Report for project: Climate change and fisheries on the Parque Nacional de Cocos, Costa Rica

December, 2023

1 Summary

In this project we set to understand the role of Cocos National Park (PNC) and the Marine Area Bicentenario (AMM) in the protection of highly migratory and commercialy important fish species.

2 Methods

2.1 Projecting species distributions

We projected changes in biomass and potential catches of exploited species using a linked climate-fish-fisheries model called the dynamic bioclimate envelope model (DBEM). See Cheung *et al* (2009, 2010, 2016) for in-depth descriptions of the model. In brief, the DBEM has a horizontal spatial resolution of 0.5 o latitude x 0.5 o longitude for the sea surface and bottom, and simulates annual average abundance and catches of each modelled species. The DBEM uses spatially explicit outputs from Earth System Models, including temperature, oxygen level, salinity, surface advection, sea ice extent and net primary production. Sea bottom and surface temperature, oxygen and salinity are used for demersal and pelagic species, respectively. These outputs are then used to calculate an index of habitat suitability for each species in each spatial cell. Other information used to calculate habitat suitability includes bathymetry and specific habitats (coral reef, continental shelf, shelf slope, and seamounts). Changes in carrying capacity in each cell is assumed to be a function of the estimated habitat suitability, and net primary production in each cell.

The model simulates the net changes in abundance in each spatial cell based on logistic population growth, fishing mortality, and movement and dispersal of adults and larvae modelled through advection–diffusion–reaction equations. Biomass is calculated from abundance by using a characteristic weight representing the average mass of an individual in the cell. The model simulates how changes in temperature and oxygen content would affect the growth of the individual using a submodel derived from a generalized von Bertalanffy growth function.

2.1.1 Rellocating fishing effort

Fishing intensity was assumed in the fisheries scenarios, represented by fishing mortality rates (F) relative to the F required to achieve maximum sustainable yield (i.e., F_{MSY}). As the model assumes logistic population growth, following the derivation from a simple surplus production model, FMSY is approximately equal to half of the intrinsic growth rate of each species.

To reallocate fishing in the DBEM from protected grids to surrounding, we took the *area protected* and divided by the *total area* of each grid cell that contain any protection. We then reallocate that protected area proportion to the surrounding cells in form of fishing effort (F):

$$prop = 1 + \frac{area_{protected}/area_{total}}{n_{surrounding}}$$

where $n_{surrounding}$ is the number of grid cells surrounding an MPA.

Thus, for example, if status = protected, prop = 0 while if status = unprotected then prop = 1. Moreover, if there are 4 cells surrounding the protected one cell, then prop = 1.25, if there are 2 surrounding cells then prop = 1.5,if there are 10 surrounding cells then prop = 1.1. If, for example, the protected cell is only partially covered by a protected area, say 50%, and there are 4 surrounding cells, then prop = .5 for the protected cell, and prop = 1.125 (1 + .5/4) for the surrounding cells.

Based on the computed prop, we re-estimated fishing mortality (F) (i.e., reallocate fishing effort) in the *surrounding* cells as:

$$\hat{F} = F * prop$$

where $\hat{F}$ is the fishing mortality adjusted for the 'spill-over' of fishing effort from the *protected* grid cell. If the cell is not protected nor surrounding a protected grid cell then $\hat{F} = F$, that is, fishing mortality will not be adjusted for the no-take MPA effects.

2.1.2 Climate change impacts on MPAs

To explore the impacts of climate change in the MPAs, we evaluated the percentage change in biomass and MCP in each grid cell (ΔB_i) between two time periods representing the present time (B_p - 1995–2014) and mid-21st century (B_m 2030–2049) to reduce climate variability.

$\Delta B_i = \frac{B_p - B_m}{B_m} * 100$ 100where B x is the biomass at mid or end of the 21 st century and B y is the biomass at present time.

where i represents every grid cell in the study area. Note that for the aggregated results we sum the biomass of all species in each grid cell prior to estimate ΔB_i

2.1.3 Climate change models and scenarios

The DBEM was forced with projections from three new-generation Earth system models (ESMs) from Phase 6 of the Coupled Model Intercomparison Project (CMIP6). The ESMs included were the Geophysical Fluid Dynamics Laboratory (GFDL)-ESM4 (Dunne et al., 2020), the Institut Pierre-Simon Laplace (IPSL)-CM6A-LR (Boucher et al., 2020), and the Max Planck Institute Earth System Model (MPI)-ESM1.2 (Gutjahr et al., 2019). Climate change projections followed two contrasting scenarios according to the shared socio-economic pathways (SSPs) and Representative Concentration Pathways (RCPs): SSP1-RCP2.6 (SSP1-2.6) and SSP5-RCP8.5 (SSP5-2.6) scenarios (Gütschow et al., 2021; Meinshausen et al., 2020). The SSP1-2.6 and SSP5-8.5 scenarios assume "strong mitigation" and "no mitigation" with radiative forcing stabilized at 2.6 W/m^2 and 8.5 W/m^2, respectively, by the end of the 21st century.

2.2 Study area

We gridded the area around the MPAs to a spatial resolution of 0.5^o latitude x 0.5^o longitude to match the DBEM resolution. We classified the grid cells into protected, surrounding, and open waters (i.e., not protected). Protected areas include cells that contain an MPA polygon (cells that fully or partially contain an MPA) while cells that were immediately adjacent to an MPA cell were classified as surrounding waters. All other ocean cells were considered unprotected (Figure 1). We limit the study area (i.e., analysis area) to 200 km (~ 2^0) around the border of the MPAs.

