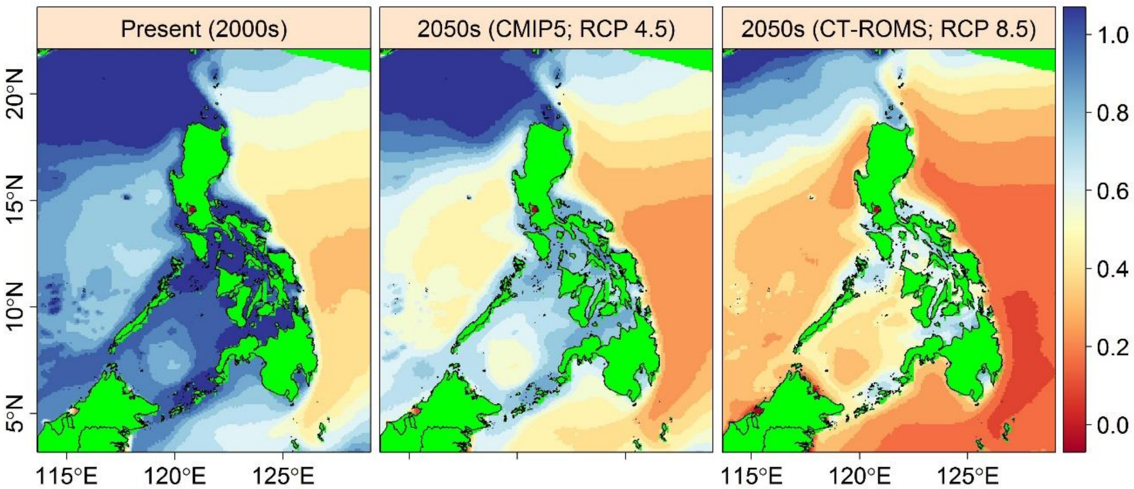
Selar crumenophthalmus
Bigeye scad (*“Matangbaka”*)

SCADS

Probability of occurrence for *Selar crumenophthalmus* by variable



Projected Suitable Habitat for *Selar crumenophthalmus*

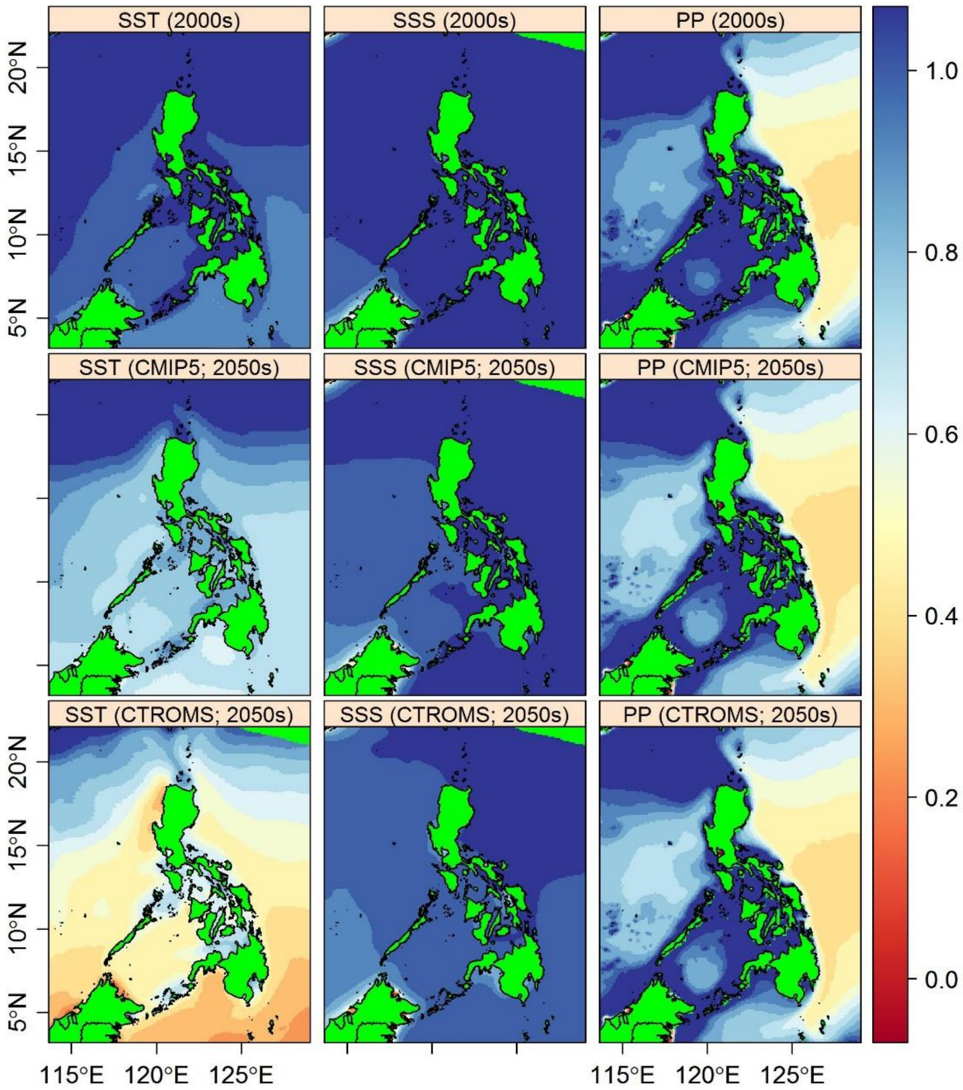


Selaroides leptolepis

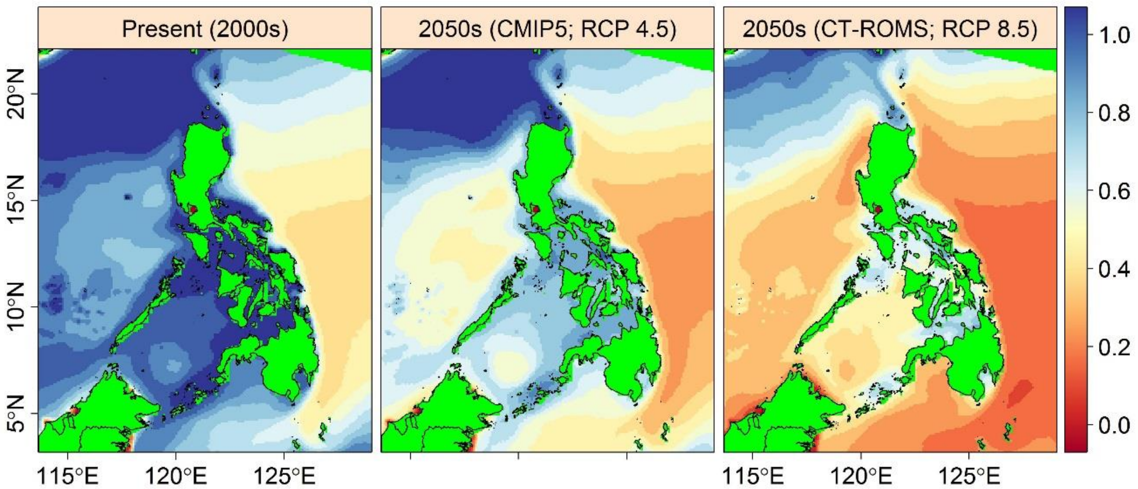
Yellowstripe scad (*"Salay-salay"*)

SCADS

Probability of occurrence for *Selaroides leptolepis* by variable



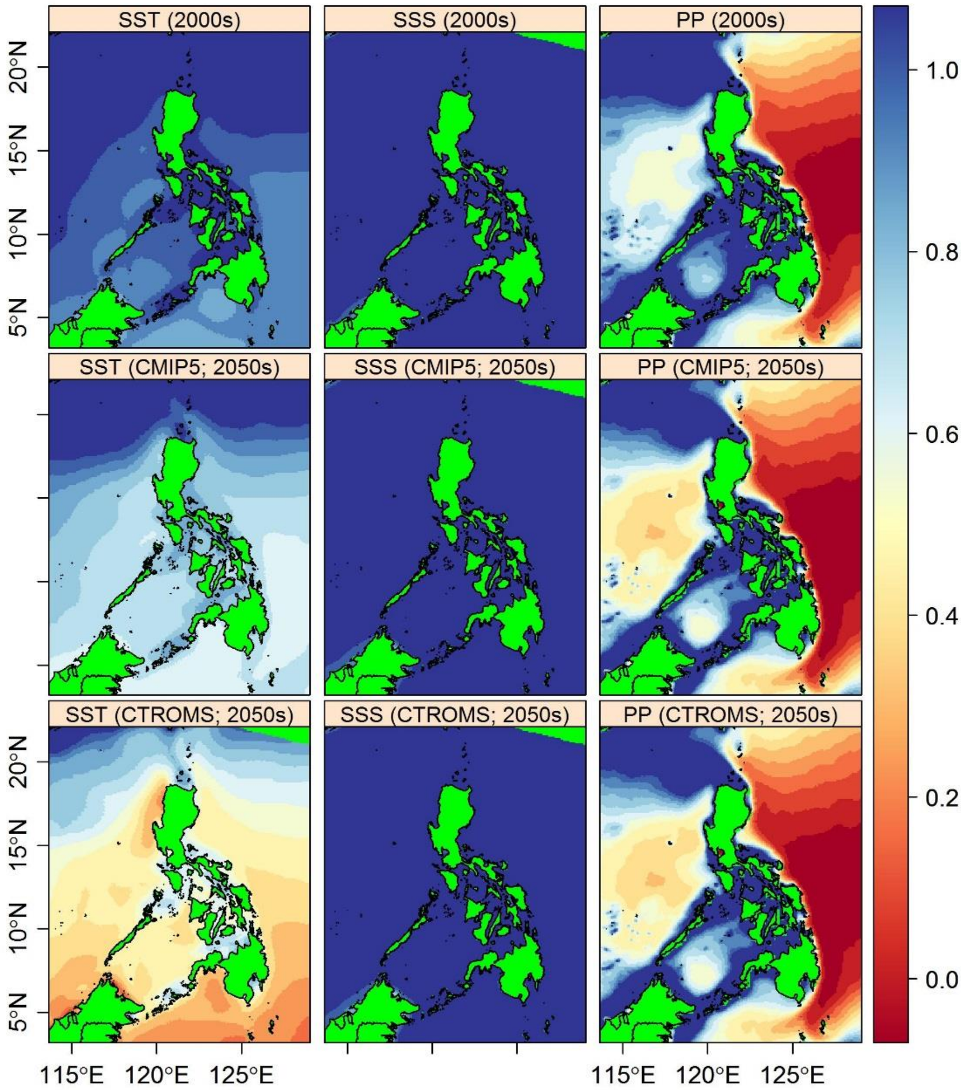
Projected Suitable Habitat for *Selaroides leptolepis*



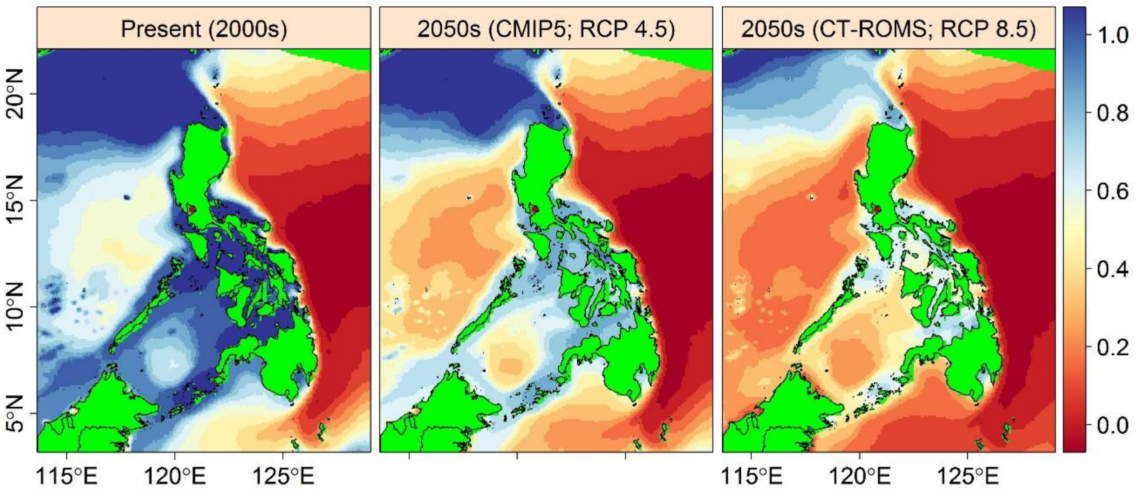
Auxis rochei

Bullet tuna (*"Tulingan"*) **TUNA**

Probability of occurrence for *Auxis rochei* by variable



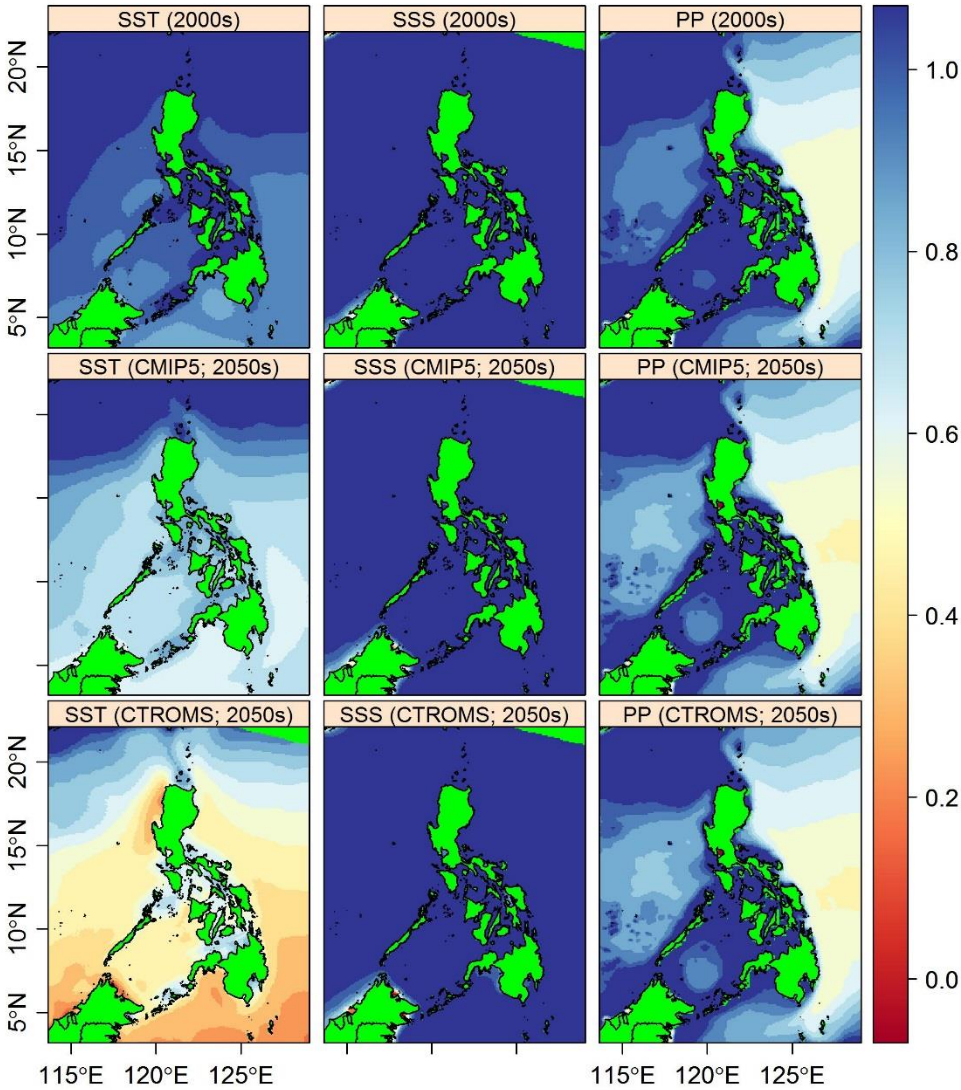
Projected Suitable Habitat for *Auxis rochei*



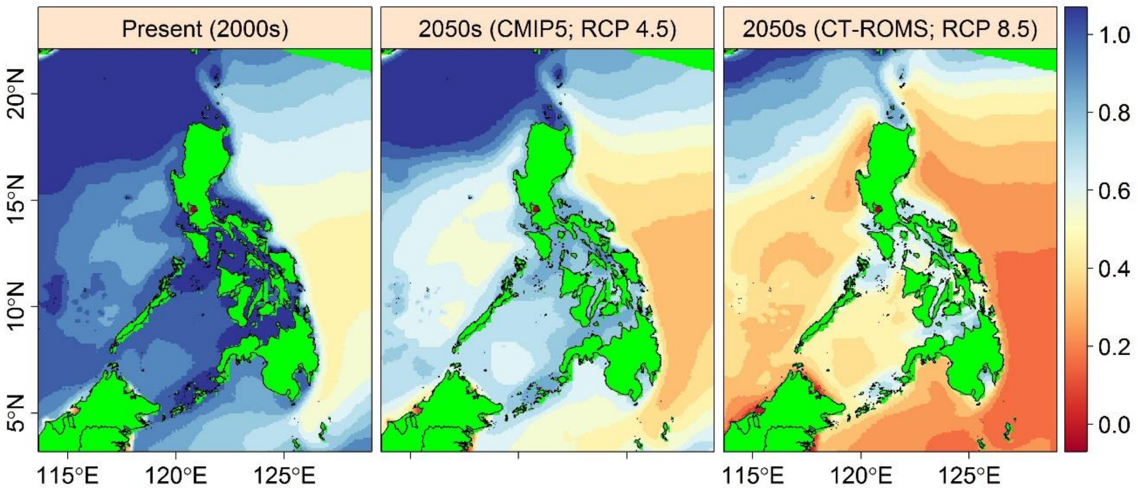
Auxis thazard

Frigate tuna (*"Tulingan"*)

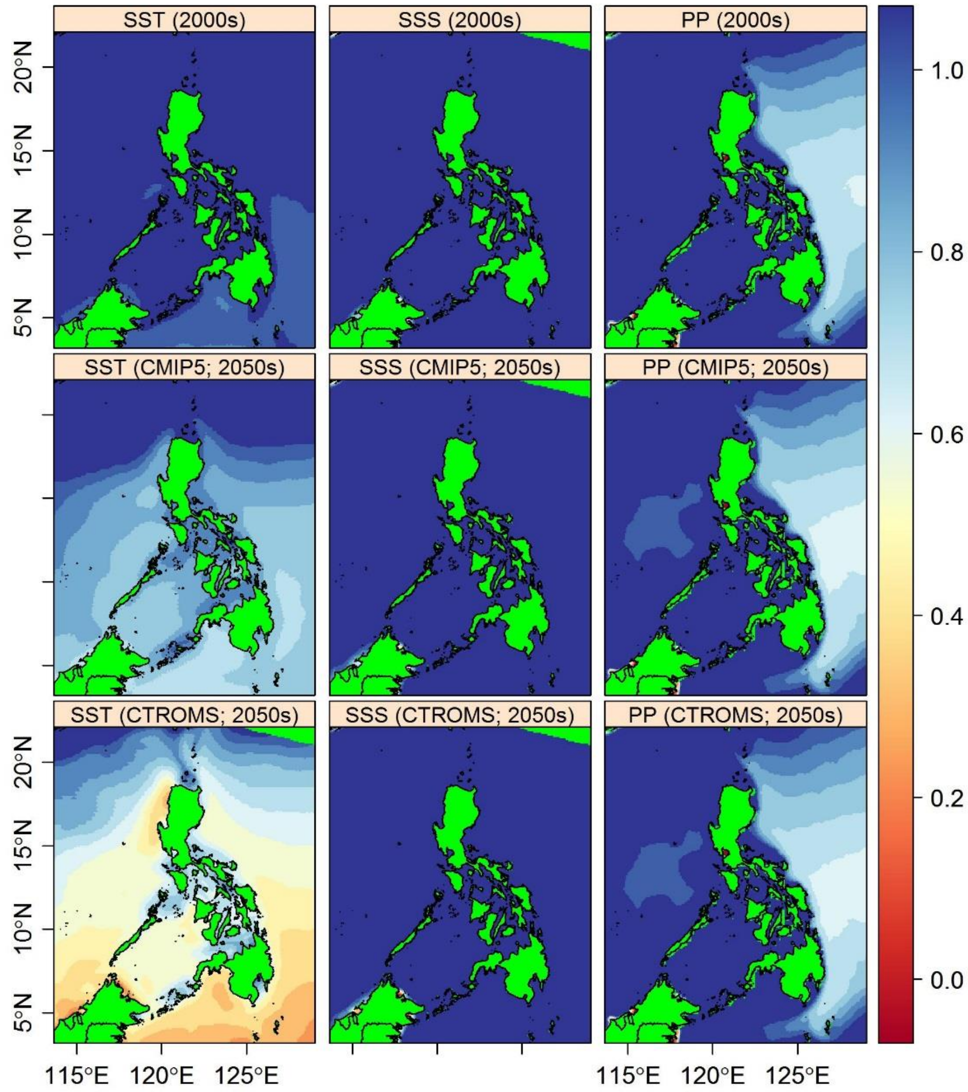
Probability of occurrence for *Auxis thazard* by variable



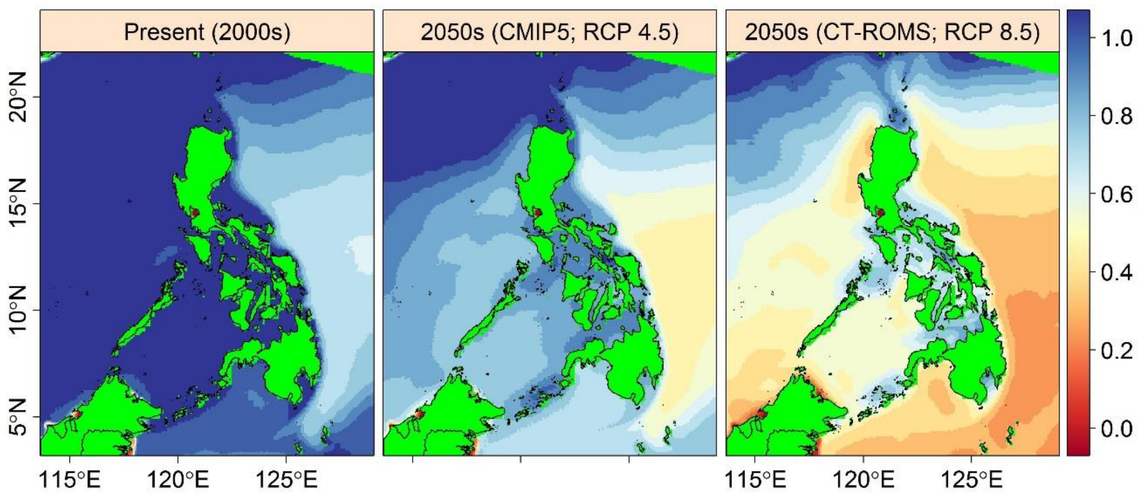
Projected Suitable Habitat for *Auxis thazard*