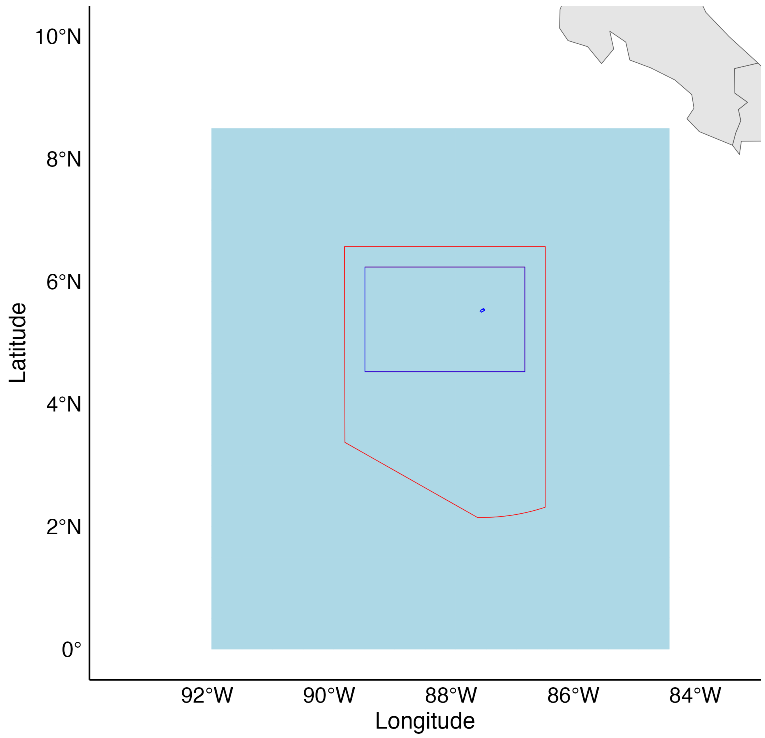


Figure 1: Coco MPA in blue and AMMB area in red over DBEM grid cells (light blue) included in the analysis

2.3 Conservation scenarios

The current project considers three different scenarios which differ in the amount and location available for fishing. The scenarios were build in collaboration with MarViva and range from a conservation inclined scenario (S1) to a more fisheries inclined scenario (S2). Below we detail each scenario:

2.3.1 Scenario S1 (Conservation inclined)

- PNC, 100% protected
- AMM, $F = \frac{1}{2}MSY$
- Everything else F = F_{MSY}
- Reallocate fishing effort from PNC and AMM to the grid cells surrounding AMM

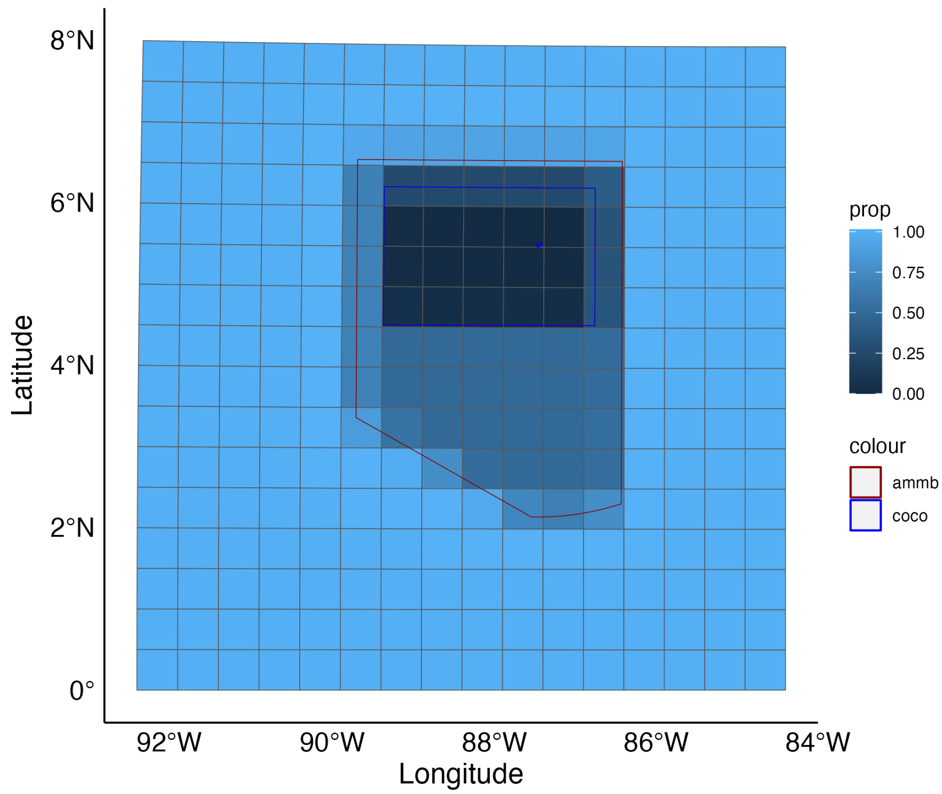


Figure 2: Scenario 1. Prop = proportion of area that is open to fishing.

2.3.2 Scenario S2 (Fishing inclined):

- PNC, 100% protected
- AMM, $F = F_{MSY}$
- Everything else $F = F_{MSY} * 1.5$
- Fishing from PNC gets reallocated to cells surrounding PNC (which are AMM cells)

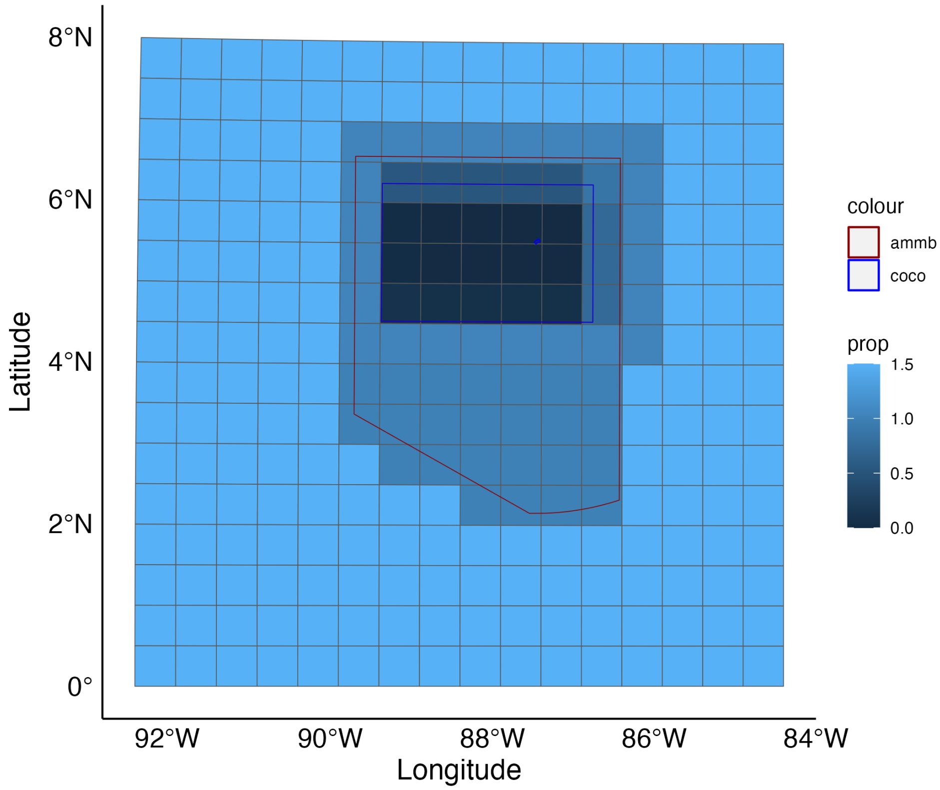


Figure 3: Scenario 2. Prop = proportion of area that is open to fishing

2.3.3 Scenario S3 (IUU inclined)

- PNC, 90% protected (Allows for 10% fishing as IUU)
- AMM, $F = F_{MSY} * 1.5$
- Everything else $F = F_{MSY} * 1.5$
- fishing from PNC gets reallocated to cells surrounding PNC (which are AMM cells)

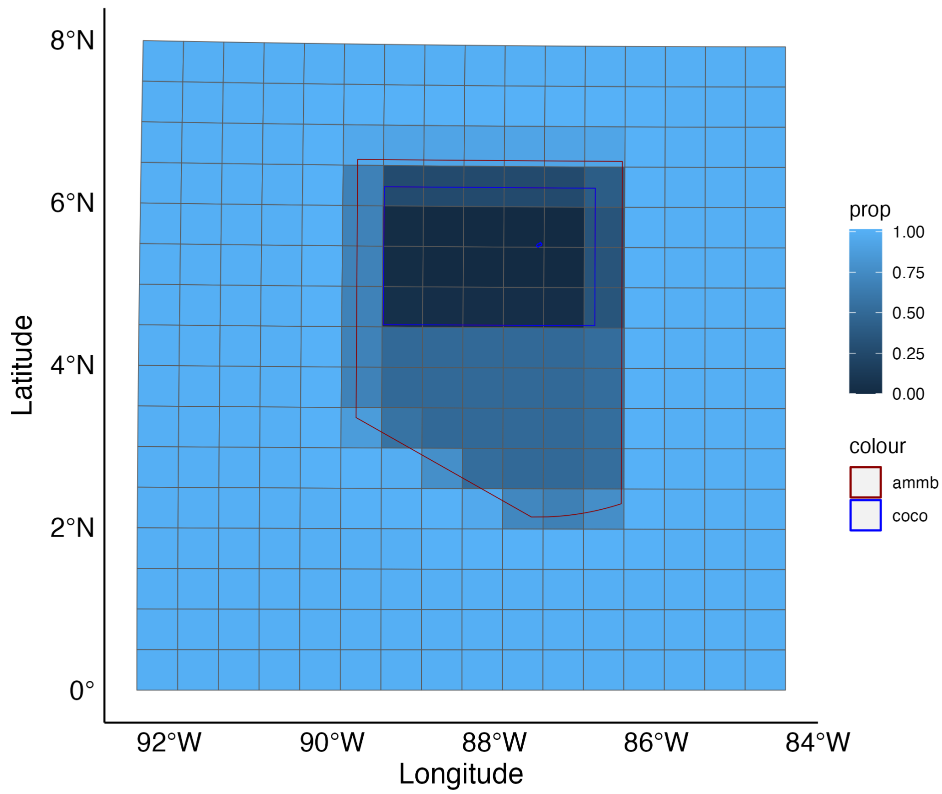


Figure 4: Scenario 3. Prop = proportion of area that is open to fishing

2.4 Species

The current analysis explored the impacts of climate change on 38 species that occur in the Eastern Tropical Pacific (See Species List on GitHub repository.

2.5 Code and Data

All of the data analysis and statistics were completed with the statistical software R version 4.3.1 (2023-06-16) and can be found at github.com/jepa/cocos_mpa. Data for this project can be downloaded from this repository.

2.6 Caveats

There are a few caveats to this report that are important to take into consideration when reading the results. First, the DBEM is a mechanistic species distribution model, thus, it does not take into consideration species interactions, species potential evolutionary adaptation trough space and time, nor any other human-induced effect (e.g., mining, shipping, pollution). Second, as any mathematical model, the DBEM is subjected to the original input data (See report Data folder, *distributions*) including resolution and distribution. The outputs from the ESMs are produced at a 1 degree Lat x Long resolution and further downscaled to 0.5 degrees to match the DBEM resolution. Yet, such resolution might not be coerce enough to capture local (coastal) processes that are affecting the ecosystem around PNC and AMM. Such element in combination with the small size of the MPA, especially cocos which represents 15 complete grid-cells and 9 partial cells, creates a substantial level of uncertainty in the projections. Third, fishing effort is redistributed proportionally around the grid-cells that are closed to fishing. In reality, it is possible that such effort is not proportionally distributed around the no-take MPA but rather localized in some areas, or not re-distributed at all. Other modelling exercises that incorporate different mechanisms in which fishing effort is re-allocated around a no-take MPA could help illuminate how social and economic factors related to fishing may affect the contribution of MPAs under climate change. For these reason, the results presented here, even at their most aggregated level, should be interpreted as an example of what could happen to the region, rather than definite predictions of what will happen to each stock of the Easter Tropical Pacific under climate change. Replicating the analysis here with finer-scale models (e.g., Regional Ocean Modeling System - ROMS) and data (if existent) would help validate the DBEM while also producing more reliable results.