Probability of occurrence for *Euthynnus affinis* by variable



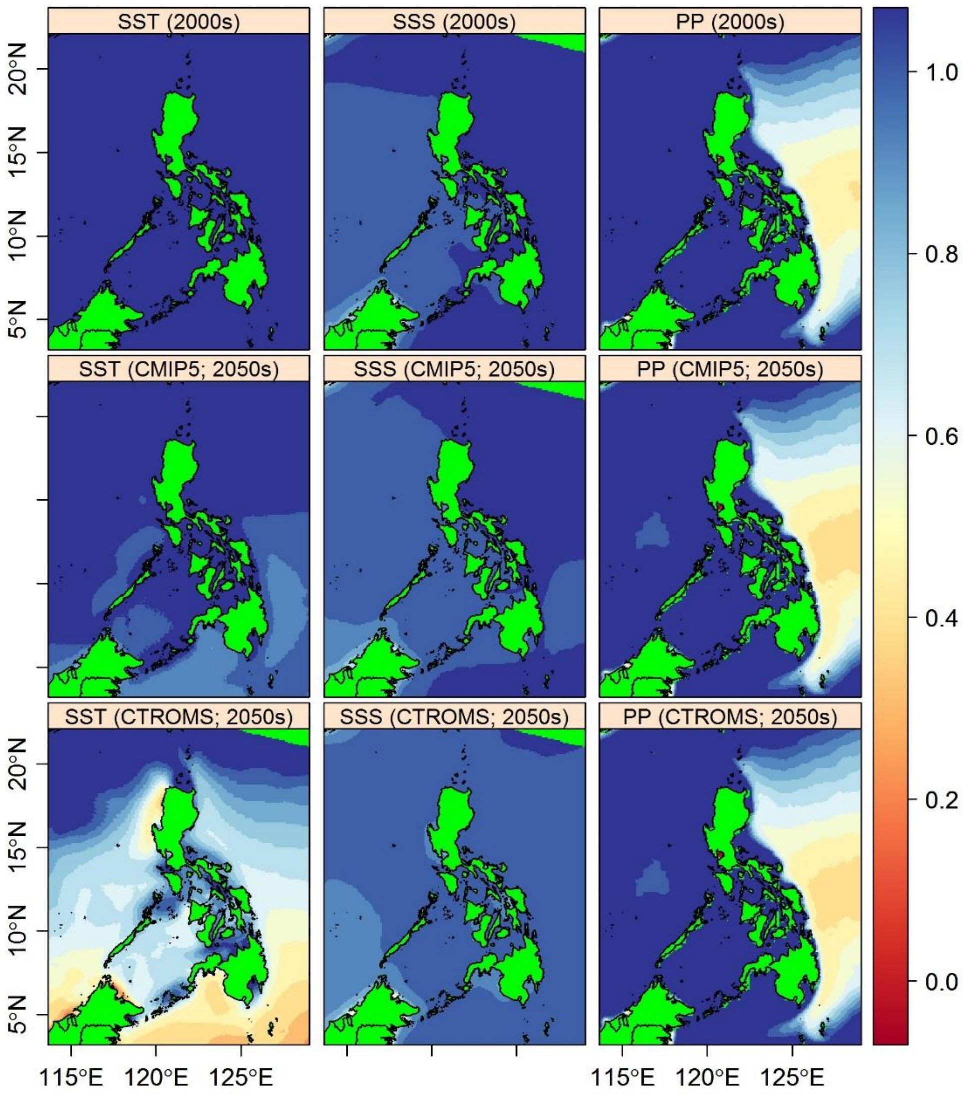
Projected Suitable Habitat for *Euthynnus affinis*



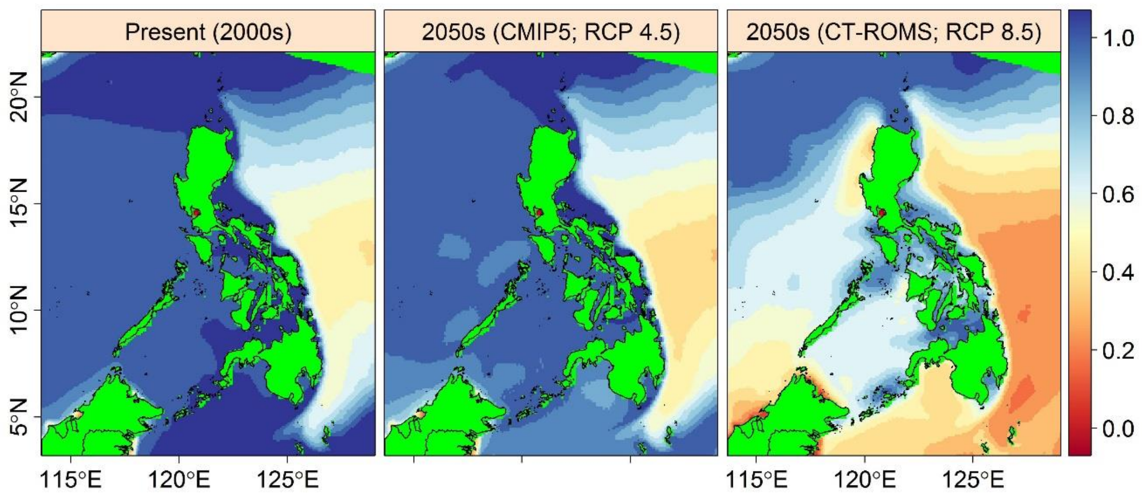
Katsuwonus pelamis

Skipjack tuna (*"Gulyasan"*)

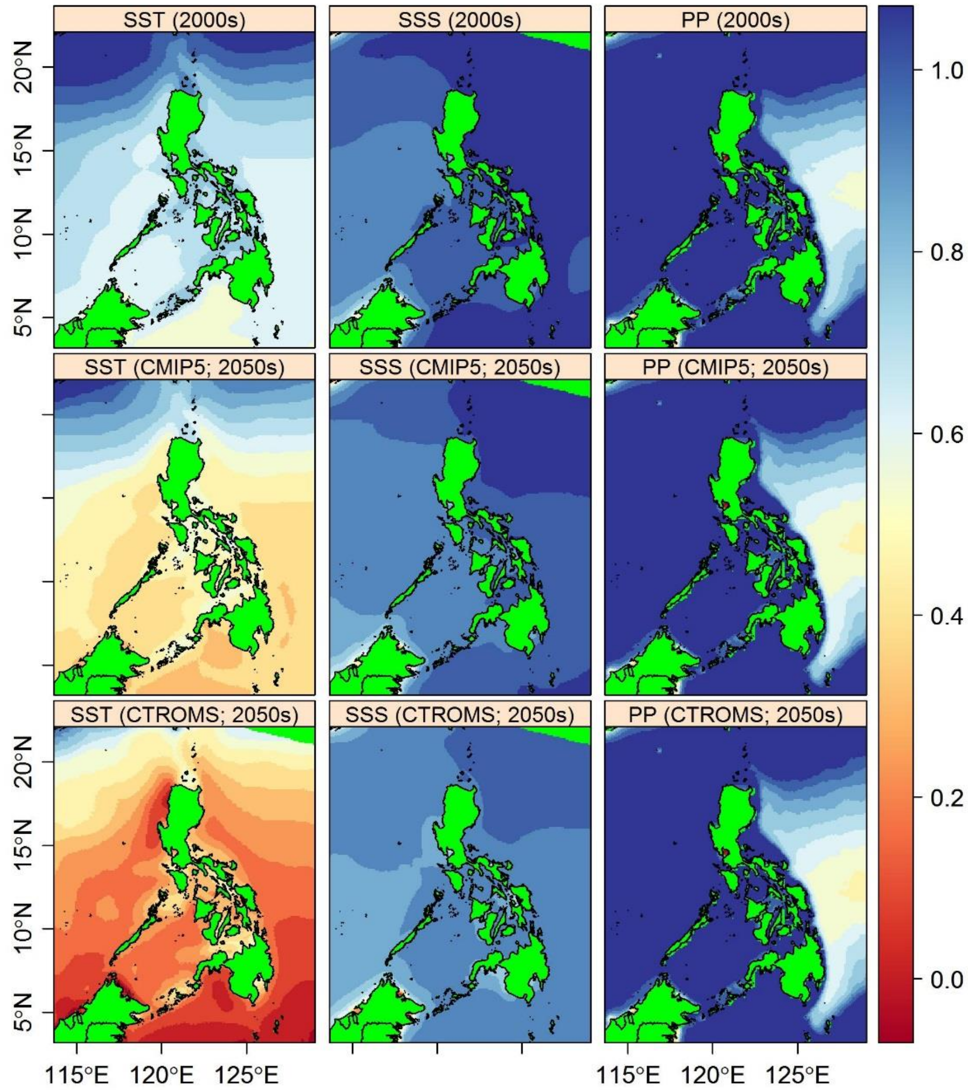
Probability of occurrence for *Katsuwonus pelamis* by variable



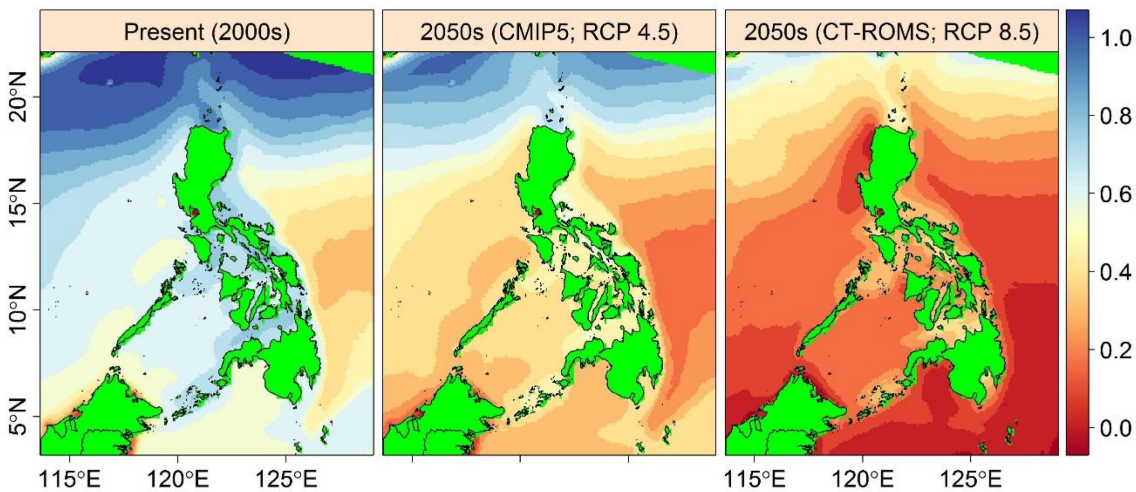
Projected Suitable Habitat for *Katsuwonus pelamis*



Probability of occurrence for *Thunnus alalunga* by variable



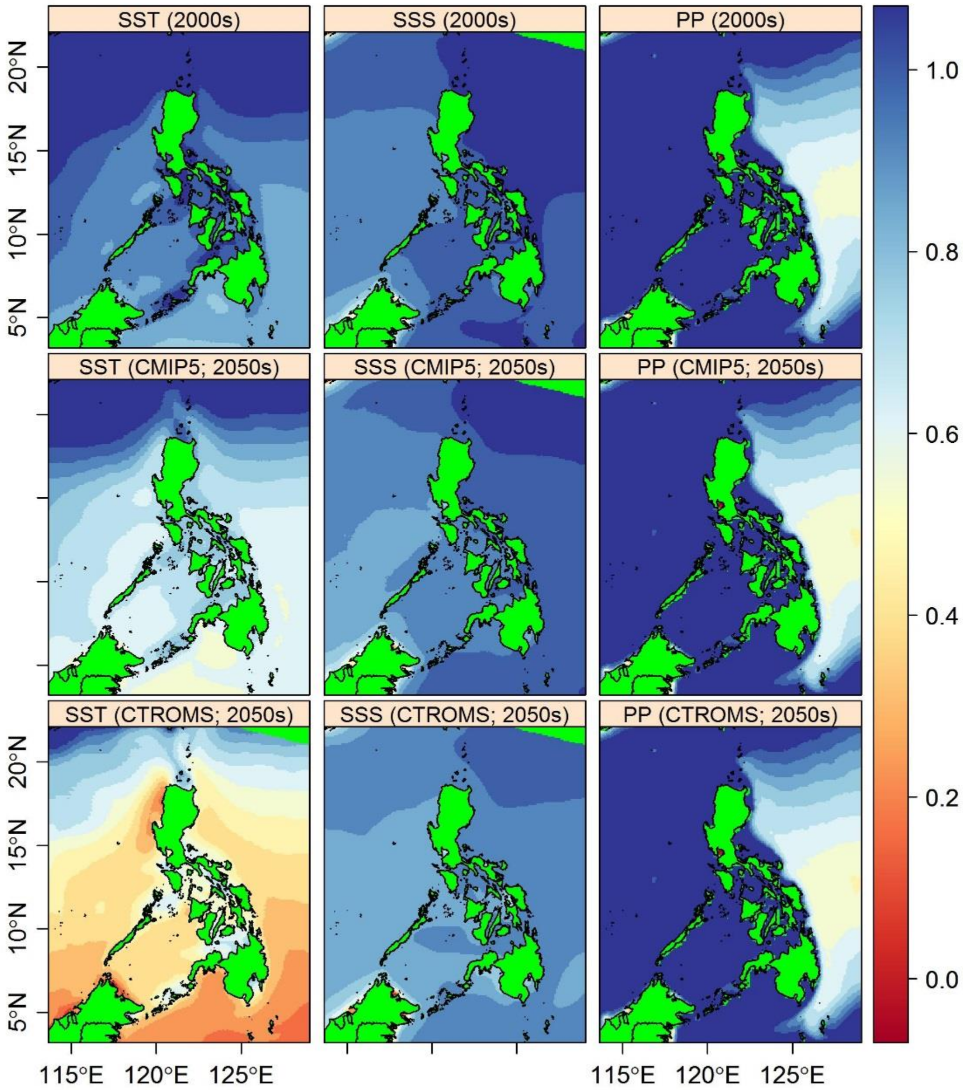
Projected Suitable Habitat for *Thunnus alalunga*



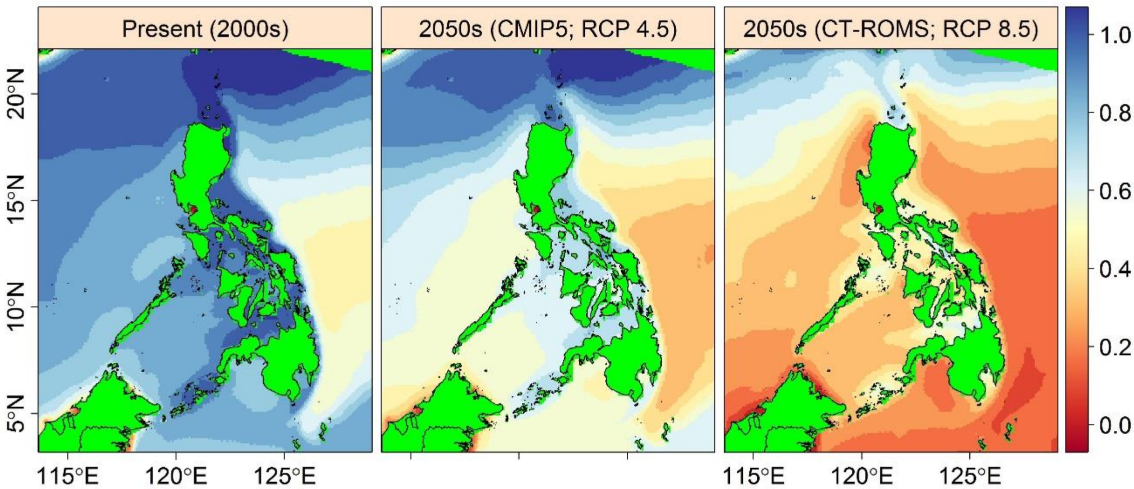
Thunnus albacares
Yellowfin tuna (*"Bariles"*)

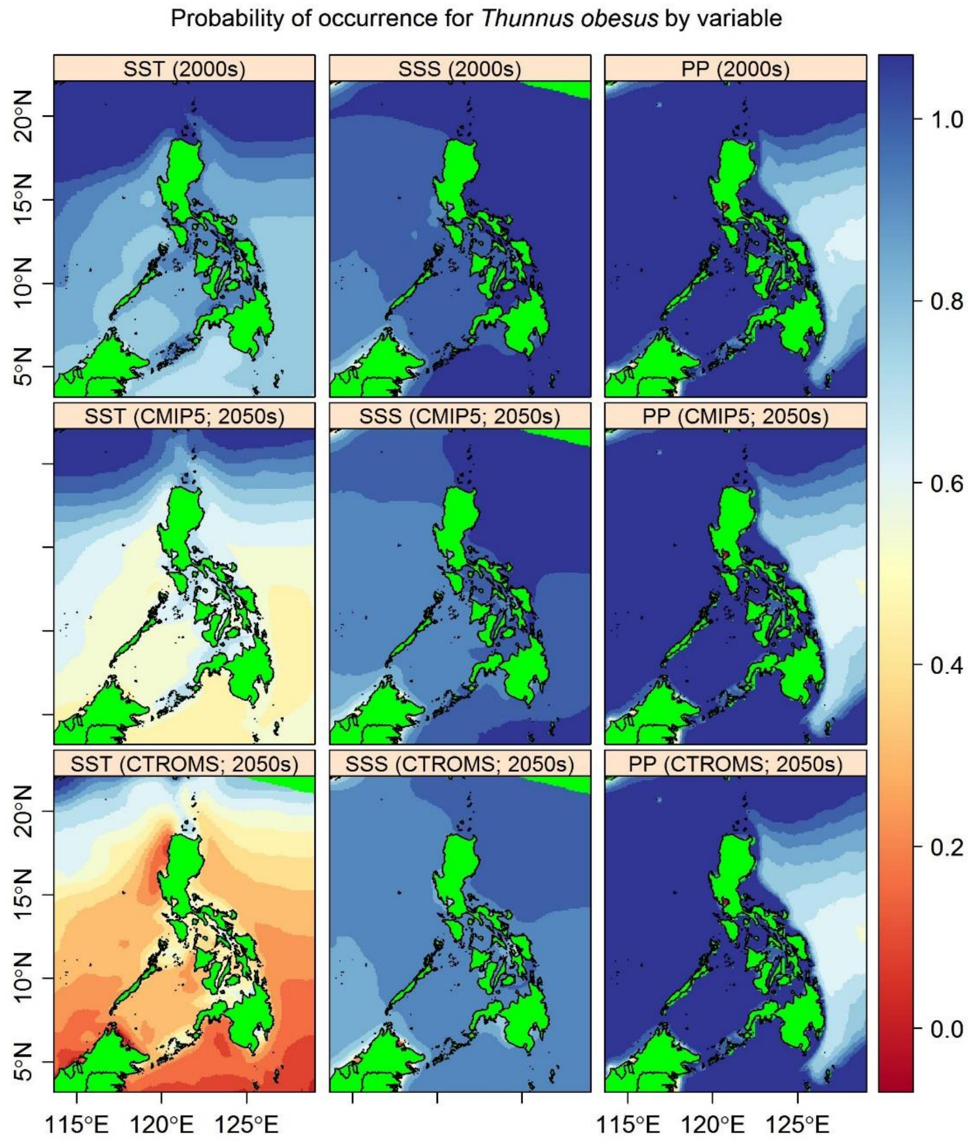
TUNA

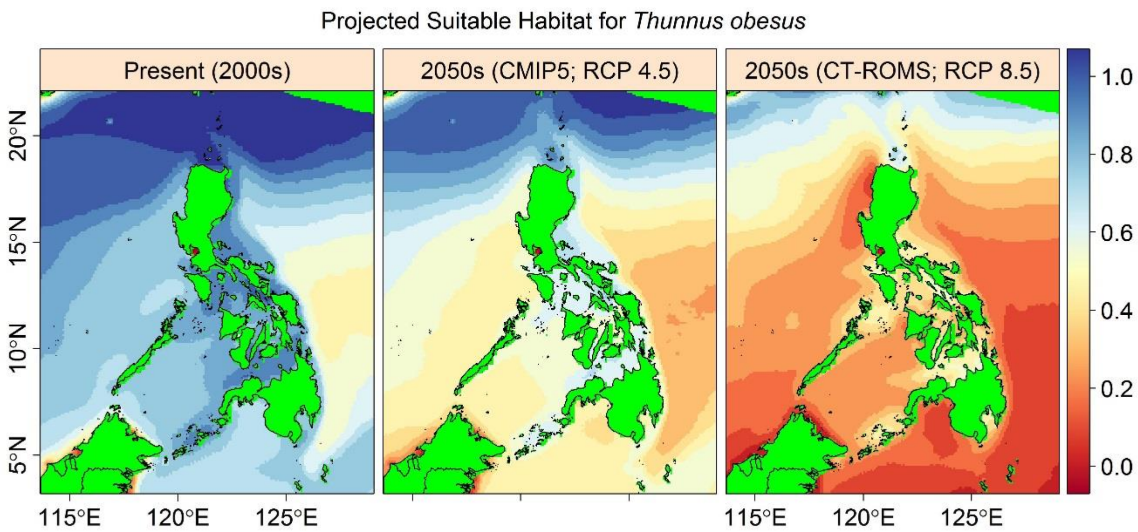
Probability of occurrence for *Thunnus albacares* by variable