3 Results

In this project we set to understand the role of *Cocos National Park* (PNC) and the *Marine Area Bicentenario* (AMM) in the protection of highly migratory and commercially important fish species under climate change. We explore this under three different management scenarios (S1, S2, and S3) and two different climate change scenarios (SSP1-26 and SSP5-85). Moreover, we analyze here the results at the aggregated level (i.e., all species lumped together) and by commercial category (e.g., sharks, tunas, etc) according to the *Sea Around Us* classification. Please note that while we provide species-specific results, it is crucial to approach these findings with caution due to the substantial level of uncertainty involved. Given the limitations of the model and data, such results should be interpreted as an academic exercises rather than definite predictions of what will happen to each stock of the Easter Tropical Pacific under climate change.

3.1 Aggregated results

According to our results, aggregated fish biomass and MCP will both see an overall decline in the study area throughout the 21^{st} century, regardless of the climate change and management scenario. This suggests that MPAs alone do not have the capacity of counteract the negative effects of climate change in the region (Figure 5). However, differences exist between scenarios. Our projections show that Scenario S1 will loose less biomass and MCP than other scenarios throughout the 21^{st} century. This suggests that the extra protection that this scenario provides (No fishing within cocos MPA) in combination with proper fisheries management (i.e., $F = F_{msy}$ in areas where fishing is allowed) provides a buffer against the negative impacts of climate change (Figure 5). On the other hand, Scenario S3, which is the least protective of all (90% of cocos under no fishing) and higher level of over fishing (i.e., fishing outside the Cocos polygon is $F = F_{msy} * 1.5$) is projected to have the largest loses due to climate change.

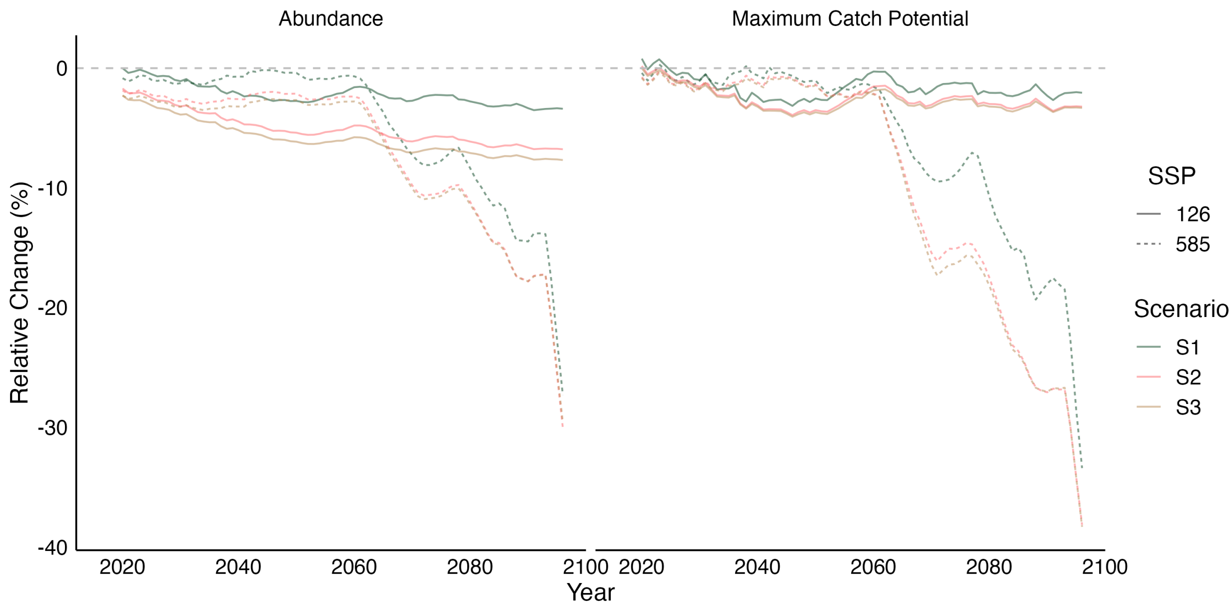


Figure 5: Trend of change in biomass relative to the historical period color-coded by management scenario and SSP (linetype). Ten years tunning average.

The difference between scenarios is substantial in terms of biomass by the middle of the 21^{st} century (Figure 6). Here, Scenario S1 will loose significantly less biomass than scenarios S2 and S3 who present no significant difference between them. This pattern is the same for both SSPs as is to be expected since SSP trajectories do not vary much before 2050. Interestingly, the reduced biomass loss does not translate to MCP as the scenarios are not significantly different to each other.

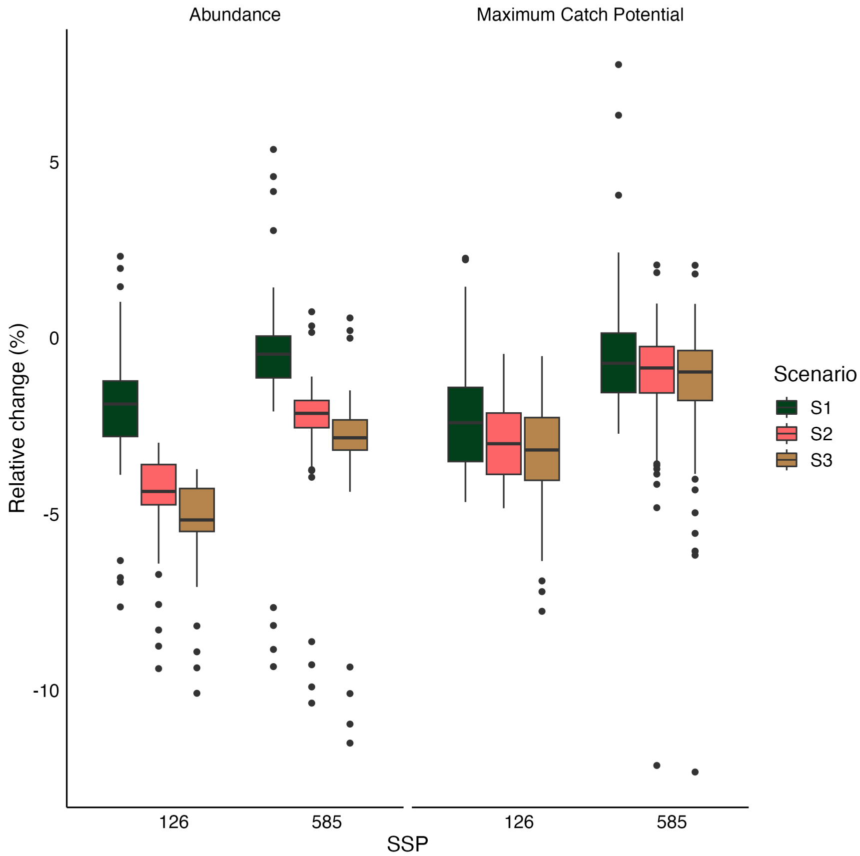


Figure 6: Coco MPA in blue and AMMB area in red over DBEM grid cells (light blue) included in the analysis

Spatially speaking, by the 21^{st} century, Scenario S1 shows areas with positive changes in biomass (up to 5%) relative to historical time period (Figure 7). Such regions are located around the north and south boundaries of the MPAs. There is no evident difference in the regions within the MPAs across scenarios except for the full protected grids within Cocos MPA ((Figure 7, Abundance). This pattern is likely due to a higher level of biomass at the beginning of the experiment for these regions that is not effectively protected by the MPA under climate change, hence it sees a larger reduction.