Projected Suitable Habitat for *Thunnus albacares*

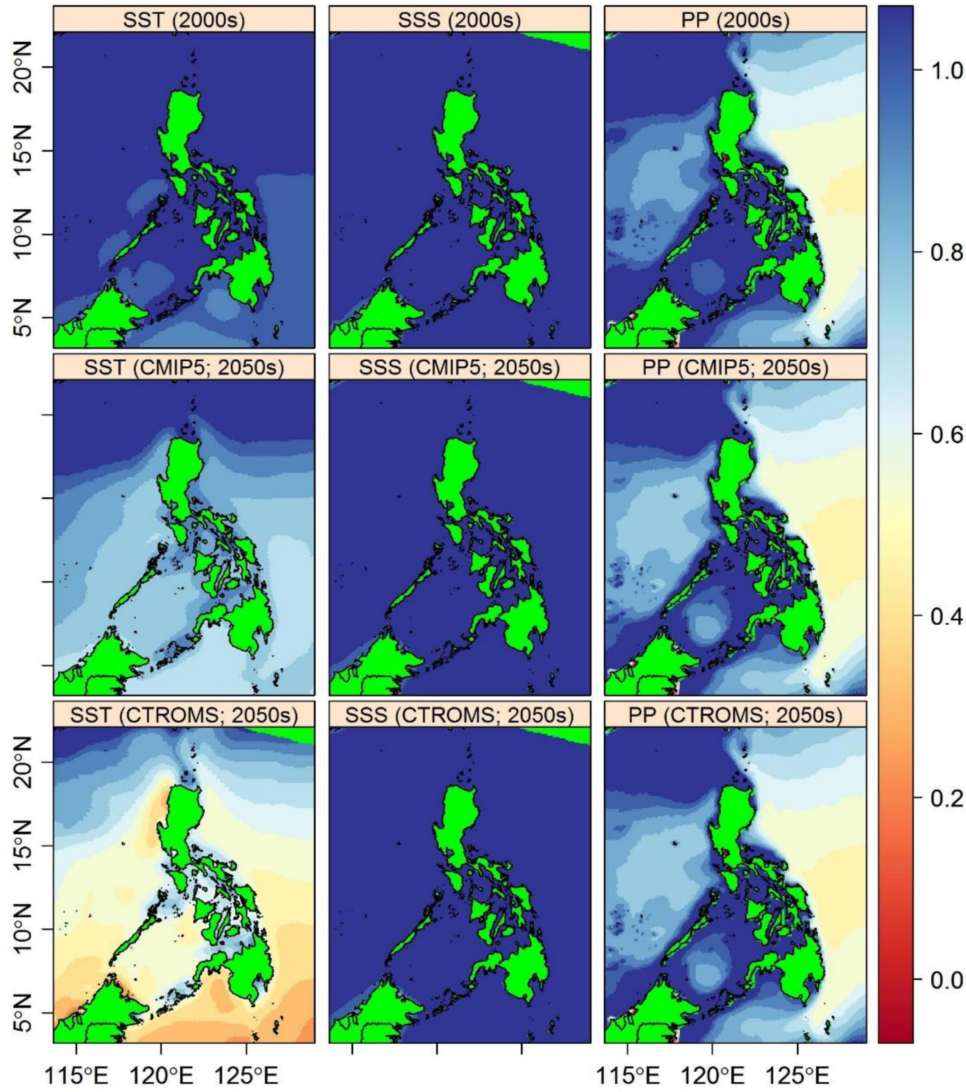



Probability of occurrence for Thunnus obesus by variable
SST (2000s)
SSS (2000s)
PP (2000s)
SST (CMIP5; 2050s)
SSS (CMIP5; 2050s)
PP (CMIP5; 2050s)
SST (CTROMS; 2050s)
SSS (CTROMS; 2050s)
PP (CTROMS; 2050s)
20°N
15°N
10°N
5°N
115°E
120°E
125°E
1.0
0.8
0.6
0.4
0.2
0.0

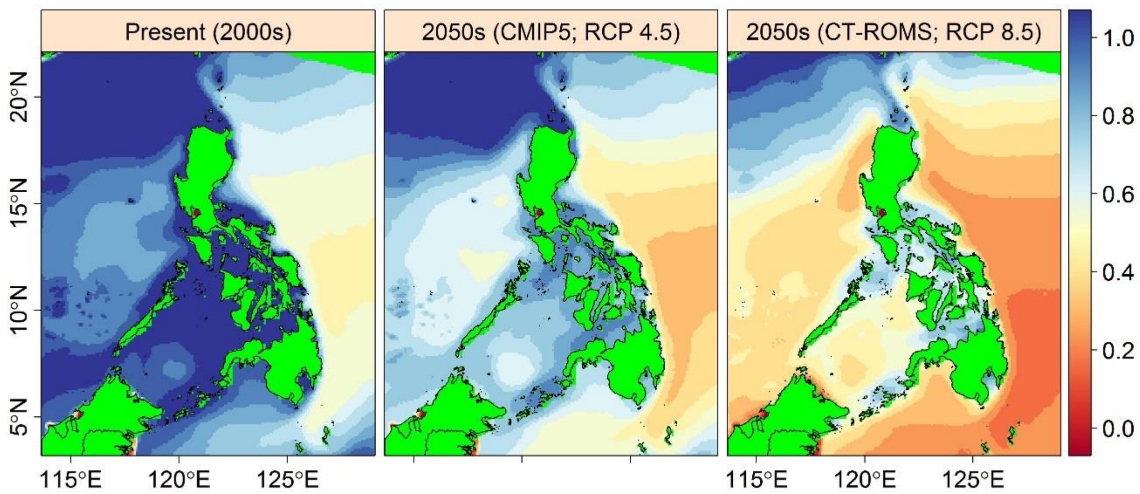

Projected Suitable Habitat for Thunnus obesus
Present (2000s)
2050s (CMIP5; RCP 4.5)
2050s (CT-ROMS; RCP 8.5)
20°N
15°N
10°N
5°N
115°E
120°E
125°E
1.0
0.8
0.6
0.4
0.2
0.0

Thunnus tonggol
Longtail tuna (*"Bariles"*)

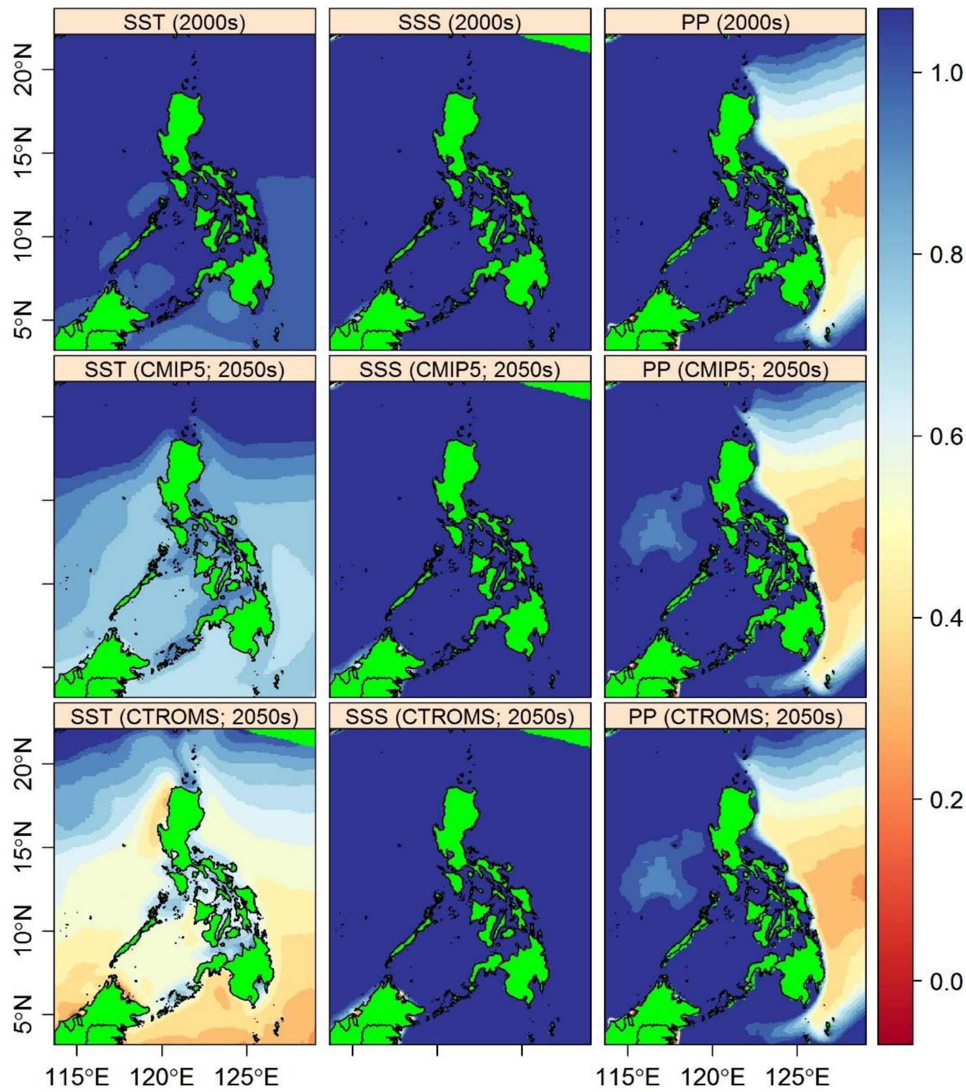
Probability of occurrence for *Thunnus tonggol* by variable



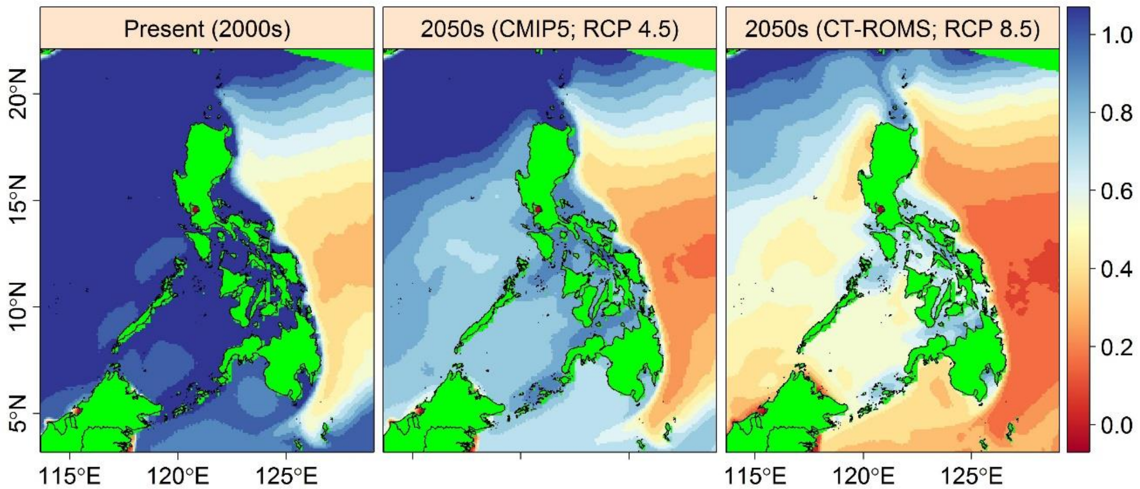
Projected Suitable Habitat for *Thunnus tonggol*



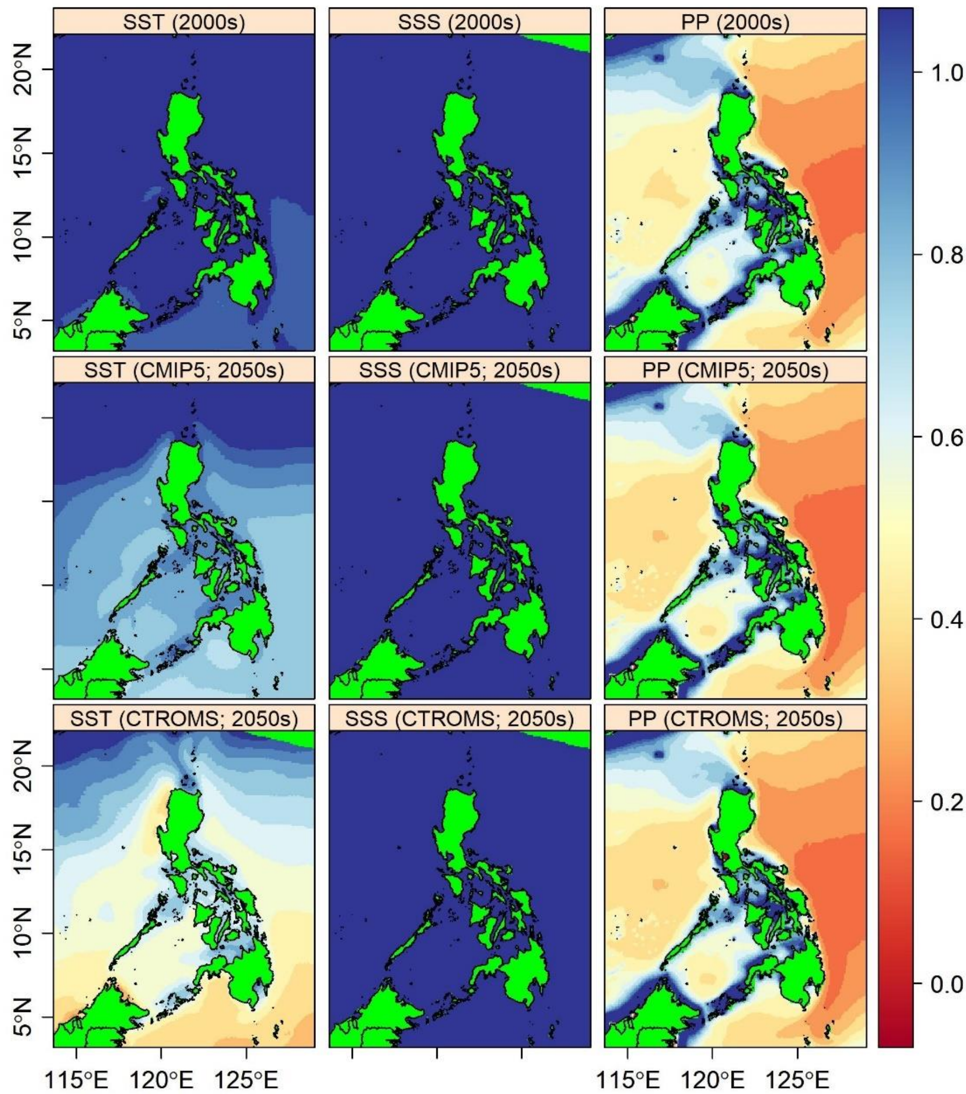
Probability of occurrence for *Sepioteuthis lessoniana* by variable



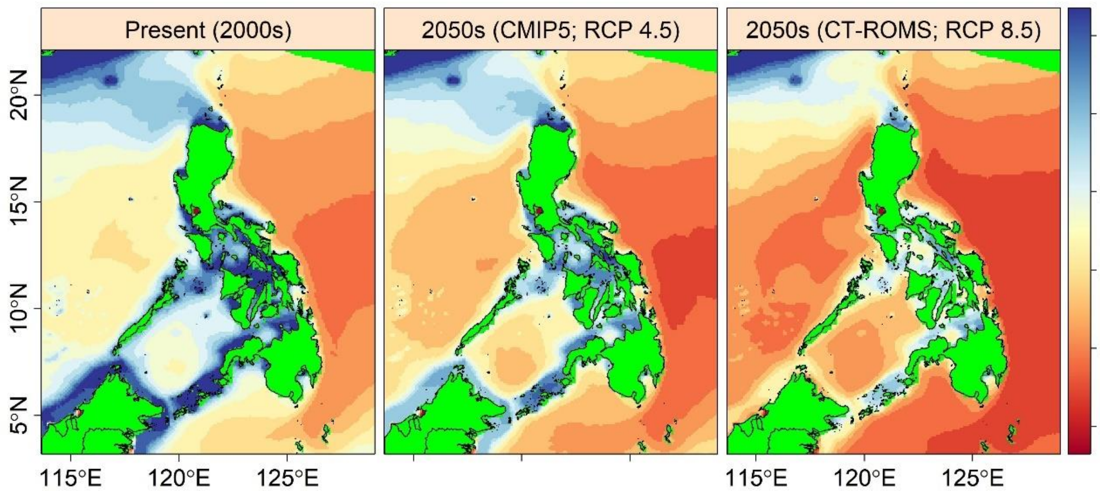
Projected Suitable Habitat for *Sepioteuthis lessoniana*

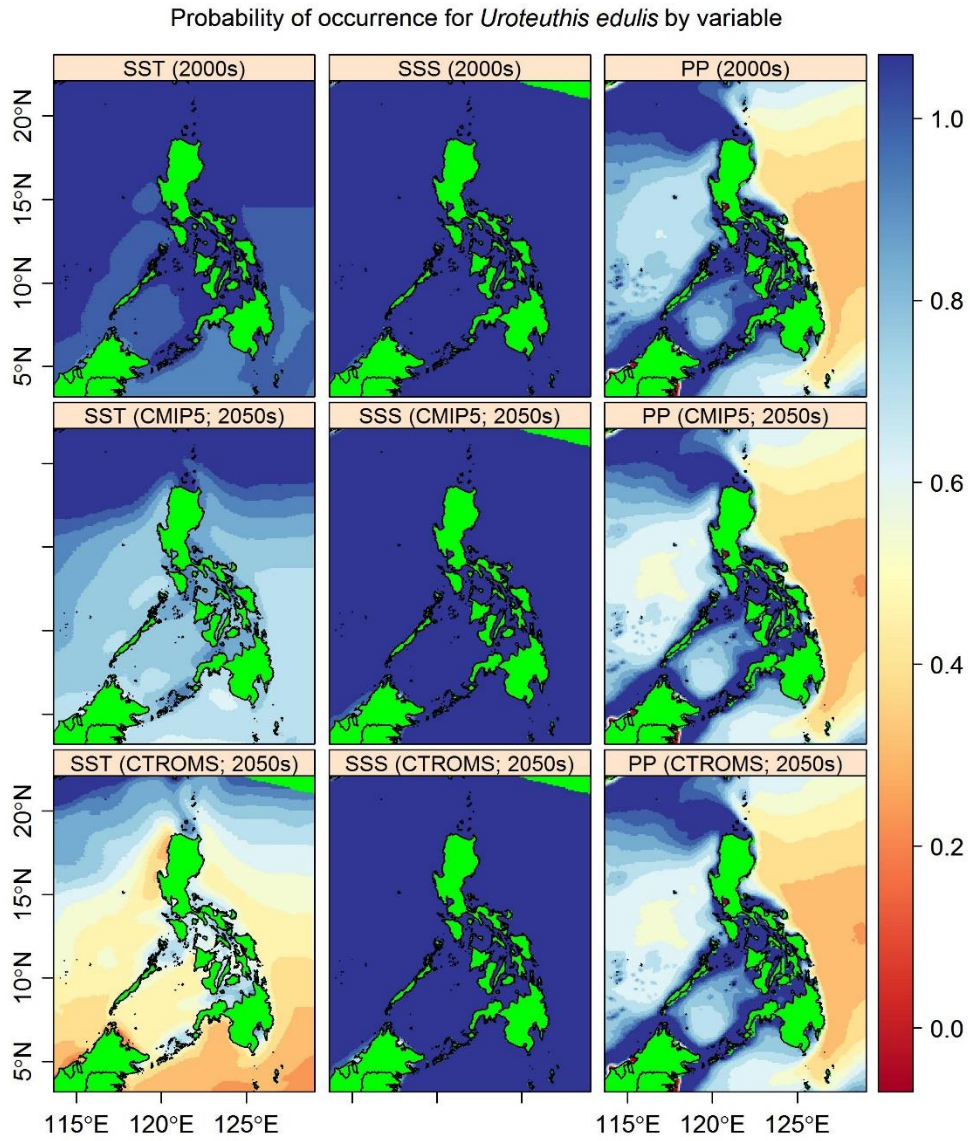


Probability of occurrence for *Uroteuthis duvaucelii* by variable

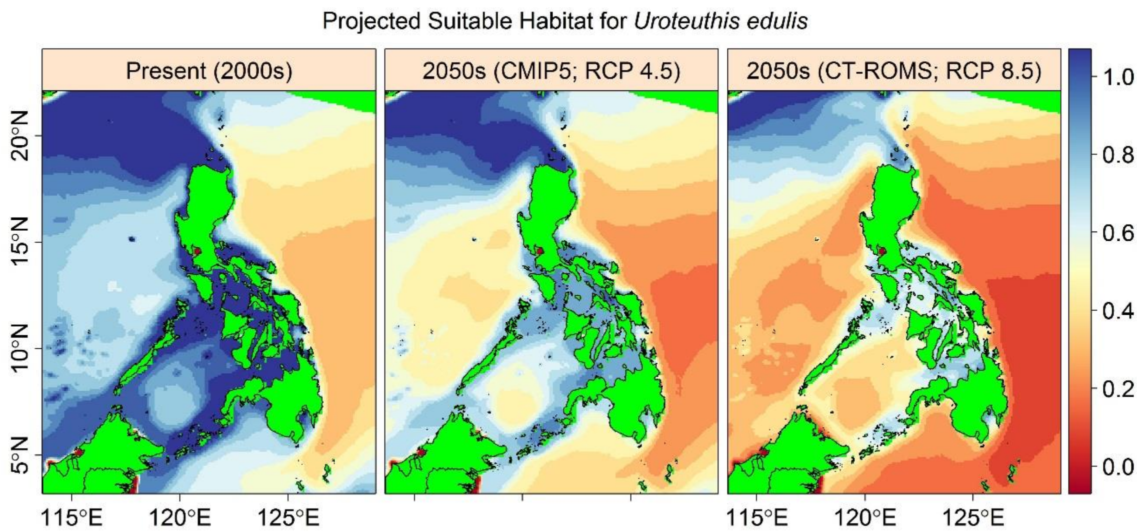


Projected Suitable Habitat for *Uroteuthis duvaucelii*



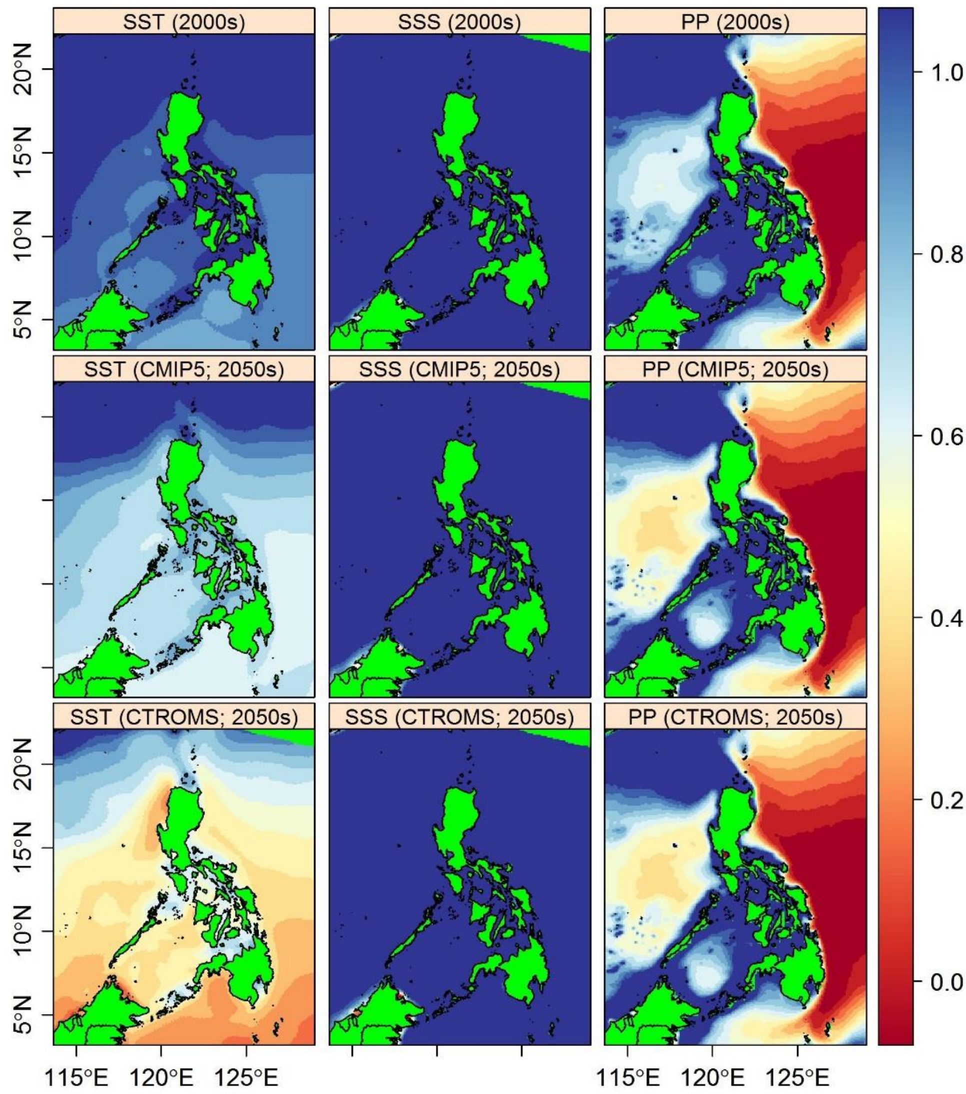


Probability of occurrence for *Uroteuthis edulis* by variable
SST (2000s)
SSS (2000s)
PP (2000s)
SST (CMIP5; 2050s)
SSS (CMIP5; 2050s)
PP (CMIP5; 2050s)
SST (CTROMS; 2050s)
SSS (CTROMS; 2050s)
PP (CTROMS; 2050s)
20°N
15°N
10°N
5°N
115°E 120°E 125°E
1.0
0.8
0.6
0.4
0.2
0.0

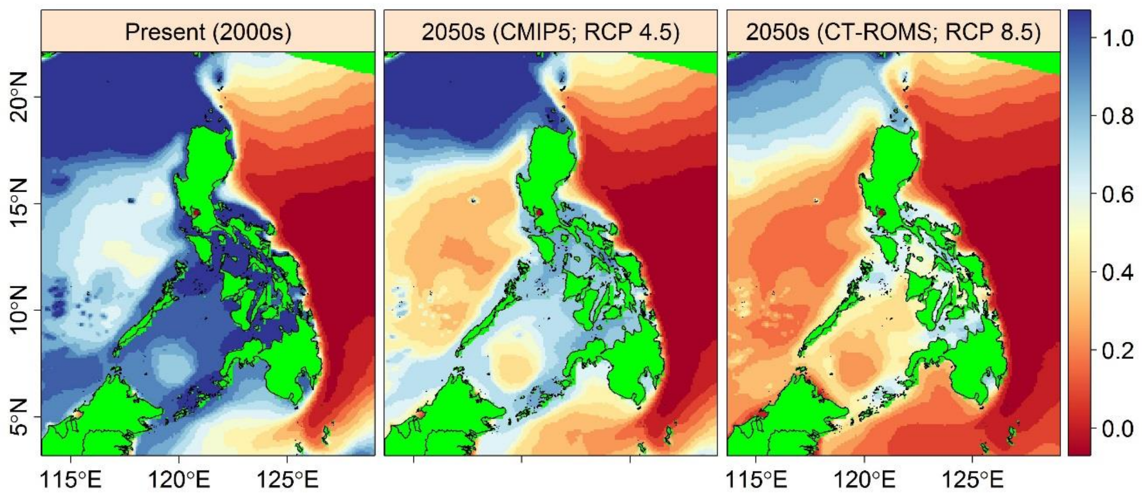


Projected Suitable Habitat for *Uroteuthis edulis*
Present (2000s)
2050s (CMIP5; RCP 4.5)
2050s (CT-ROMS; RCP 8.5)
20°N
15°N
10°N
5°N
115°E 120°E 125°E
1.0
0.8
0.6
0.4
0.2
0.0

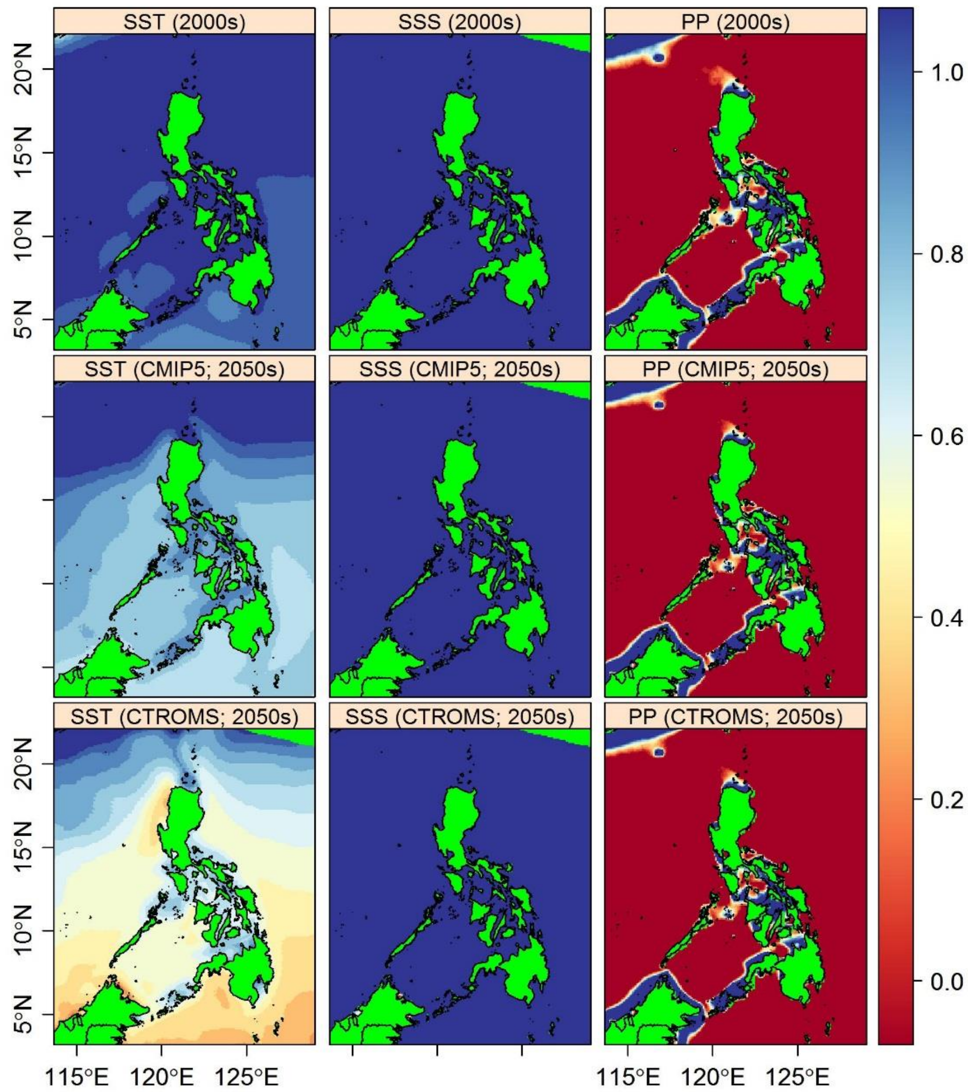
Probability of occurrence for *Ablennes hians* by variable



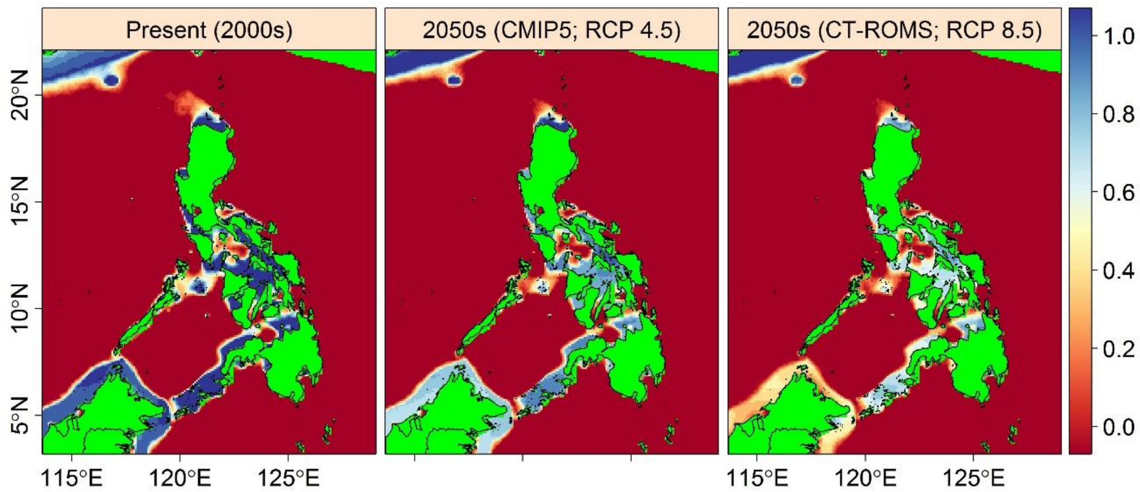
Projected Suitable Habitat for *Ablennes hians*



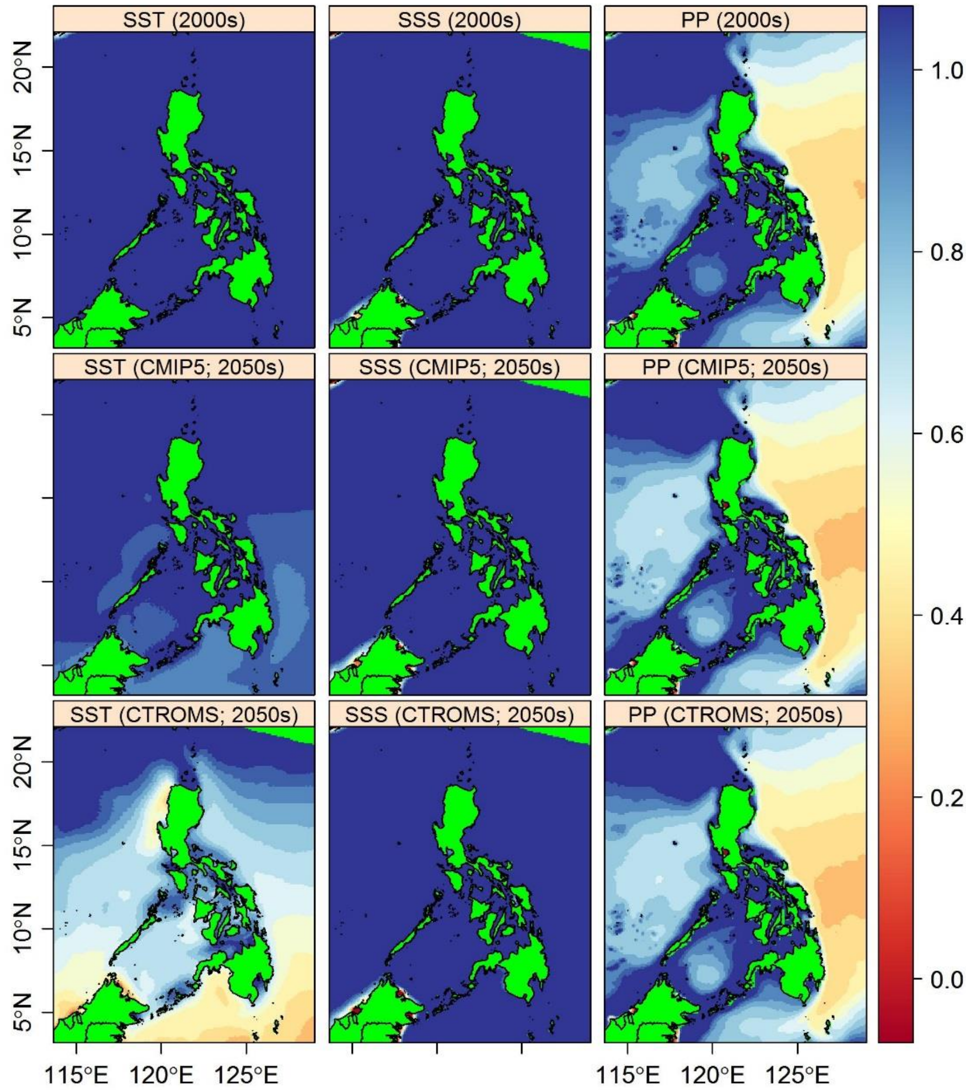
Probability of occurrence for *Dussumieria acuta* by variable



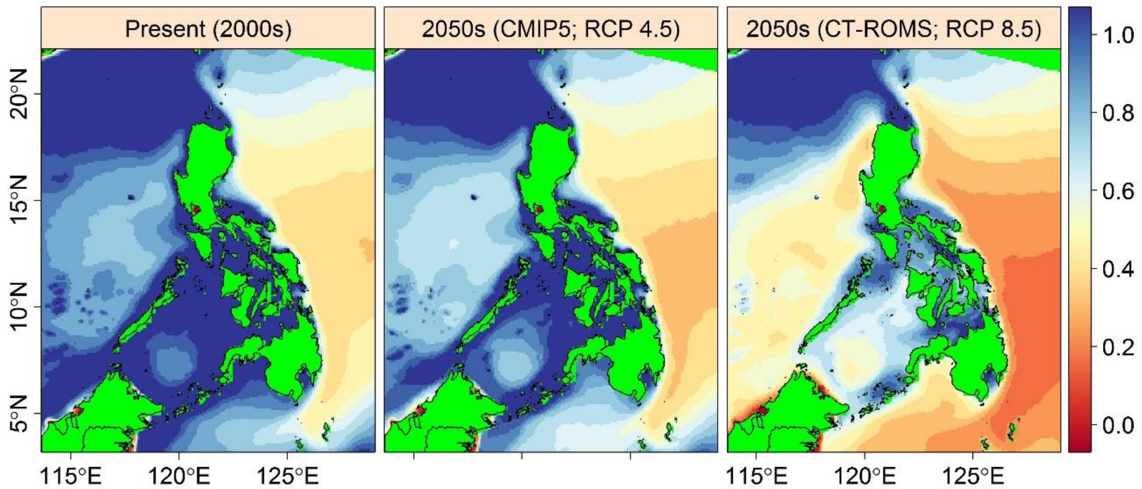
Projected Suitable Habitat for *Dussumieria acuta*



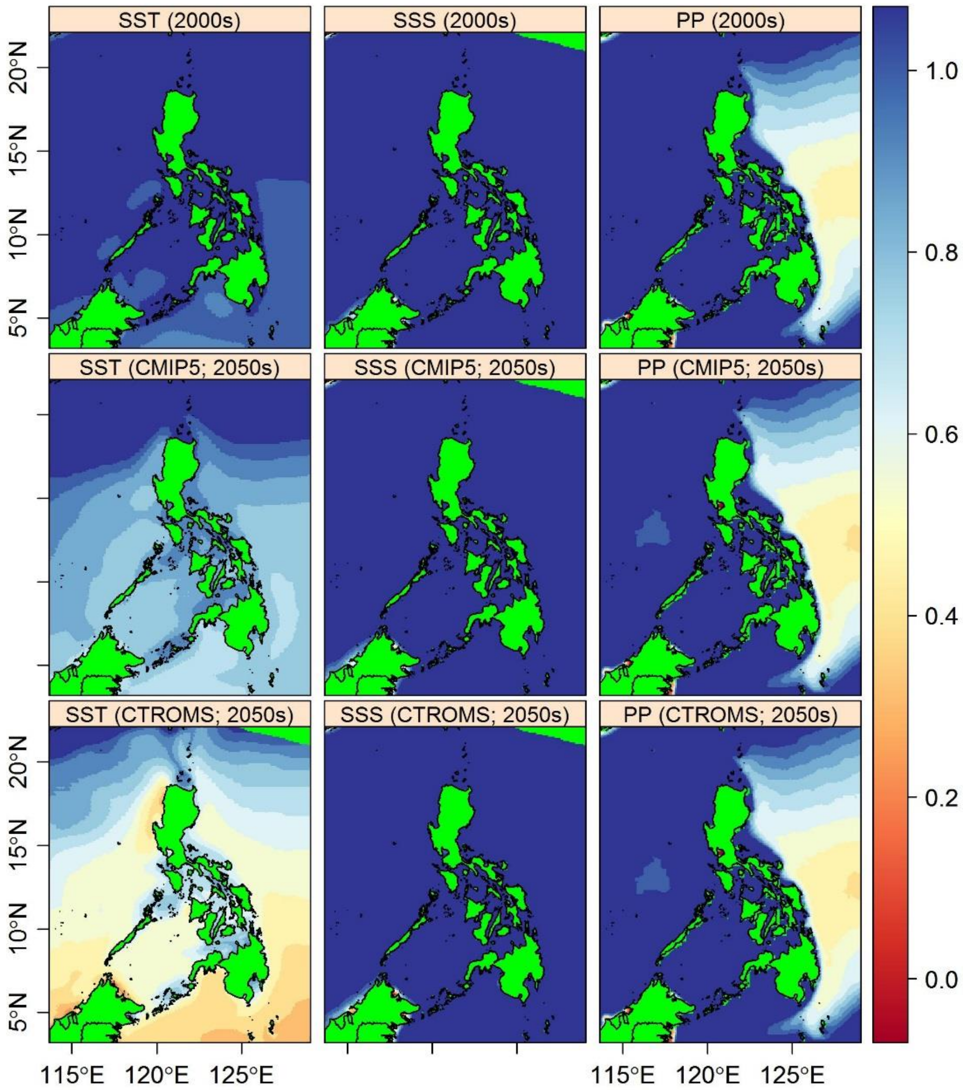
Probability of occurrence for *Mene maculata* by variable



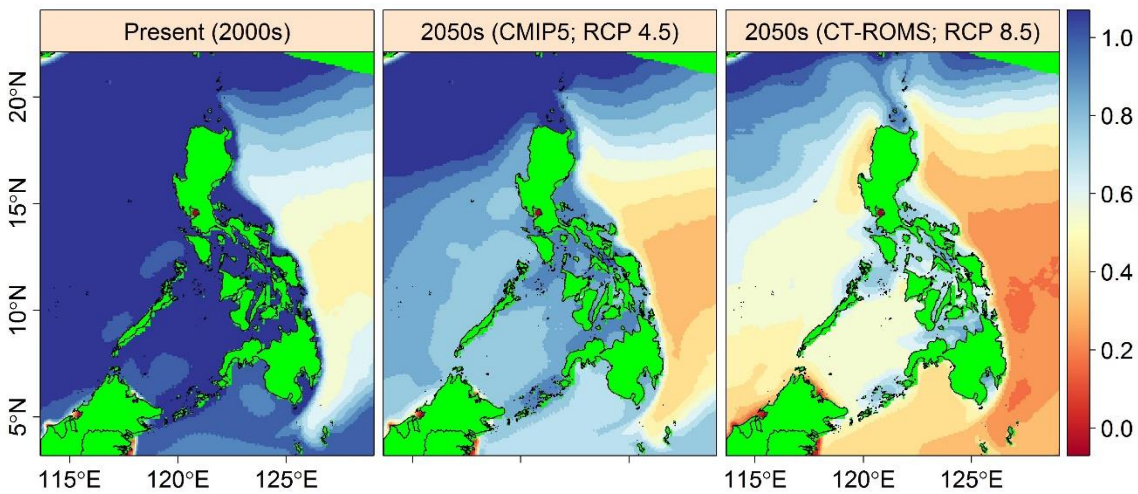
Projected Suitable Habitat for *Mene maculata*



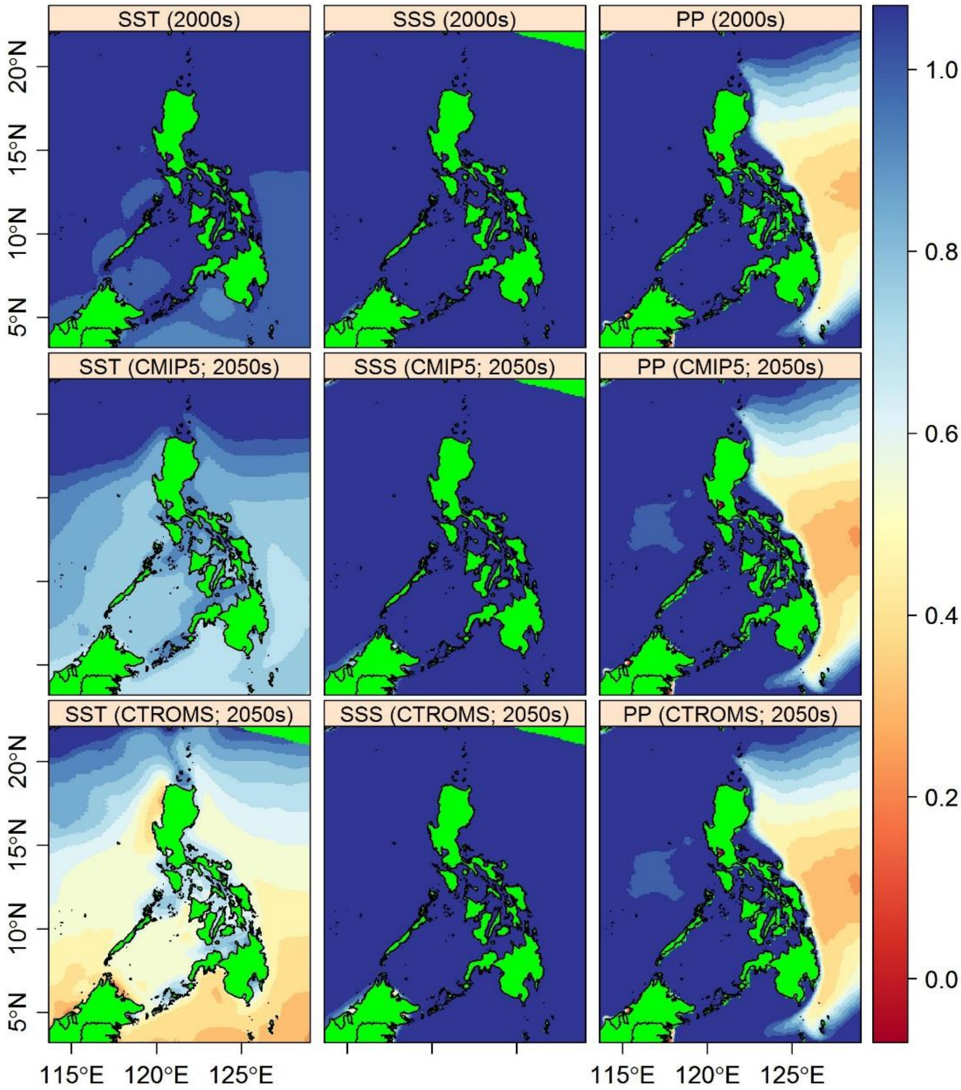
Probability of occurrence for *Spratelloides delicatulus* by variable