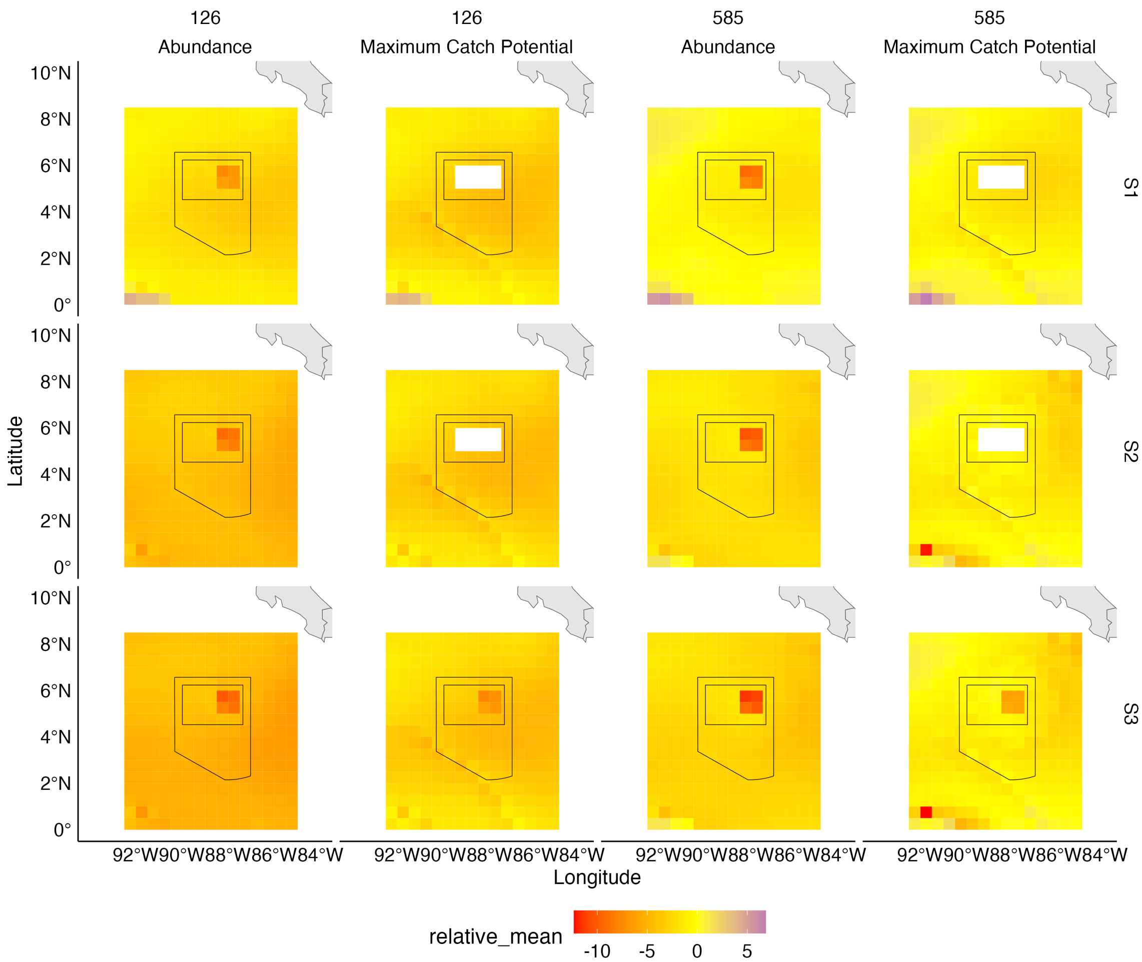
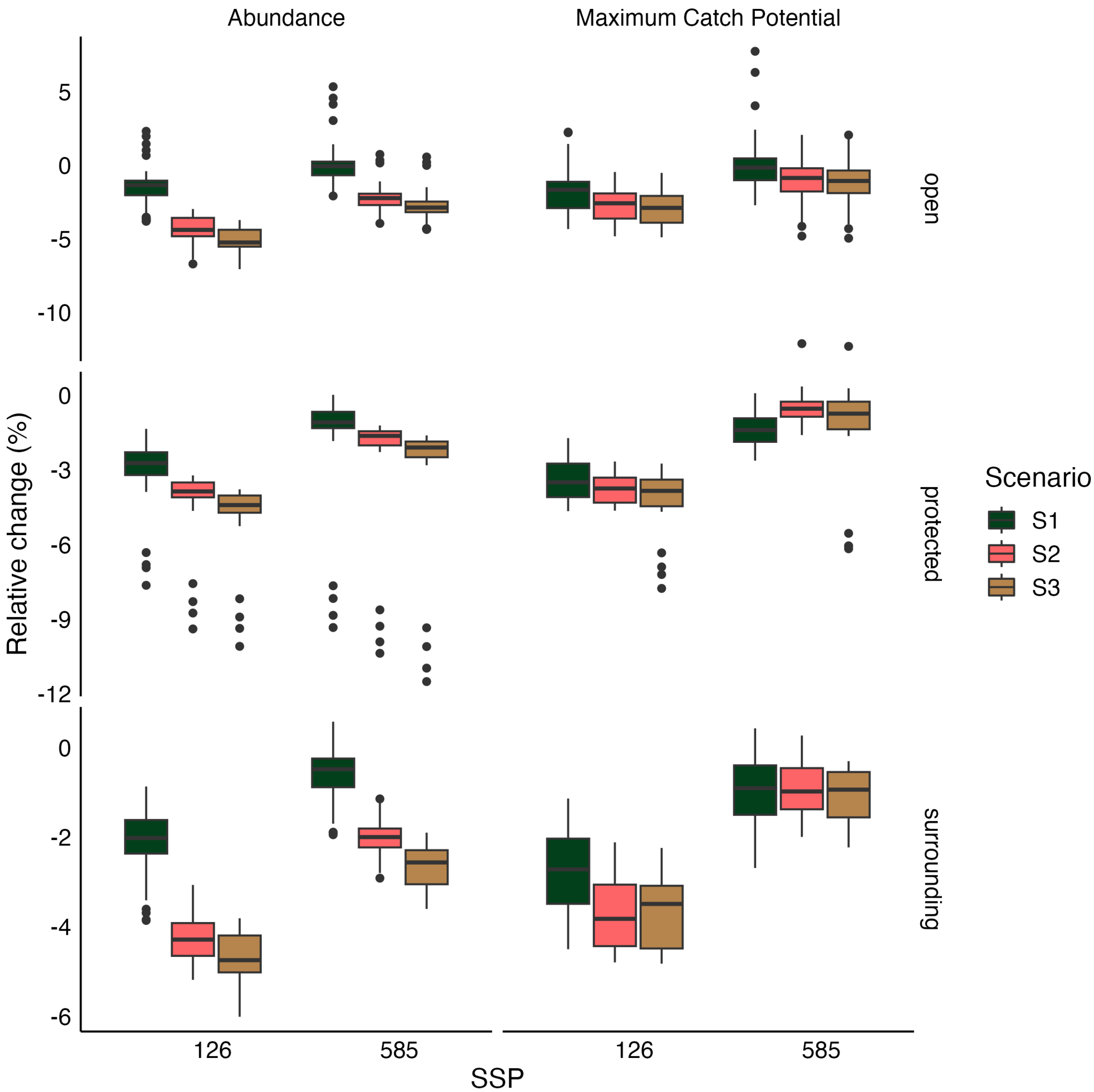


Figure 7: Coco MPA in blue and AMMB area in red over DBEM grid cells (light blue) included in the analysis