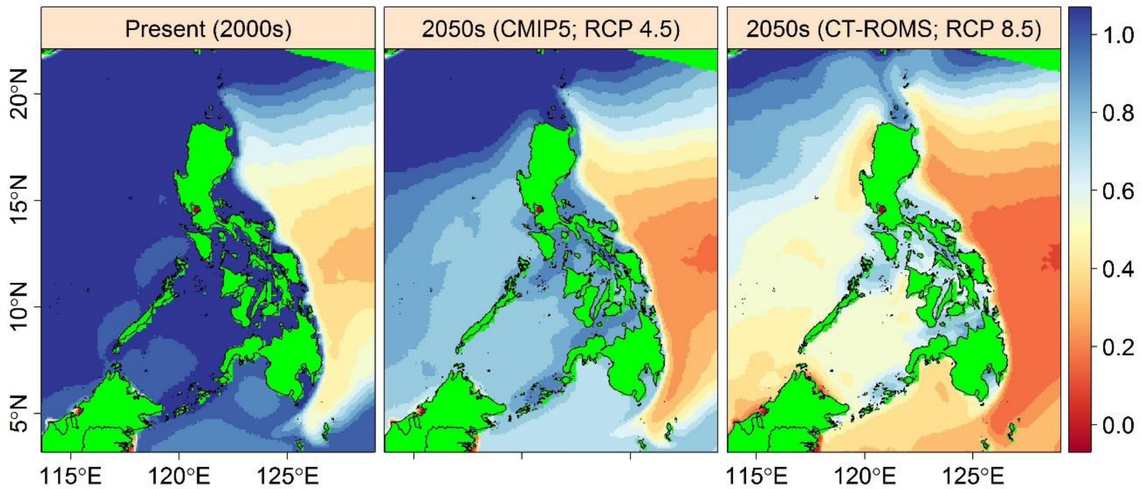
Projected Suitable Habitat for *Spratelloides delicatulus*



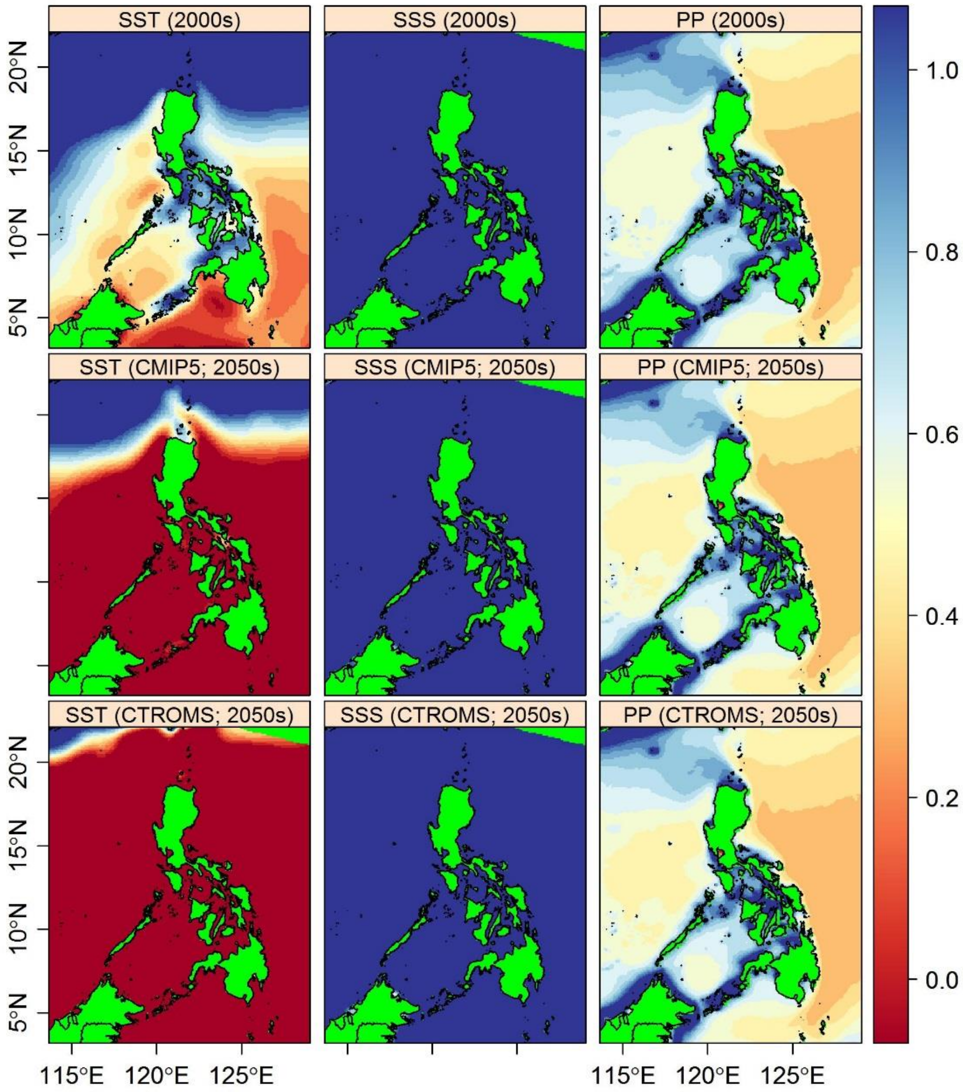
Probability of occurrence for *Spratelloides gracilis* by variable



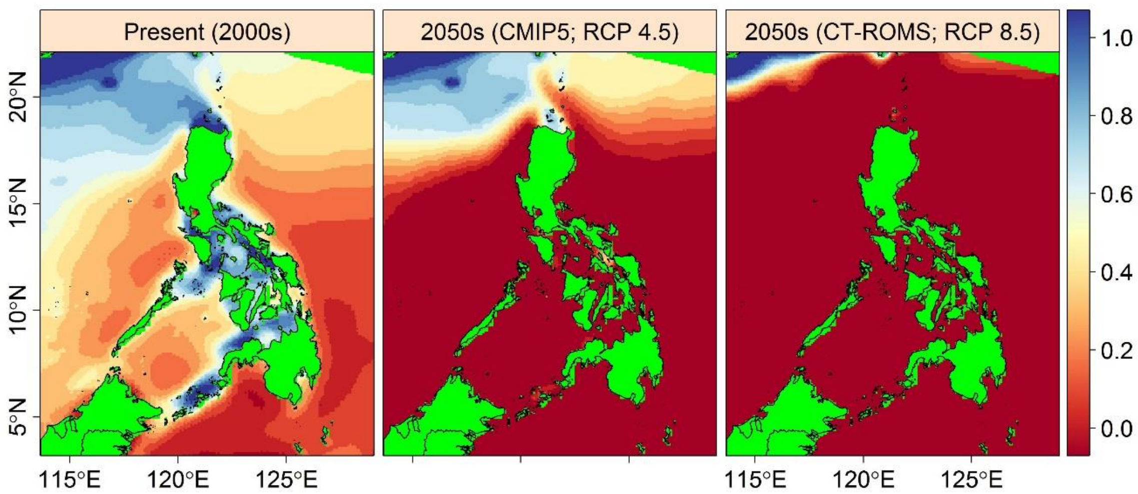
Projected Suitable Habitat for *Spratelloides gracilis*



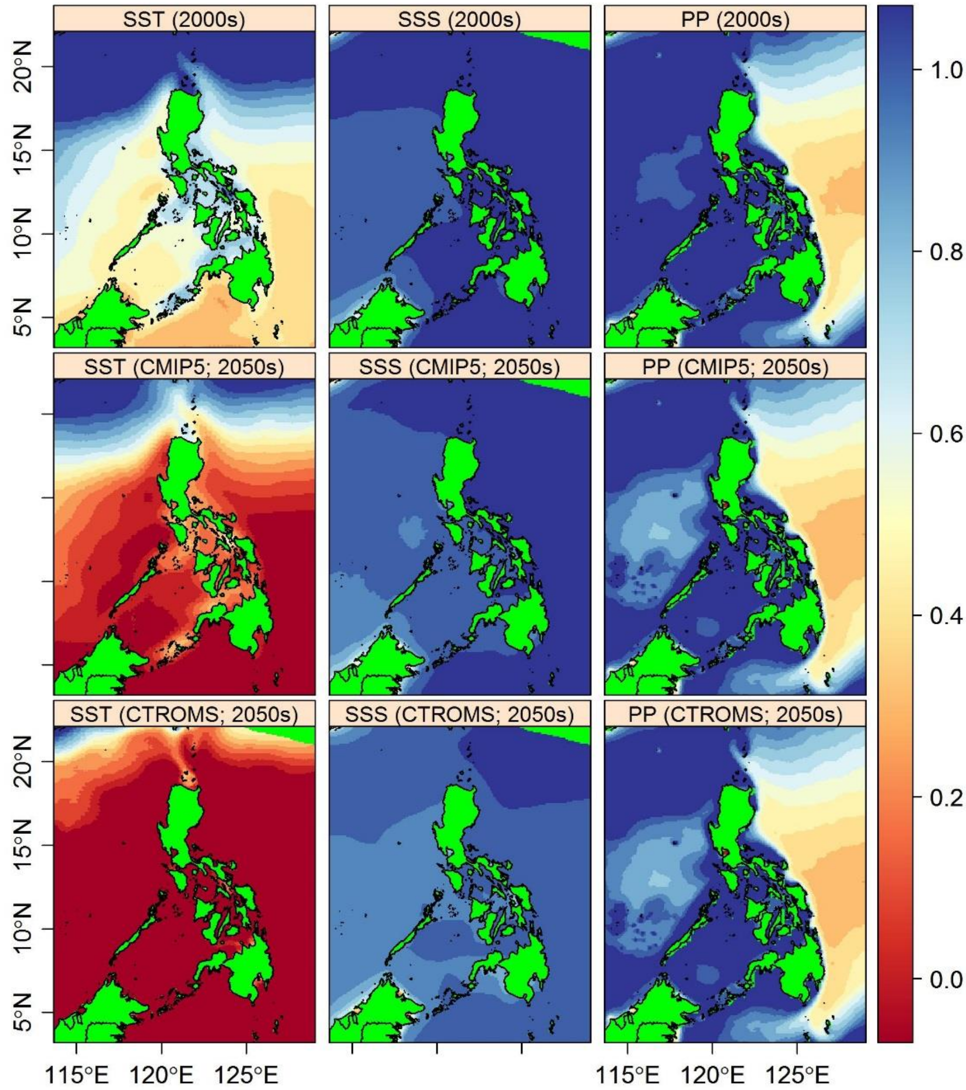
Probability of occurrence for *Trichiurus lepturus* by variable



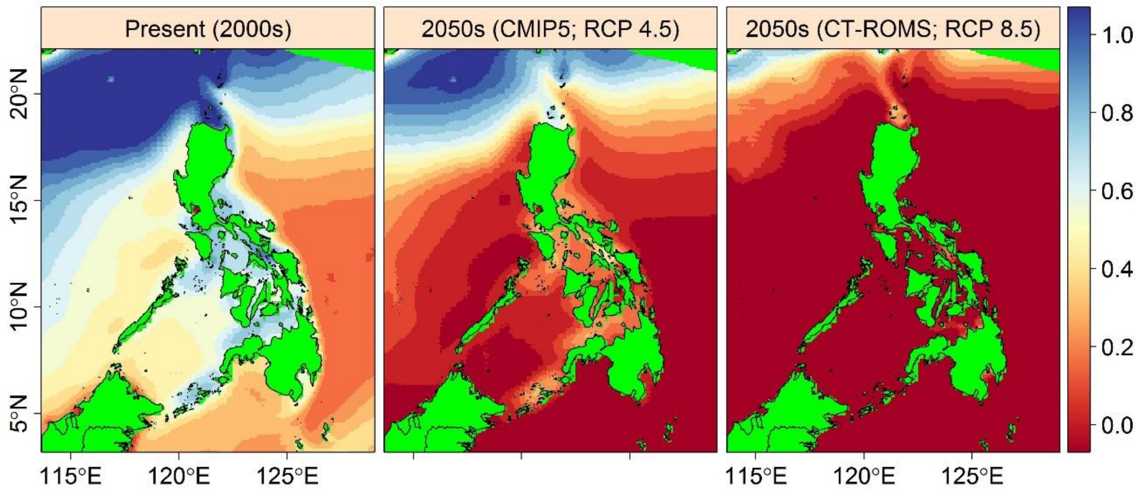
Projected Suitable Habitat for *Trichiurus lepturus*

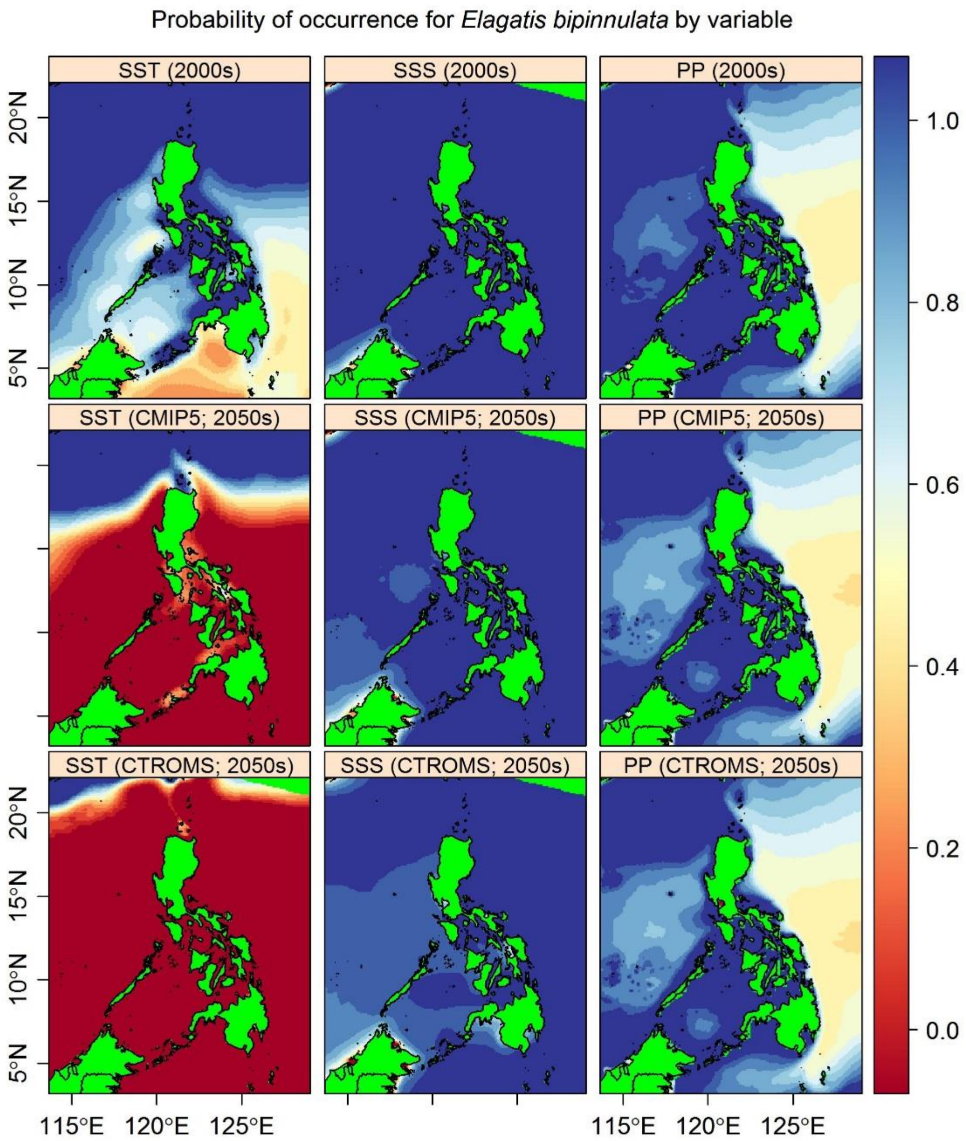


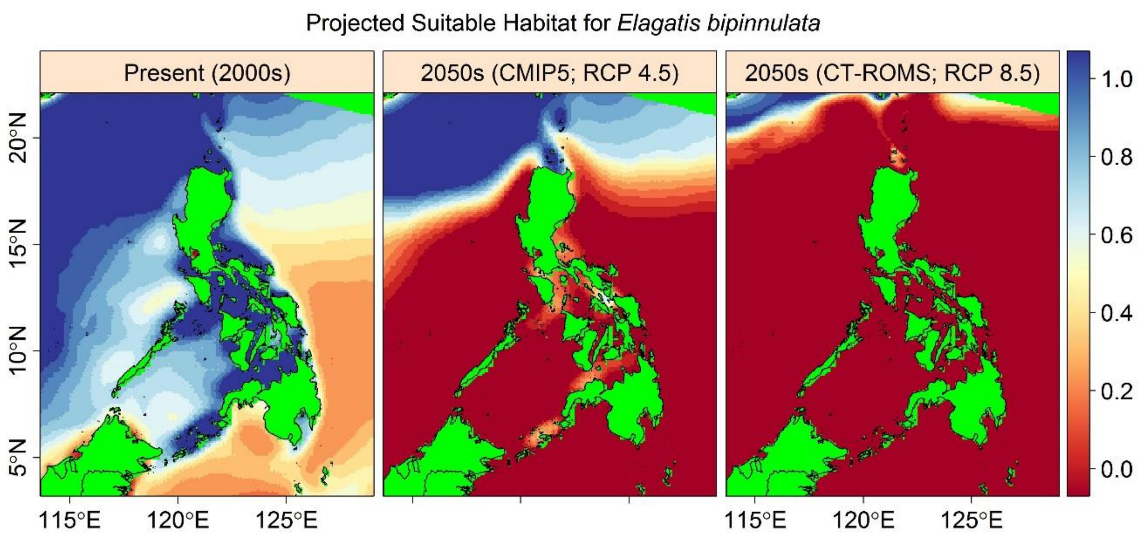
Probability of occurrence for *Coryphaena hippurus* by variable



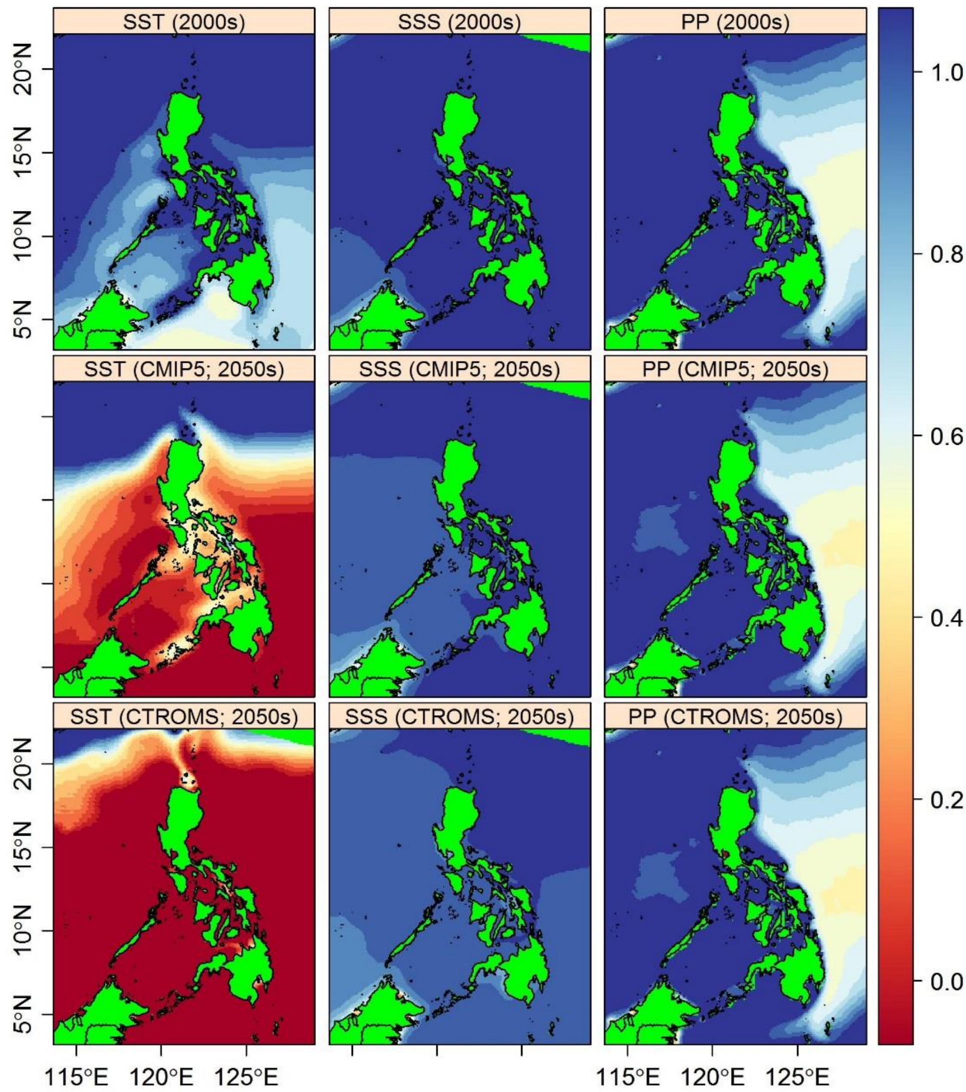
Projected Suitable Habitat for *Coryphaena hippurus*



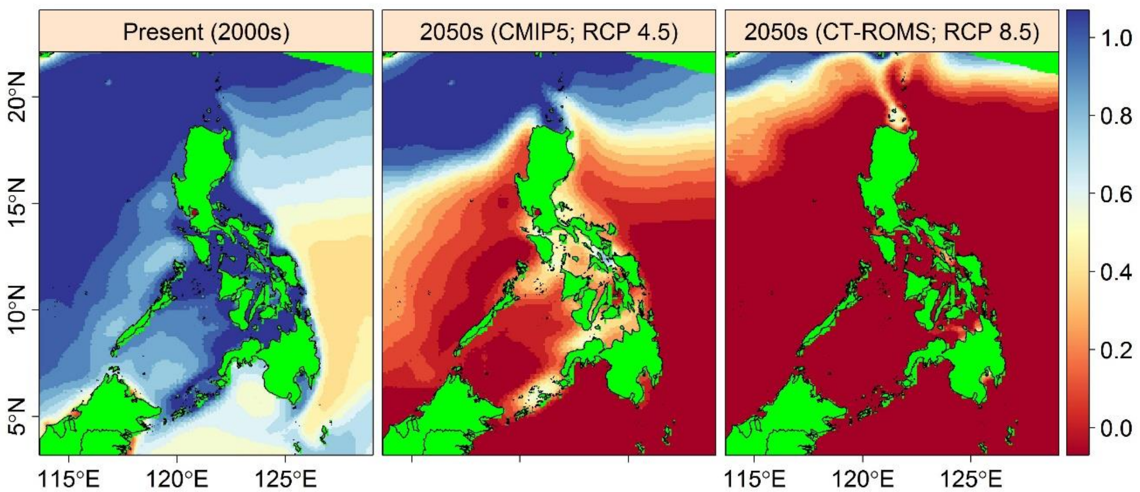

Probability of occurrence for Elagatis bipinnulata by variable
SST (2000s)
SSS (2000s)
PP (2000s)
SST (CMIP5; 2050s)
SSS (CMIP5; 2050s)
PP (CMIP5; 2050s)
SST (CTROMS; 2050s)
SSS (CTROMS; 2050s)
PP (CTROMS; 2050s)
20°N
15°N
10°N
5°N
115°E
120°E
125°E
1.0
0.8
0.6
0.4
0.2
0.0


Projected Suitable Habitat for Elagatis bipinnulata
Present (2000s)
2050s (CMIP5; RCP 4.5)
2050s (CT-ROMS; RCP 8.5)
20°N
15°N
10°N
5°N
115°E
120°E
125°E
1.0
0.8
0.6
0.4
0.2
0.0

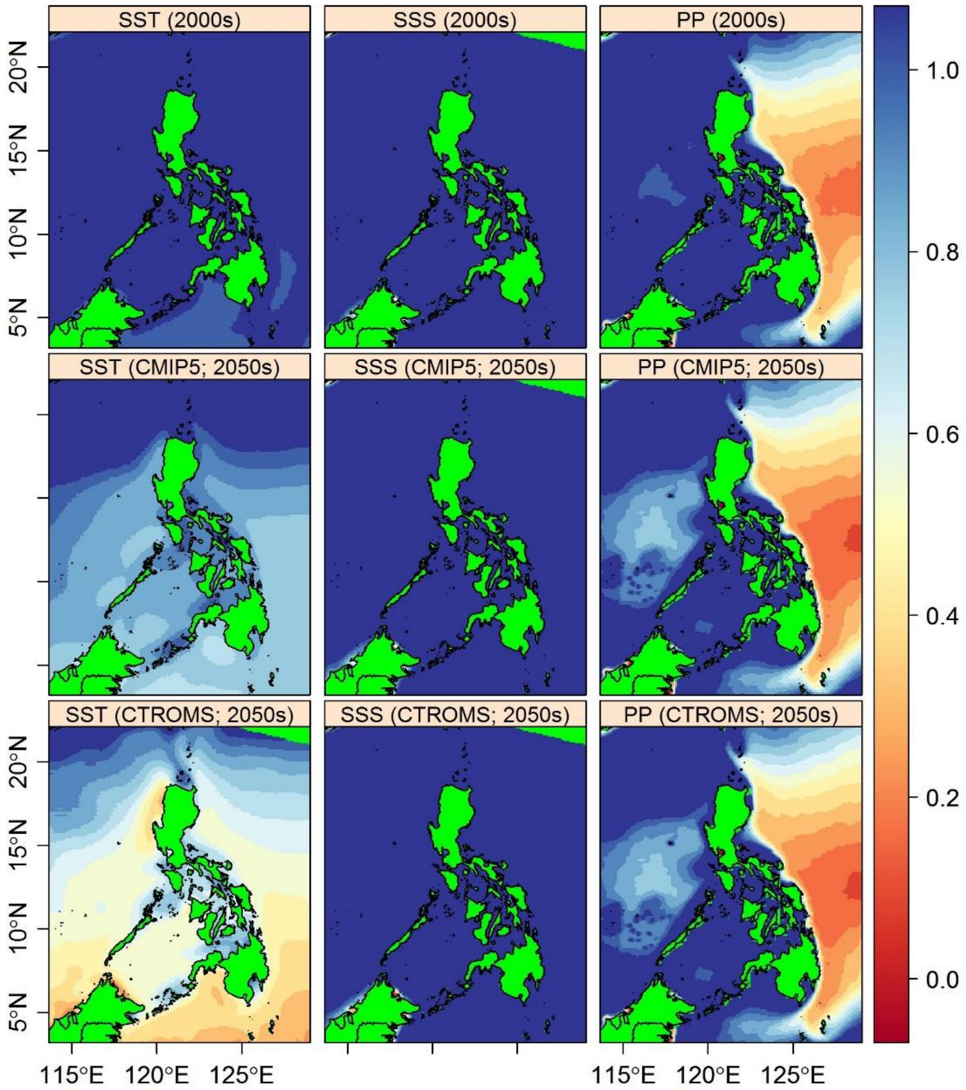
Probability of occurrence for *Istiophorus platypterus* by variable



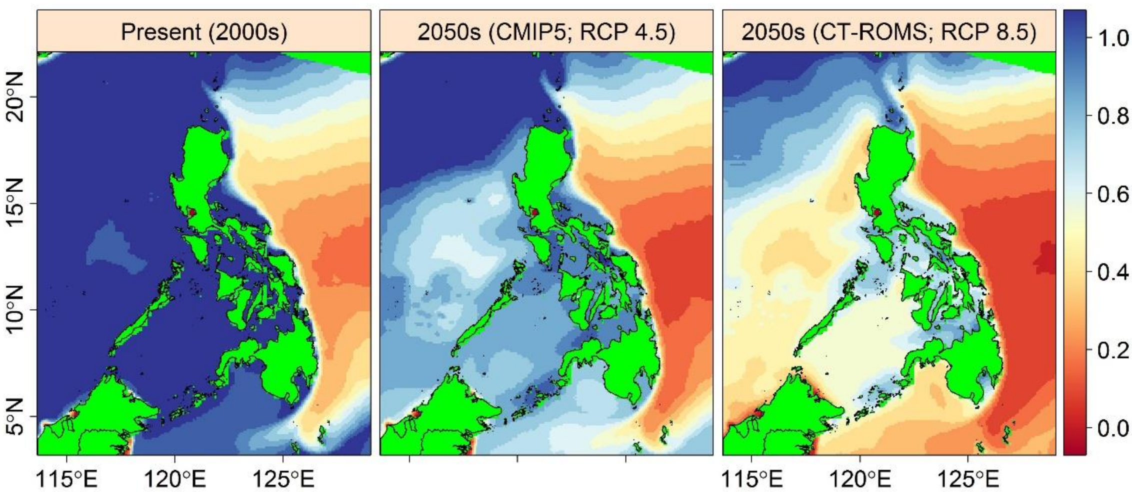
Projected Suitable Habitat for *Istiophorus platypterus*



Probability of occurrence for *Makaira mazara* by variable



Projected Suitable Habitat for *Makaira mazara*

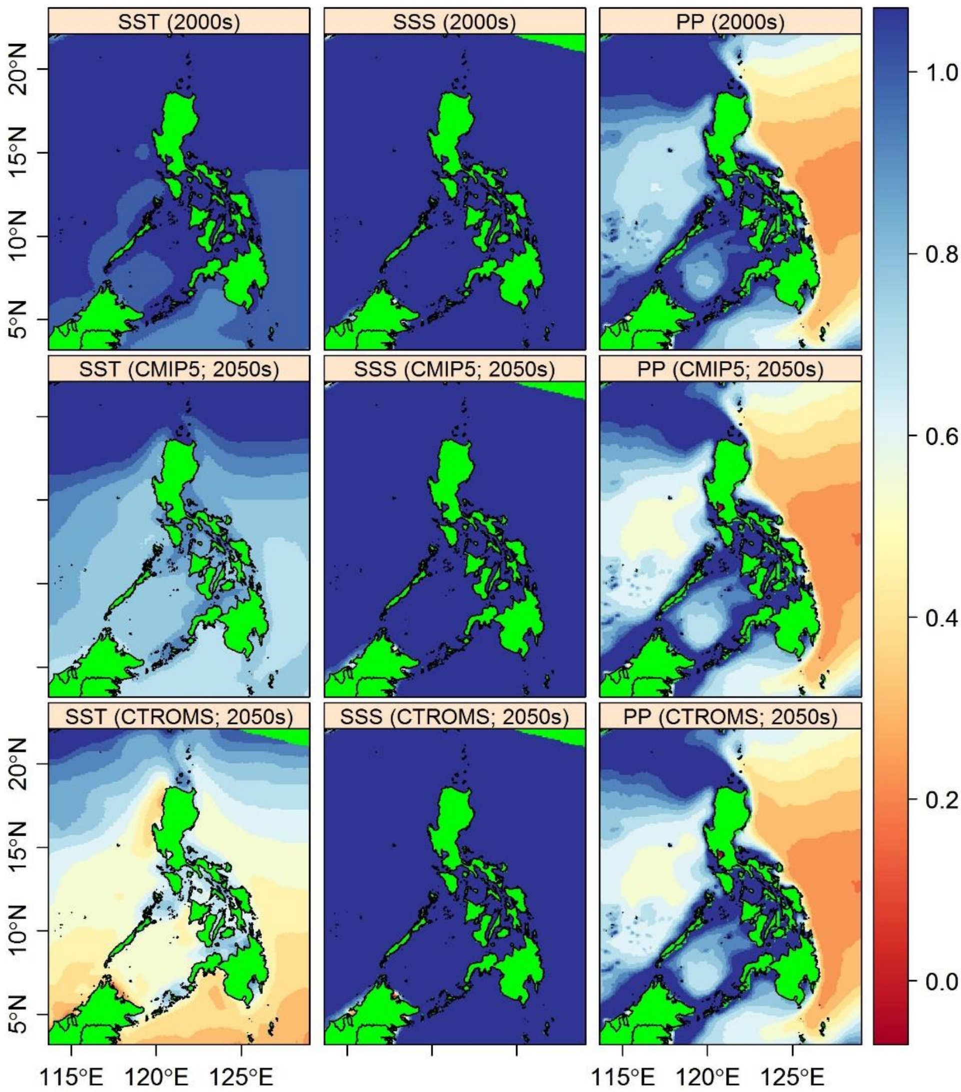


Eubleekeria splendens

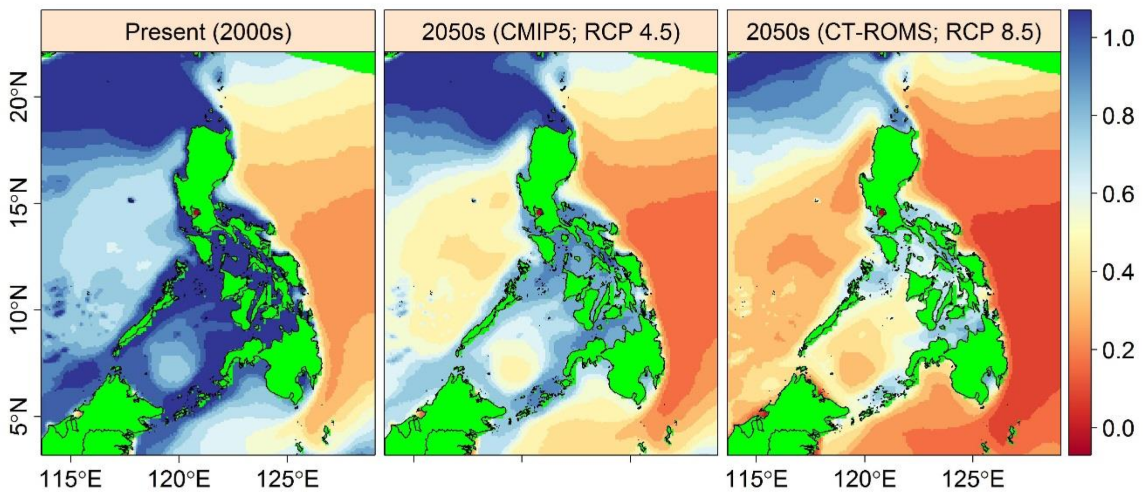
Splendid ponyfish (*"Lawayan"*)

MISCELLANEOUS DEMERSALS

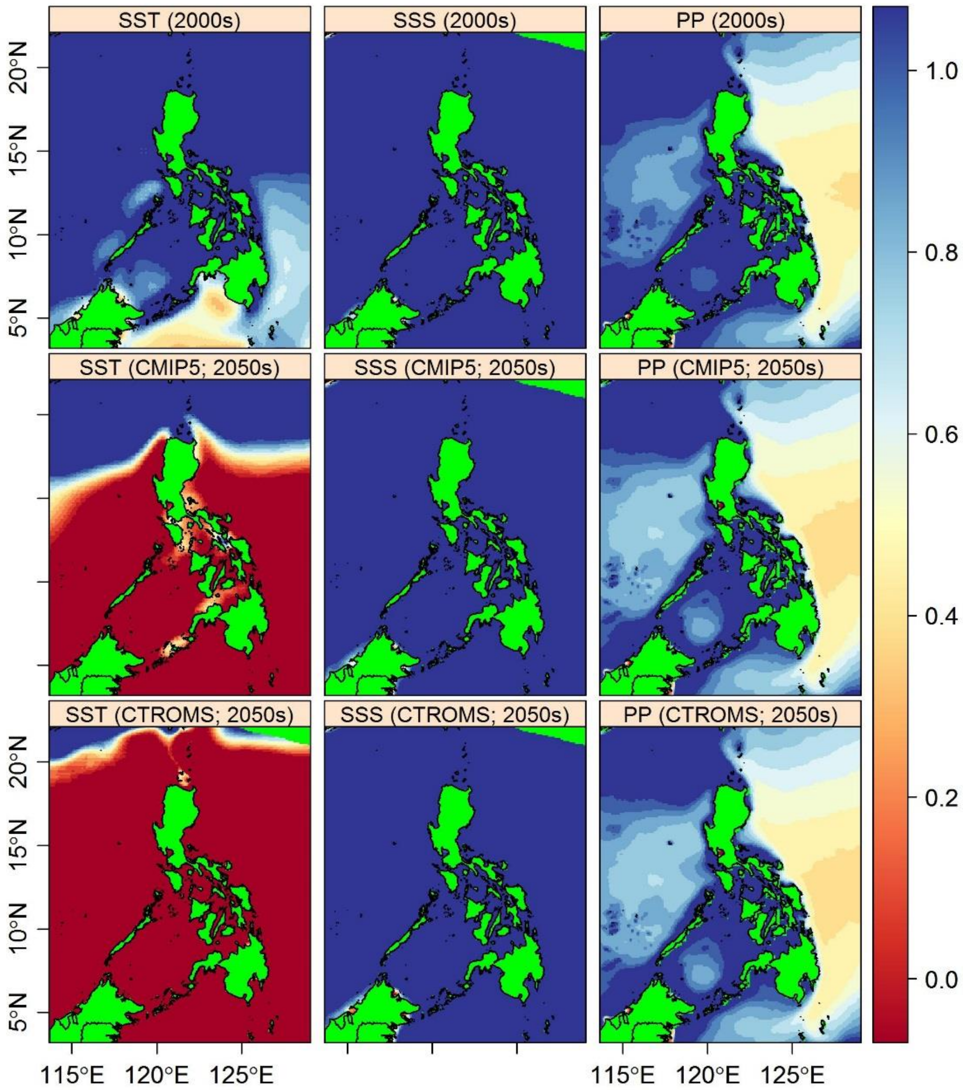
Probability of occurrence for *Eubleekeria splendens* by variable



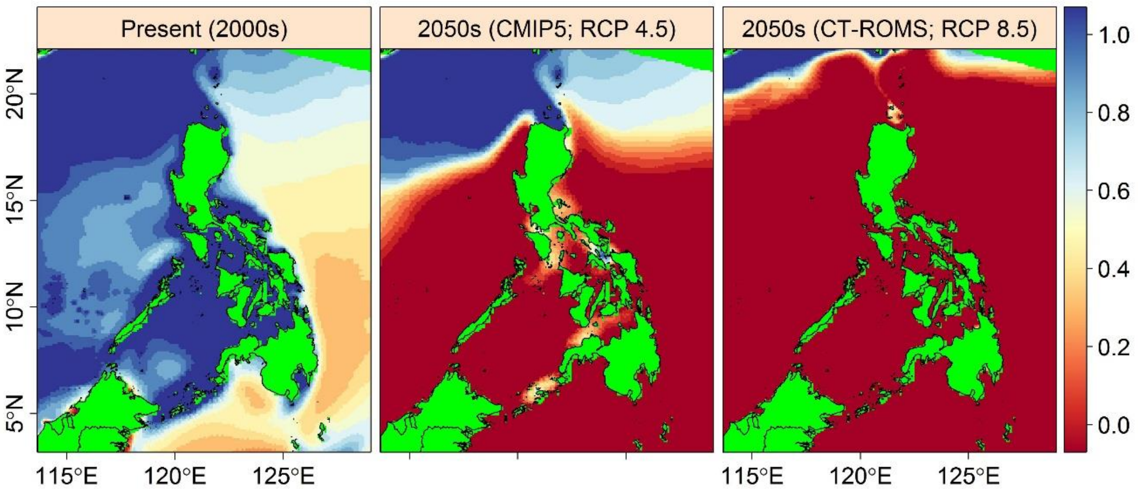
Projected Suitable Habitat for *Eubleekeria splendens*



Probability of occurrence for *Gazza minuta* by variable

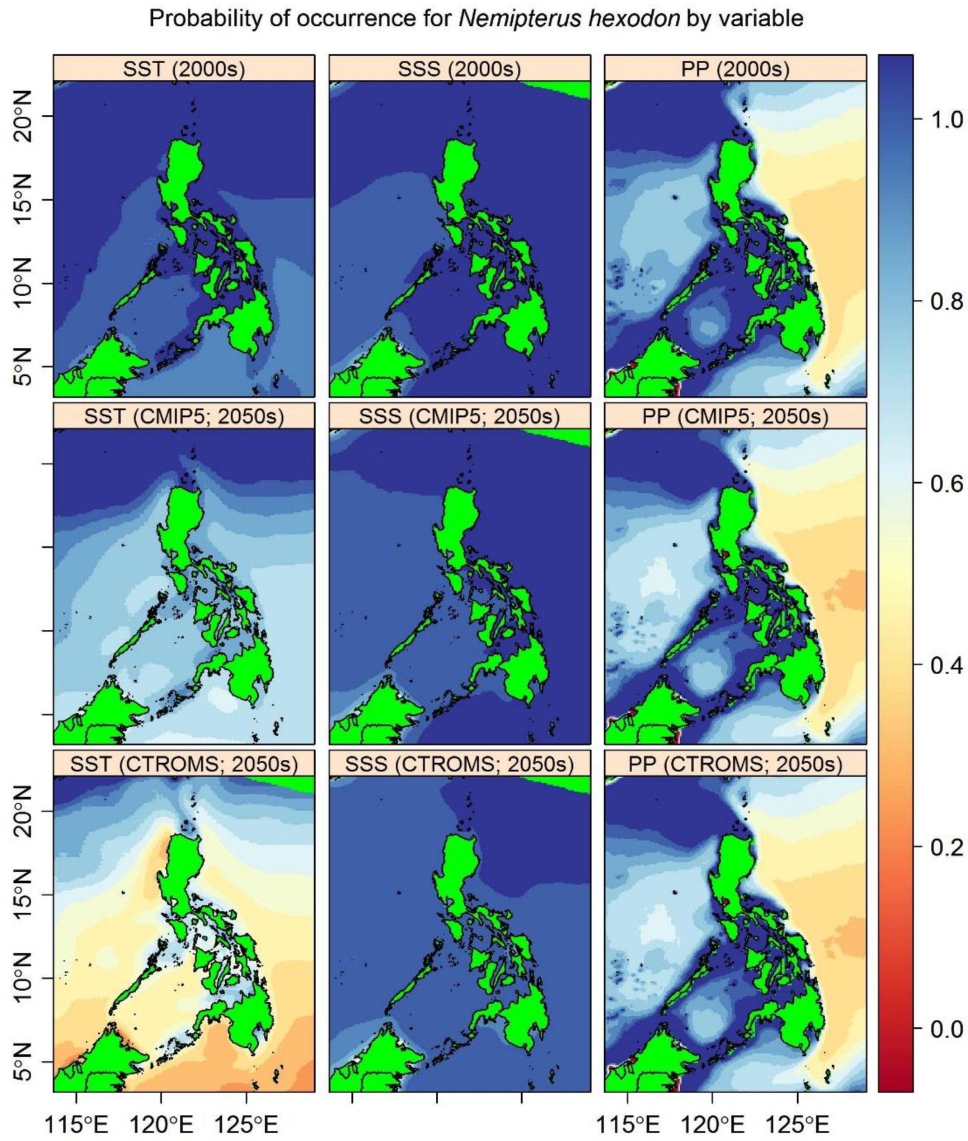


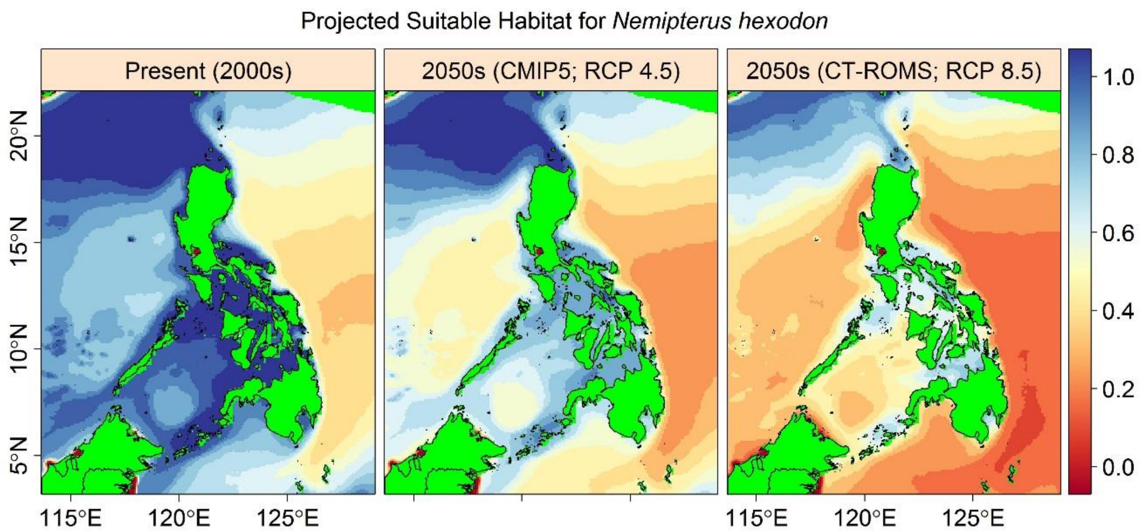
Projected Suitable Habitat for *Gazza minuta*



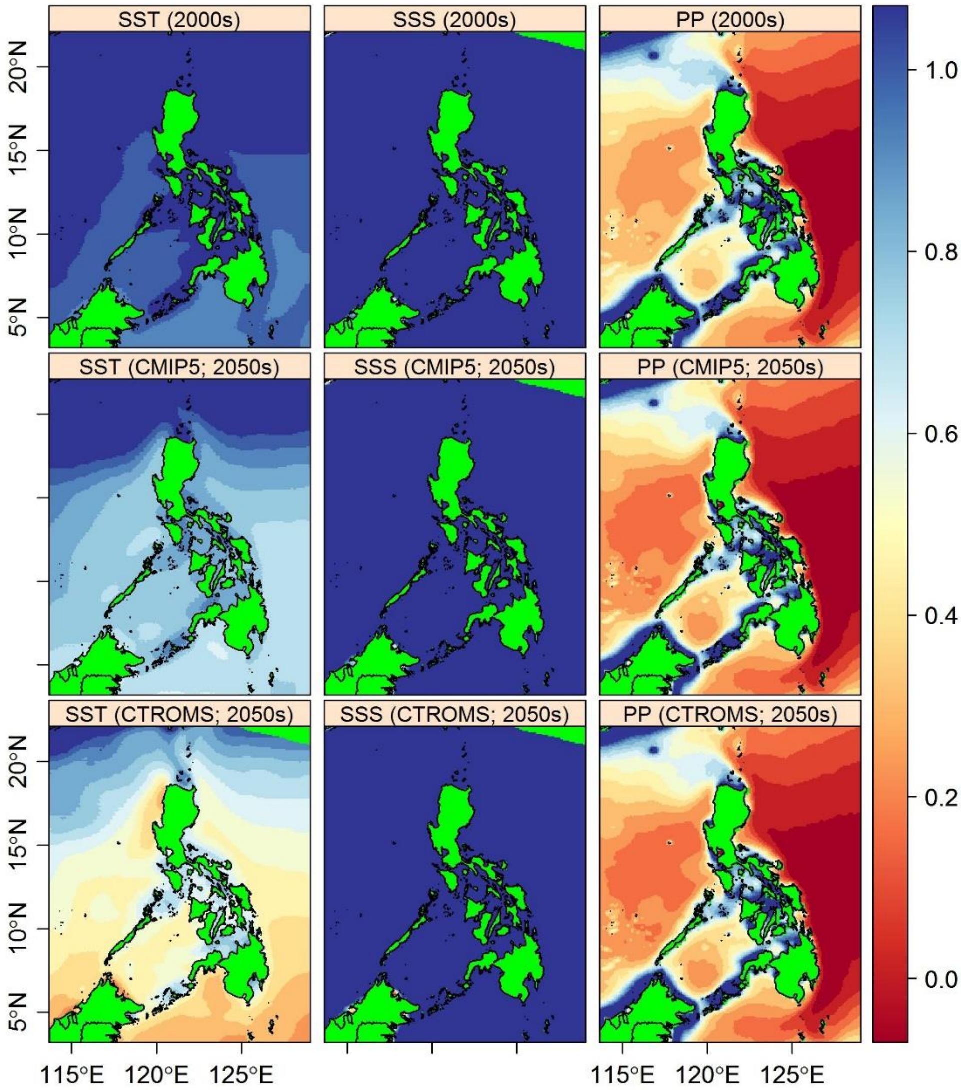
Nemipterus hexodon
Ornate threadfin bream (*"Sagisi-on*)