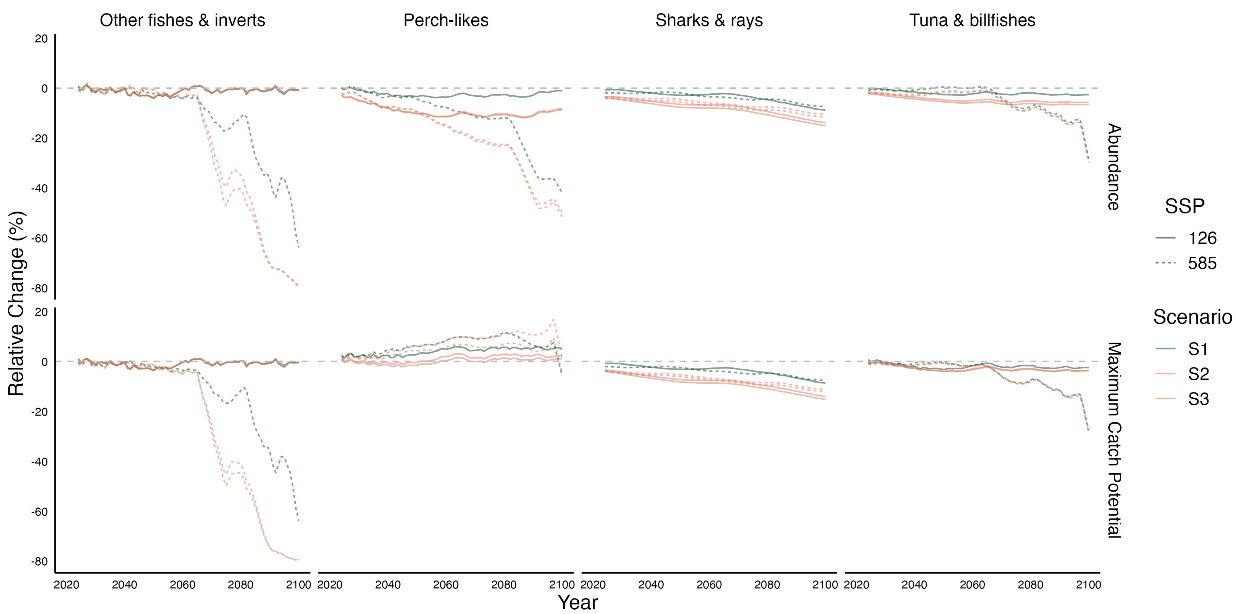
We also looked at the projections based on the protection category of grid cell: *protected* for grid cells containing an MPA, *surrounding* for those immediately adjacent to a protected grid cell and *open* for the rest of grid cells (Figure 6). For the *open* ocean, abundance on S1 is significantly less reduced than the other two scenarios, whereas for MCP this is only true under SSP 126 (Figure 6, *open*). Most *protected* grids will see a decrease in biomass with Scenario S1 presenting the least reduction in both SSPs (Figure 6, *protected*). Inversely, for MCP, the difference between scenarios is less clear. Finally, the spill-over effect from *protected* grid cells becomes evident as the relative change in abundance of *surrounding* cells is substantially lower in Scenario S1 than the other scenarios (Figure 6, *surrounding*). This is likely supported by the fishing management status of the scenario S1 (i.e., $F = F_{msy}$) that allows for a sustainable harvest. For MCP this effect is only seen if emissions are mitigated (SSP 126) suggesting that fisheries could benefit from the spill-over effect of these protected areas. Under SSP 585, however, the effect is not different between scenarios as the effects of climate change are too strong for the management or cell status to be influential.



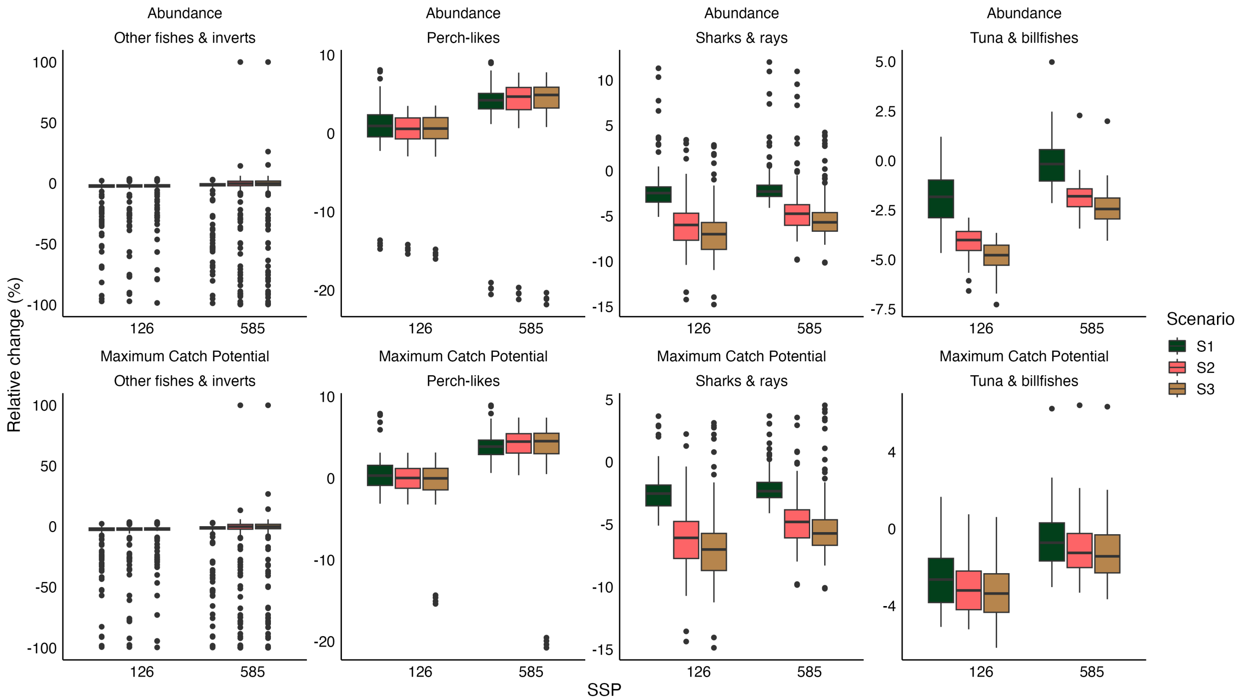
3.2 By commercial group

We grouped the species into four different commercial groups according to the Sea Around Us: perch-likes ($n = 5$), sharks and rays ($n = 8$), tunas and billfishes ($n = 9$) and other fishes ($n = 2$). While this approach provides a more de-aggregated perspective and mitigates some of the uncertainties related to the species-level analysis,it still retains a considerable degree of uncertainty and offers insights into potential trajectories for each group under climate change, rather than definitive outcomes.