MISCELLANEOUS DEMERSALS

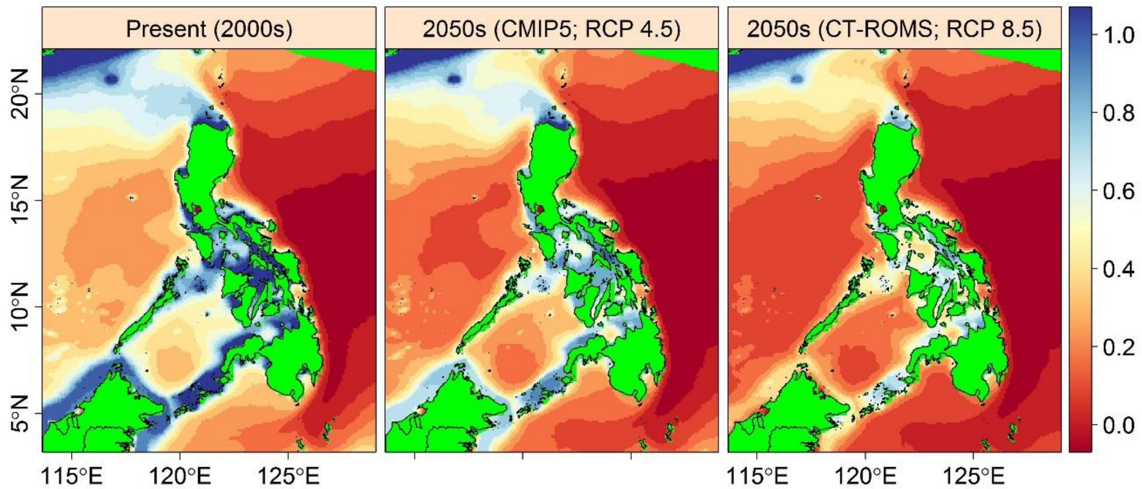




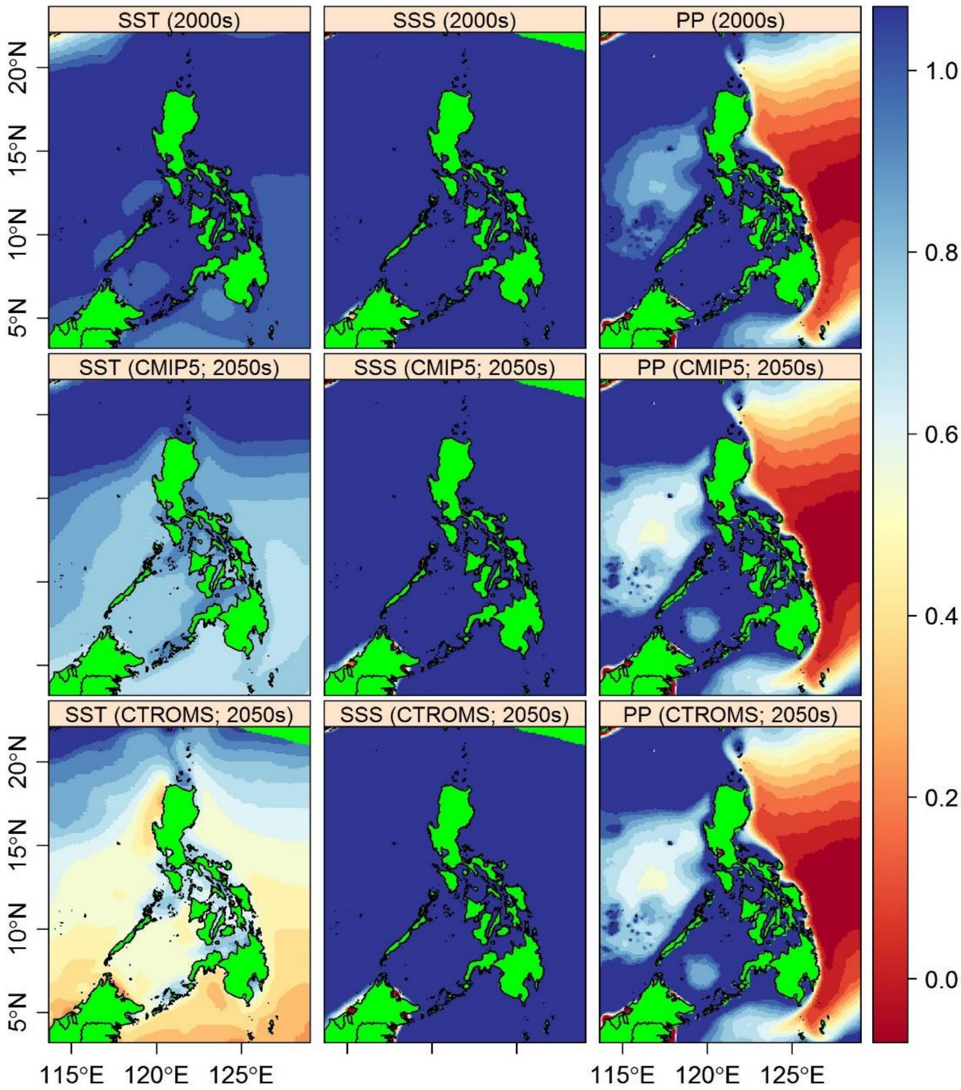
Probability of occurrence for *Otolithes ruber* by variable



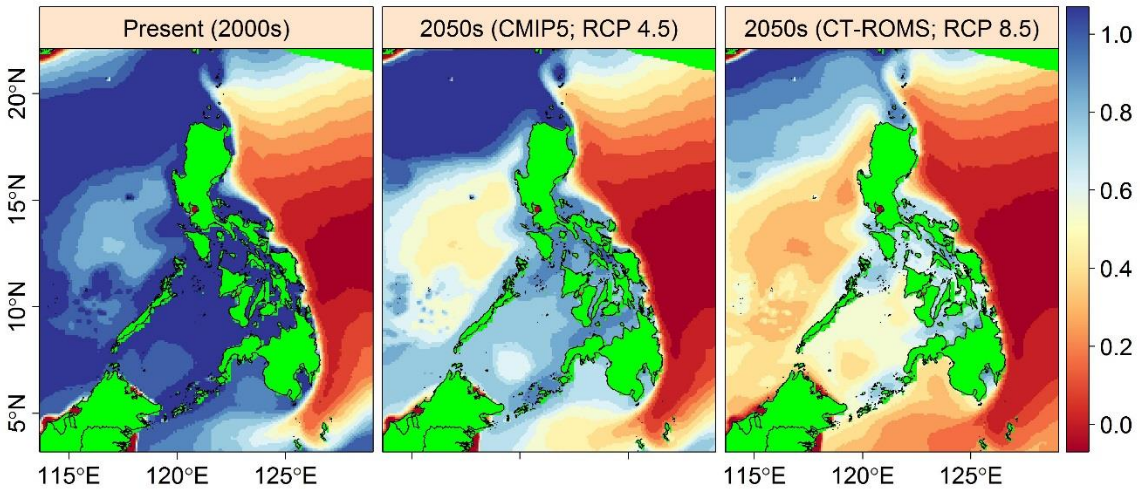
Projected Suitable Habitat for *Otolithes ruber*



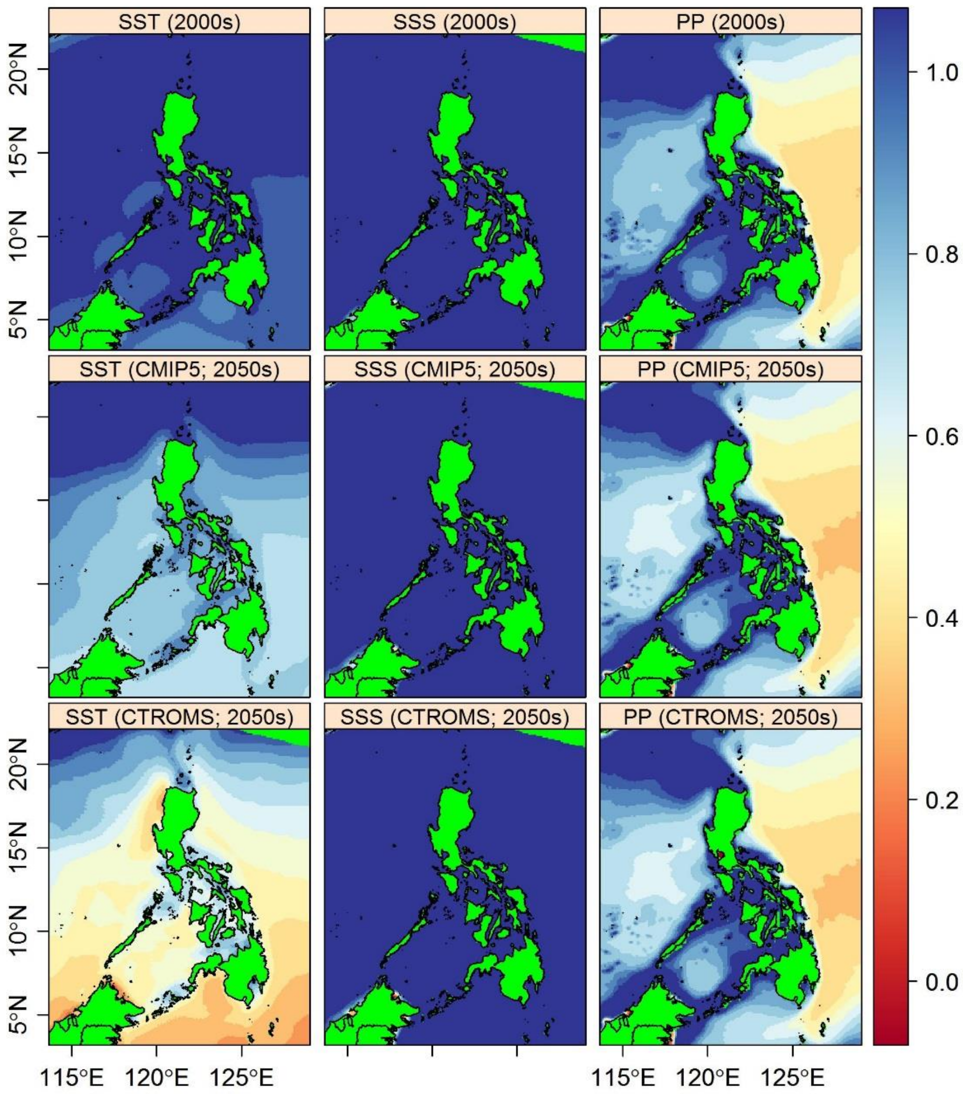
Probability of occurrence for *Oxyporhamphus micropterus* by variable



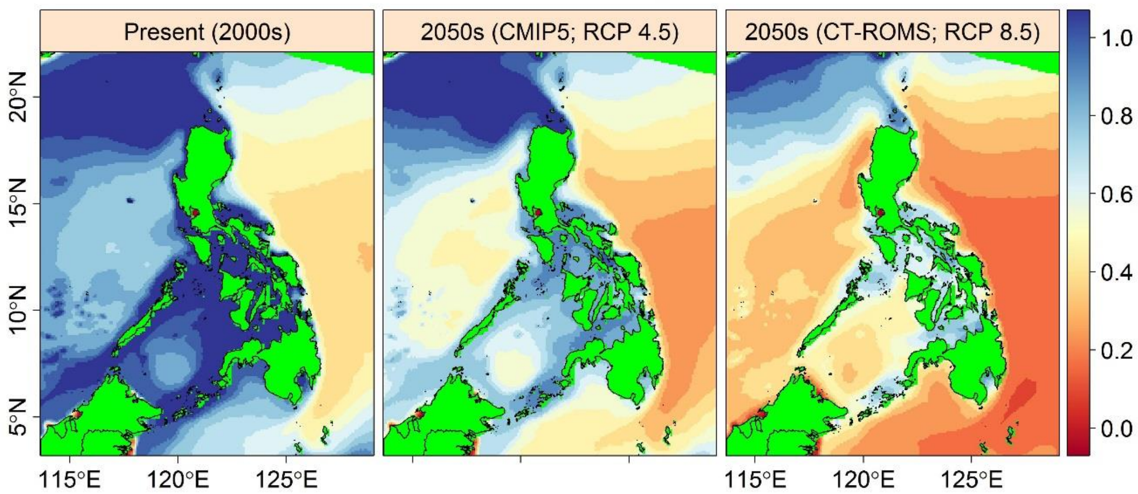
Projected Suitable Habitat for *Oxyporhamphus micropterus*



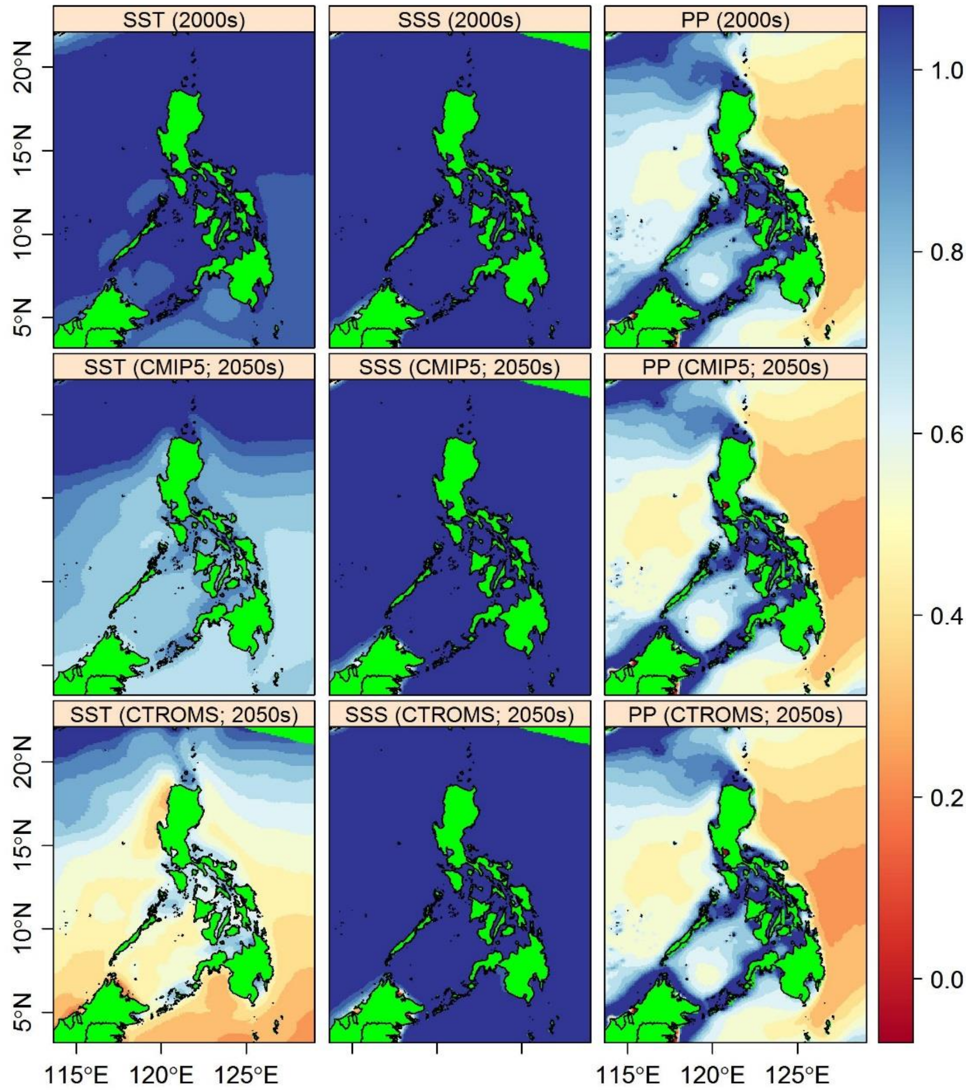
Probability of occurrence for *Pentaprion longimanus* by variable



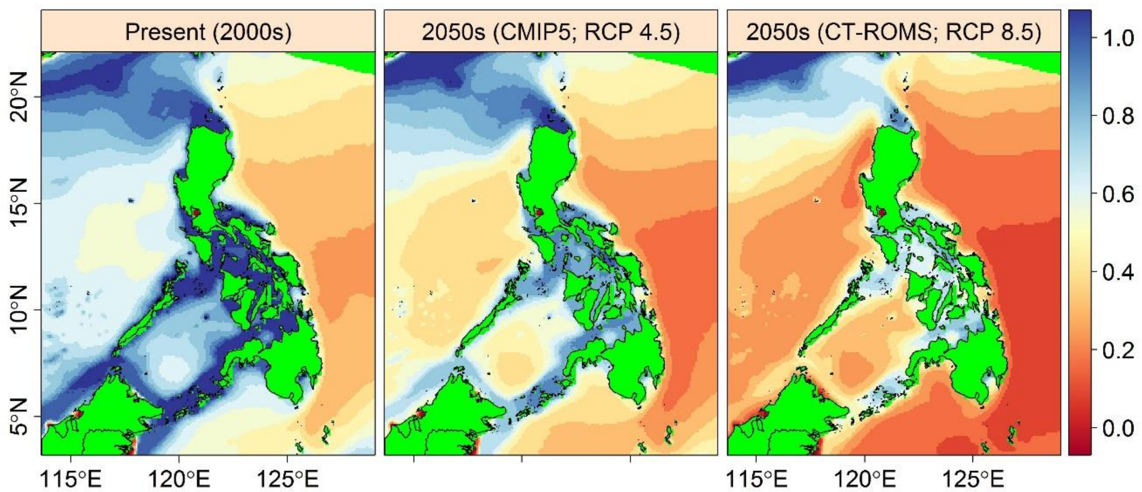
Projected Suitable Habitat for *Pentaprion longimanus*



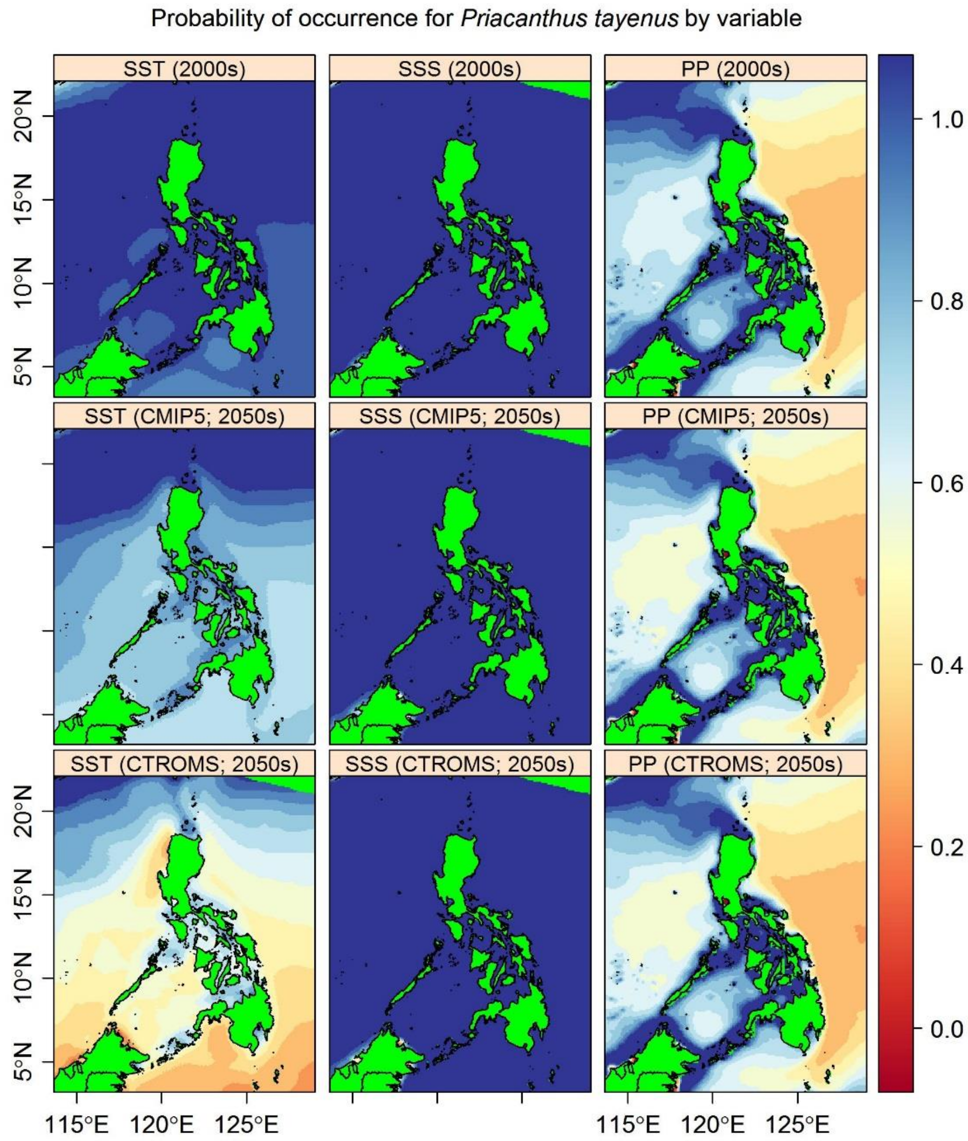
Probability of occurrence for *Photopectoralis bindus* by variable