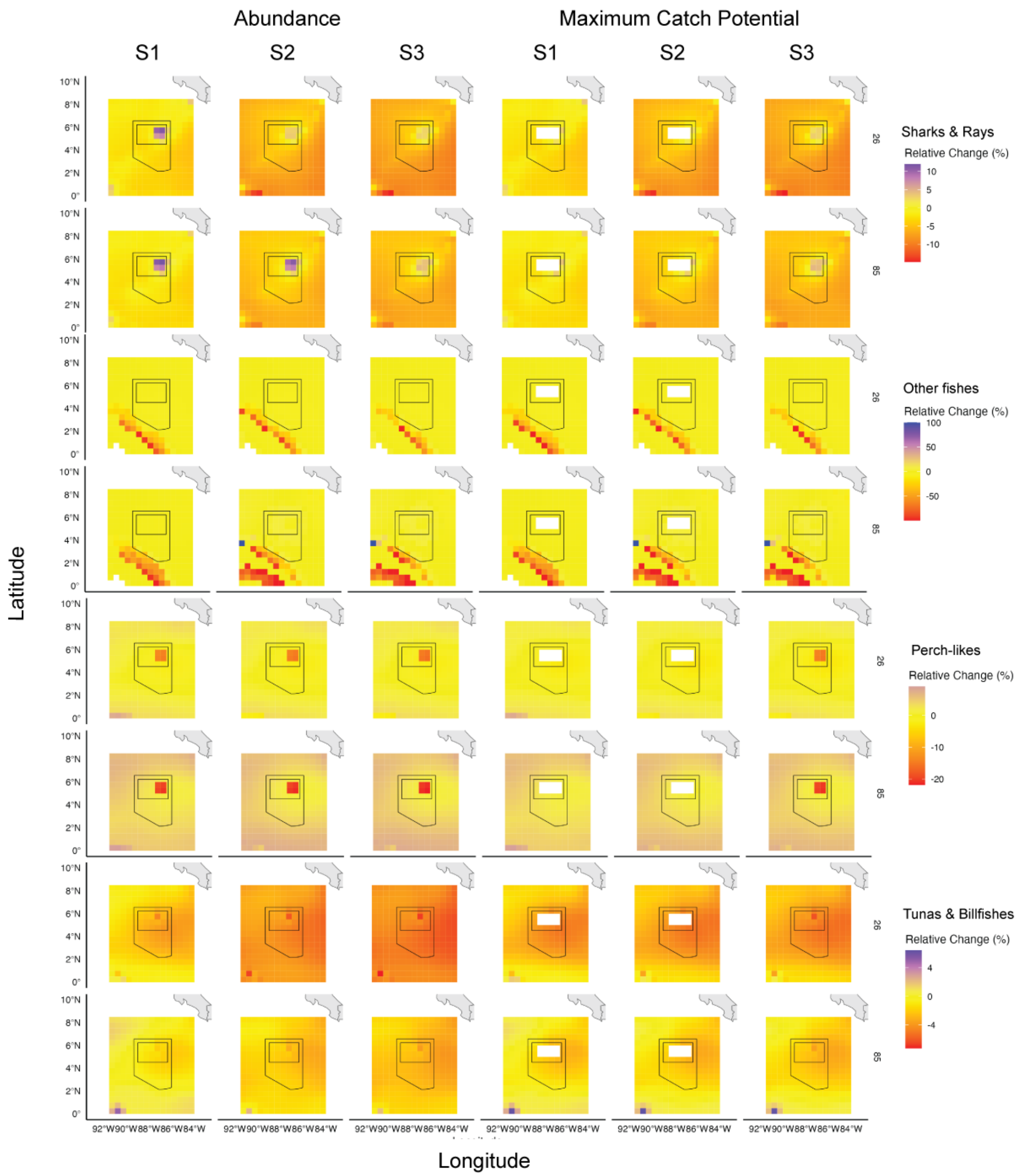
Overall, all four groups are projected to lose abundance in the region, regardless of the climate change or management scenario with SSP 126 resulting in less change than SSP 585 for all groups (Figure @ref(fig:scen_trend_commercial)). Scenario 1, where cocos is 100% protected results in the best outcome for all commercial groups while Scenario 3, where no area is 100% closed to fishing, results in the worst outcome. The small difference between scenarios be seen as evidence of no real impact into having areas completely closed, however, the fact that Scenario 1 outperforms the others in every commercial group suggests that there is a benefit of having areas closed and that the model is not detailed enough to truly capture what that difference really is. One interesting patter worth highlighting is the apparent decrease in abundance of Perch-like species contrasting the increase in MCP (Figure @ref(fig:scen_trend_commercial)-*Perch-likes*). This contradicting pattern could be explain because of the effect of the MPAs creating higher biomass at the beginning of the study period and thus being highly impacted by climate change.



When comparing the mid of the 21st century relative to today, we can see that all but Perch-likes seem to be negatively impacted by climate change (Figure @ref(fig:scenario_delta_box_commercial)). Indeed Perch-like species are projected to see a small-to-no-change increase under SSP 126 and an increase under SSP 585 with no difference across Scenarios. On the other hand, both sharks & rays and tunas & billfishes are expected to decrease in abundance (and MCP). For these groups, however, there is a significant difference between the Scenario 1 and the other two in all cases but MCP for tunas & billfishes.



The spread of the change impacts across the region is relative homogeneous across commercial groups (Figure @ref(fig:commercial_map)). In most cases there will be no change-to-small-decreases (e.g., from 0 to -10$) in abundance across the region. Scenario 1 shows less abundance impacts for Sharks & rays and tunas & billfishes than the other two scenarios, while Perch-like species seem to have no difference between scenarios.


Abundance
Maximum Catch Potential
S1
S2
S3
S1
S2
S3
Latitude
Longitude
10°N
8°N
6°N
4°N
2°N
0°
92°W90°W88°W86°W84°W
26
85
Sharks & Rays
Relative Change (%)
10
5
0
-5
-10
Other fishes
Relative Change (%)
100
50
0
-50
Perch-likes
Relative Change (%)
0
-10
-20
Tunas & Billfishes
Relative Change (%)
4
0
-4

4 Conclusions

... Sarah Heeeeeeeeeeelp!!!!