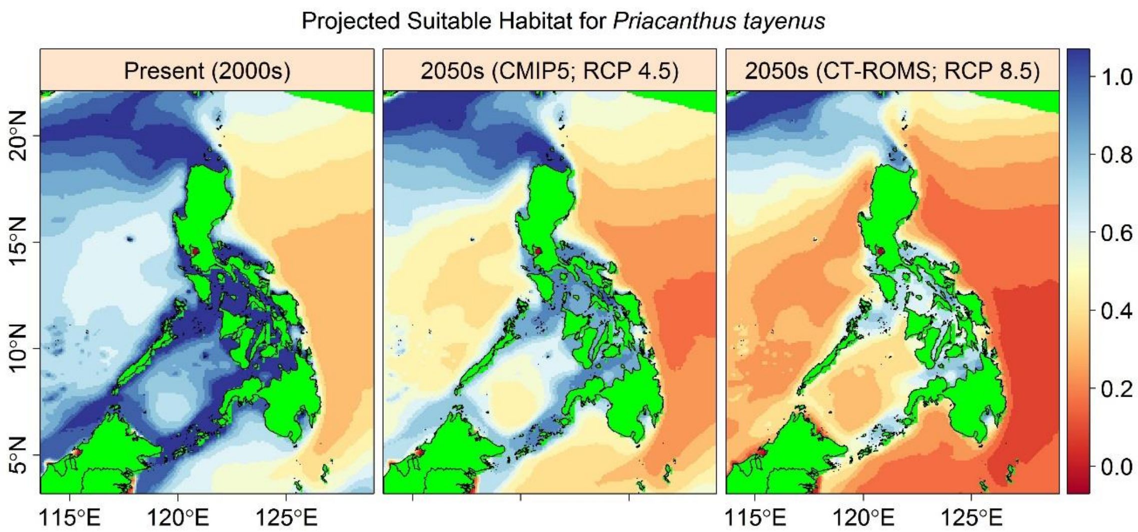


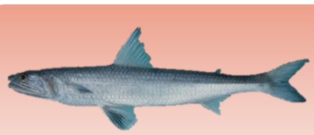
Projected Suitable Habitat for *Photopectoralis bindus*



Priacanthus tayenus
Purple-spotted bigeye (*"Siga"*)



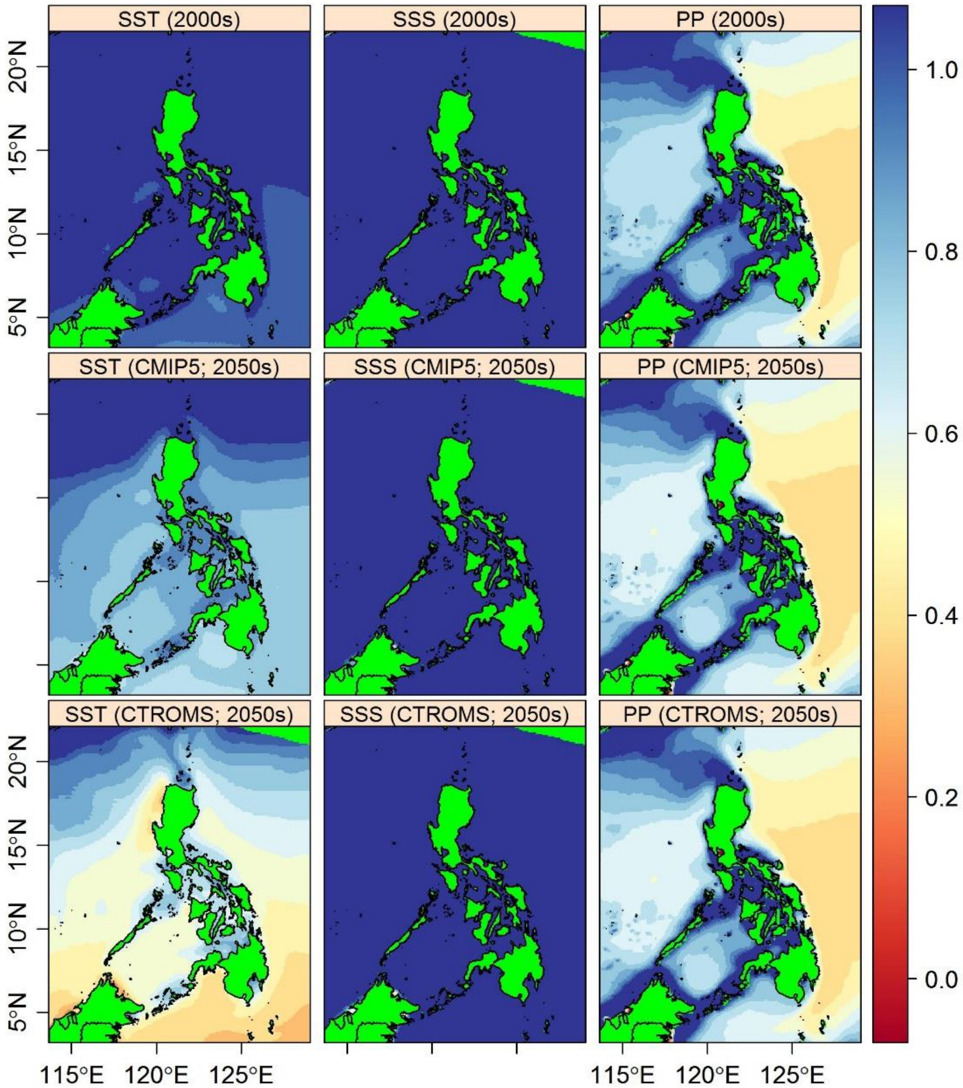




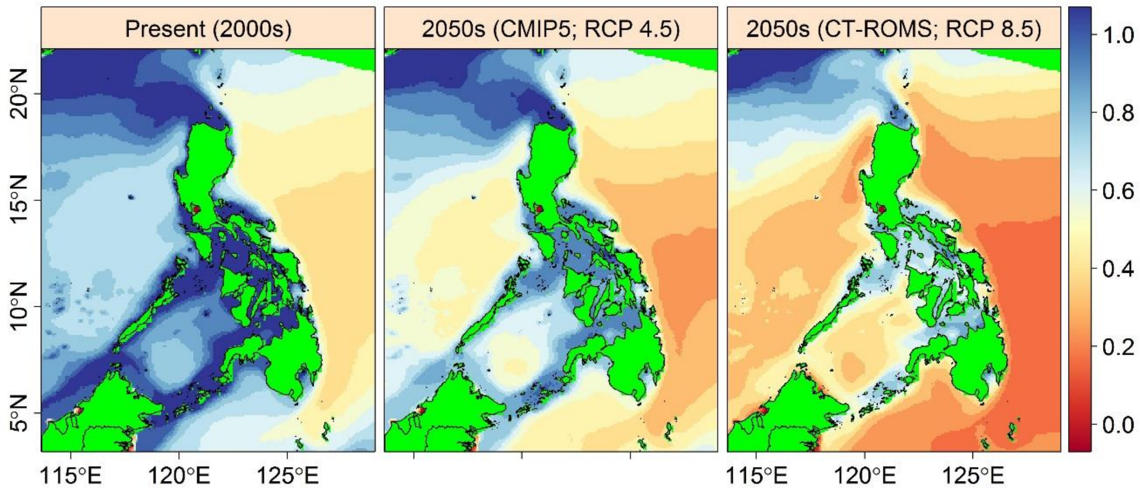
Saurida tumbil
Greater lizardfish (*"Bukto-bukto"*)

MISCELLANEOUS DEMERSALS

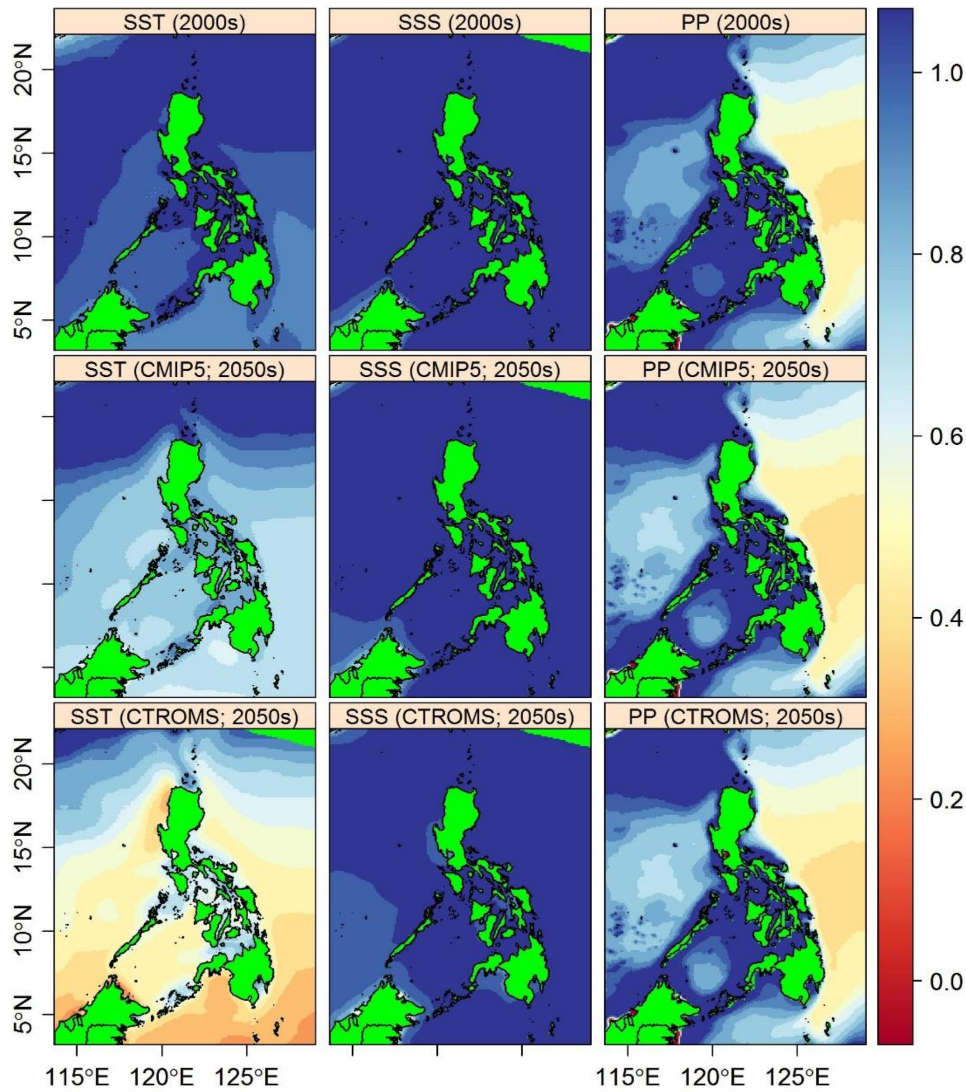
Probability of occurrence for *Saurida tumbil* by variable



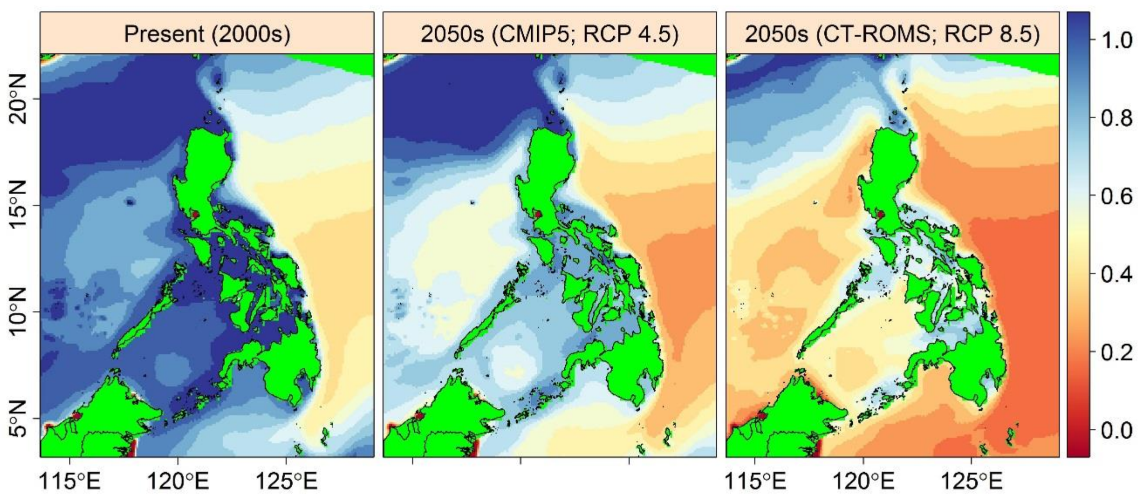
Projected Suitable Habitat for *Saurida tumbil*



Probability of occurrence for *Scolopsis taenioptera* by variable



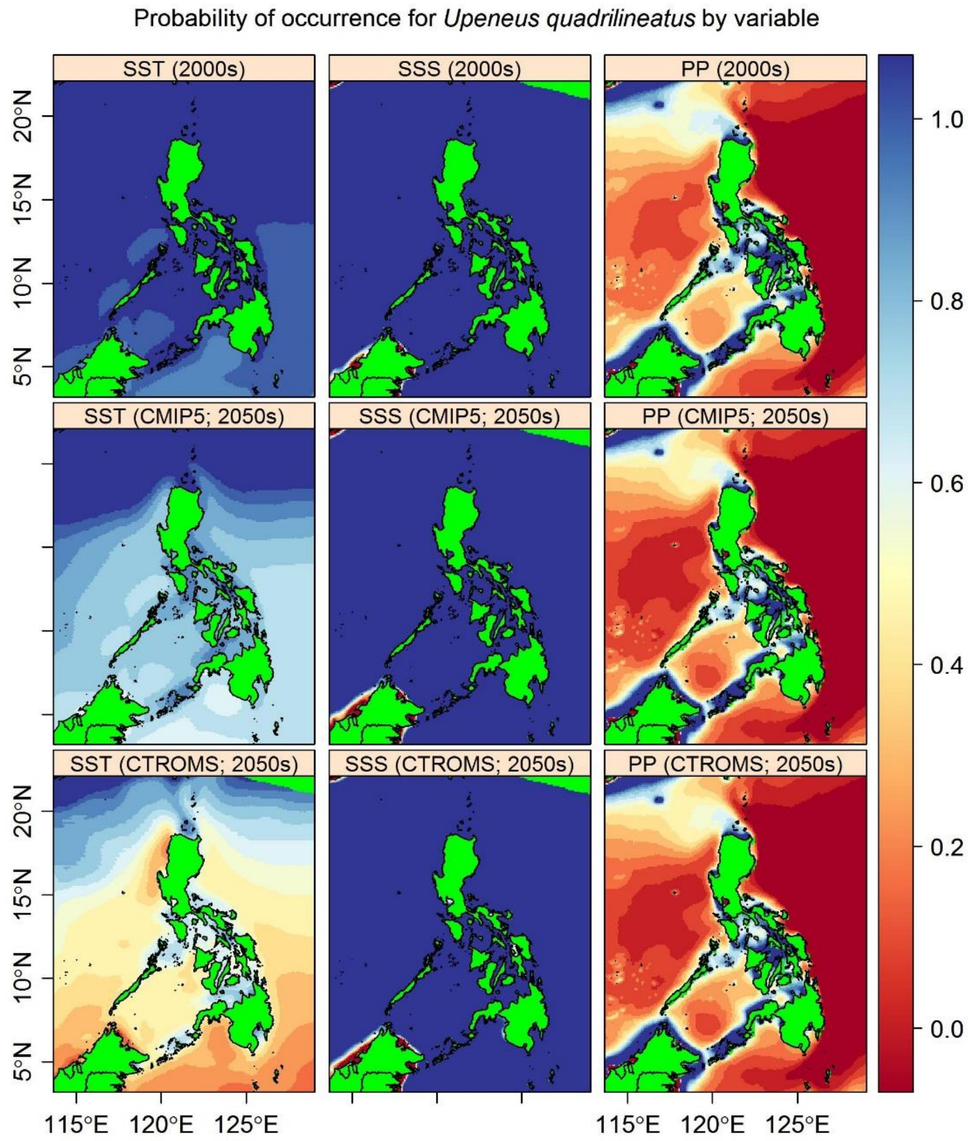
Projected Suitable Habitat for *Scolopsis taenioptera*

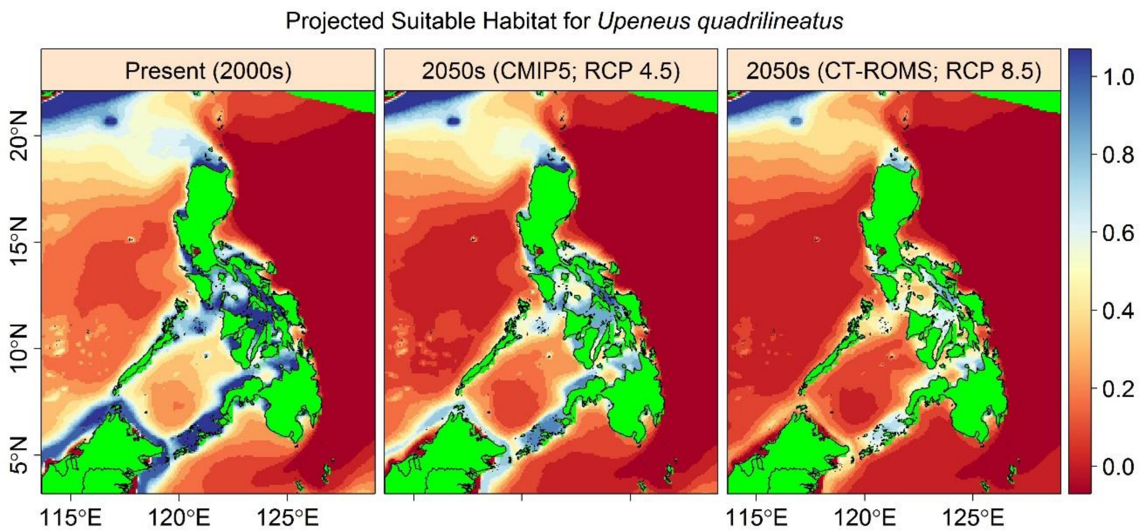


Upeneus quadrilineatus

Four-stripe goatfish (*"Tiaw"*)

MISCELLANEOUS DEMERSALS





REFERENCES

Assis, J., Tyberghein, L., Bosch, S., Verbruggen, H., Serrão, E.A. & De Clerck, O. (2018). Bio-ORACLE v2.0: Extending marine data layers for bioclimatic modelling. *Glob. Ecol. Biogeogr.*, 27, 277–284.

Behrenfeld, M. & Falkowski, P. (1997). Photosynthetic rates derived from satellite based chlorophyll concentration. *Limnol. Oceanogr.*, 42, 1–20.

Castruccio, F.S., Curchitser, E.N. & Kleypas, J.A. (2013). A model for quantifying oceanic transport and mesoscale variability in the Coral Triangle of the Indonesian/Philippines Archipelago. *J. Geophys. Res. Ocean.*, 118, 6123–6144.

Cheung, W.W.L., Bruggeman, J. & Butenschön, M. (2018). Projected changes in global and national potential marine fisheries catch under climate change scenarios in the twenty-first century. In: *Impacts of climate change on fisheries and aquaculture Synthesis of current knowledge, adaptation and mitigation options* (eds. Barange, M., Bahri, T., Beveridge, M.C.M., Cochraine, K.L., Funge-Smith, S. & Poulain, F.). Food and Agriculture Organization of the United Nations, Rome, pp. 63–85.

Cheung, W.W.L., Lam, V.W.Y. & Pauly, D. (2008). Dynamic bioclimate envelope model to predict cliamte-induced changes in distribution of marine fishes and invertebrates. In: *Modelling present and climate-shifted distribution of marine fishes and invertebrates*. Fisheries Centre, University of British Columbia, Vancouver, Canada, pp. 5–50.

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R. & Pauly, D. (2009). Projecting global marine biodiversity impacts under climate change scenarios. *Fish Fish.*, 10, 235–251.

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R., Zeller, D., *et al.* (2010). Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Glob. Chang. Biol.*, 16, 24–35.

Ferrera, C.M., Jacinto, G.S., Chen, C.T., San Diego-McGlone, M.L., Datoc, M.F.K.T., Lagumen, M.C.T., *et al.* (2017). Carbonate parameters in high and low productivity areas of the Sulu Sea, Philippines. *Mar. Chem.*, 195, 2–14.

Kaschner, K., Kesner-Reyes, K., Garilao, C., Rius-Barile, J., Rees, T. & Froese, R. (2016a). *AquaMaps: Predicted range maps for aquatic species. World wide web Electron. Publ. www.aquamaps.org*.

Kaschner, K., B. Schneider, C. Garilao, K. Kesner-Reyes, J. Rius-Barile and R. Froese (eds.). (2016b) *AquaMaps Environmental Dataset: Half-Degree Cells Authority File (HCAF).* World Wide Web electronic publication, www.aquamaps.org/data/main.php, ver. 6, 08/2016.

Khalil, I., Atkinson, P.M. & Challenor, P. (2016). Looking back and looking forwards: Historical and future trends in seasurface temperature (SST) in the Indo-Pacific region from 1982 to 2100. *Int. J. Appl. Earth Obs. Geoinf.*, 45, 14–26.

Kleypas, J. a, Castruccio, F.S., Curchitser, E.N. & McLeod, E. (2015). The impact of ENSO on coral heat stress in the western equatorial Pacific. *Glob. Chang. Biol.*, 21, 2525–2539.

Lam, V.W.Y., Cheung, W.W.L., Reygondeau, G. & Sumaila, U.R. (2016). Projected change in global fisheries revenues under climate change. *Sci. Rep.*, 6, 32607.

Paun, A., Acton, L. & Wai-Shin, C. (2018). *Fragile Planet: Scoring climate risks around the world*.

Peñaflor, E.L., Skirving, W.J., Strong, A.E., Heron, S.F. & David, L.T. (2009). Sea-surface temperature and thermal stress in the Coral Triangle over the past two decades. *Coral Reefs*, 28, 841–850.

Santos, M.D., Barut, N.C. & Bayate, A.D. (Eds.). (2017). *National Stock Assessment Program: The Philippine Capture Fisheries Atlas*. Bureau of Fisheries and Aquatic Resources - National Fisheries Research and Development Institute, Quezon City, Philippines.

Stock, C.A., John, J.G., Rykaczewski, R.R., Asch, R.G., Cheung, W.W.L., Dunne, J.P., *et al.* (2017). Reconciling fisheries catch and ocean productivity. *Proc. Natl. Acad. Sci.*, 114, E1441–E1449.

Sumaila, U.R., Cheung, W.W.L., Lam, V.W.Y., Pauly, D. & Herrick, S. (2011). Climate change impacts on the biophysics and economics of world fisheries. *Nat. Clim. Chang.*, 1, 449–456.

Thompson, D.M., Kleypas, J., Castruccio, F., Curchitser, E.N., Pinsky, M.L., Jönsson, B., *et al.* (2018). Variability in oceanographic barriers to coral larval dispersal: Do currents shape biodiversity? *Prog. Oceanogr.*, 165, 110–122.

Villanoy, C.L., Cabrera, O.C., Yniguez, A., Camoying, M., Guzman, A. De & David, L.T. (2011). Monsoon-Driven coastal upwelling off zamboanga peninsula. *Oceanography*, 24, 156–165.

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