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Implications for the global tuna fishing industry of climate change-driven alterations in productivity and body sizes

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# Keywords

*Tuna fishery, climate change, fishing pressure, future scenarios, Ecosystem-Based Model, Size Spectrum, Bioclimatic Envelope Model*

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# Abstract

Tunas and billfishes are the main large pelagic commercial fish species. Tunas comprised around 5.5 million t and USD 40 billion in 2018. Climate change studies and projections estimate that overall, global fisheries productivity will decrease due to climate change. However, there are seldom projections of the climate-driven productivity of the higher trophic levels where tunas and billfishes belong. In this work, we use a mechanistic model to evaluate the effects of climate change and fishing for globally distributed and commercially exploited seven tuna species and swordfish which are divided into 30 stocks for management purposes, under a range of climate change (RCP 2.6 and 8.5) and fishing scenarios (from no fishing to 1.5 times the fishing mortality (F) at the Maximum Sustainable Yield, FMSY) from two Earth System Models (IPSL and MEDUSA). The results suggest that high trophic level species will be more impacted by climate change than by fishing pressure under the assumption that they remain nearby their MSY levels. However, no-fishing scenarios project much higher biomass. The overall productivity of the target species will decrease by 36% and only the Pacific bluefin showing a slight increase in the future. Five species; Atlantic and Southern bluefins, swordfish, bigeye, and albacore are estimated to decrease in biomass and size at different rates. These species represent almost a third of the landings in the Atlantic Ocean and 10% in the Pacific Ocean being the bluefins, the highest-valued tuna species. On average, the body size is expected to decrease up to 15% by 2050. Fish price and demand are partially driven by body size and therefore, revenues can be reduced even in stocks with an increase in productivity. The fishing industry can adapt to the changing climate by increasing the value of fish through sustainability certifications and reducing fuel consumption and time at sea with higher digitalization. Reducing fuel consumption would also be an additional mitigation measure to climate change since it would reduce CO2 emissions.

# 1. Introduction

Climate change is one of the main stressors over marine ecosystems and fisheries ([Brander, 2010](#_ENREF_21)), which is modulating the distribution of biodiversity and productivity with a direct impact on fishing communities, fishery managers, economies, and ultimately the future fishing opportunities for mankind ([Burrows et al., 2011](#_ENREF_24); [Cheung et al., 2009](#_ENREF_31); [Hobday et al., 2015](#_ENREF_68); [Karp et al., 2019](#_ENREF_89); [Pecl et al., 2017](#_ENREF_112); [Peterson et al., 2002](#_ENREF_115); [Weng et al., 2015](#_ENREF_144)). Under climate change scenarios, an amplification of the hydroclimatic signal is predicted up the plankton food web ([Chust et al., 2014](#_ENREF_34)) to higher trophic levels’ productivity in the future ([Lotze et al., 2019](#_ENREF_97); [Tittensor et al., 2021](#_ENREF_133)). Climate change also causes regime shifts (permanent changes in the spatial distribution of species ([Karp et al., 2019](#_ENREF_89))) and size-structure modifications (generally, through a reduction of the average body size ([Audzijonyte et al., 2016](#_ENREF_7); [Baudron et al., 2014](#_ENREF_13); [Cheung et al., 2012](#_ENREF_32); [Daufresne et al., 2009](#_ENREF_41); [Genner et al., 2010](#_ENREF_63); [Perkins, 2022](#_ENREF_113); [Pomeranz et al., 2021](#_ENREF_118); [Queirós et al., 2018](#_ENREF_120))). The combined impacts of climate change and fishing pressure have been studied for small pelagic fishes ([Barange et al., 2010](#_ENREF_9); [Merino et al., 2010a](#_ENREF_98); [Merino et al., 2010b](#_ENREF_99)) but the combined effects remain insufficiently investigated over top predators ([Perry et al., 2010](#_ENREF_114); [Planque et al., 2010](#_ENREF_117)). Climate-driven changes in fisheries' productivity will directly impact the outcome of fish stock assessments and management measures ([Fernandes et al., 2020a](#_ENREF_57); [Karp et al., 2019](#_ENREF_89)) as well as fishing communities that are more vulnerable to changes in fisheries production ([Allison et al., 2009](#_ENREF_2)).

Few studies have attempted the evaluation of climate change impacts on tuna and billfish and their fisheries. Most of the efforts have been focused on models of specific species and/or areas ([Bell et al., 2013](#_ENREF_16); [Bell et al., 2021](#_ENREF_17); [Chust et al., 2019](#_ENREF_35); [Dueri et al., 2014](#_ENREF_43); [Dueri et al., 2016](#_ENREF_44); [Lehodey et al., 2017](#_ENREF_93); [Lehodey et al., 2013](#_ENREF_94); [Lehodey et al., 2008](#_ENREF_95); [Nicol et al., 2022](#_ENREF_103); [Senina et al., 2018](#_ENREF_123); [Senina et al., 2016](#_ENREF_124)), or multispecies studies at global scale ([Arrizabalaga et al., 2015](#_ENREF_4); [Erauskin-Extramiana et al., 2019](#_ENREF_47)), where the impact of life-history parameters has been evaluated ignoring trophic interactions. Shifts in tuna migration time ([Chust et al., 2019](#_ENREF_35)) and distribution ([Erauskin-Extramiana et al., 2019](#_ENREF_47)) have been detected during the last decades driven by changes in the environmental conditions that have produced an overall decrease in habitat suitability of the tropical areas whilst increasing habitat suitability have been predicted for higher latitude areas ([Barange et al., 2014](#_ENREF_10); [Dueri et al., 2014](#_ENREF_43); [Erauskin-Extramiana et al., 2019](#_ENREF_47)). Those models only project an improvement or deterioration of the habitat suitability, and mechanistic relations need to be included to better predict the direct impact of climate change on fish stocks globally. Another group of studies, which used ecosystem-based models (SEAPODYM, APESCOM) that include some mechanistic processes, have also been applied to specific regions or species ([Dueri et al., 2014](#_ENREF_43); [Lehodey et al., 2008](#_ENREF_95); [Senina et al., 2016](#_ENREF_124)). Positive impacts have been projected for some particular areas and species such as skipjack in the central-eastern Pacific ([Bell et al., 2013](#_ENREF_16); [Dueri et al., 2016](#_ENREF_44); [Lehodey et al., 2013](#_ENREF_94)). Due to the ecological importance of these top predator species that are heavily exploited to satisfy their high commercial demand, a global multispecies ecosystem-based model for tuna and tuna-like species that includes spatial structure, population dynamics and environmental processes is needed to complement the current research on climate impacts of marine renewable resources. Resolving the combined effect of climate warming and exploitation in a food web context is key for predicting future biomass production, size structure and potential yields of marine fishes ([Lindmark et al., 2022](#_ENREF_96)).

Tuna and tuna-like species are some of the most valuable fishery resources ([FAO, 2011](#_ENREF_51); [FAO, 2020](#_ENREF_52); [Galland et al., 2020](#_ENREF_62)) and contributed with ~5.5 million t of high-quality food and USD 40 billion to the global economy in 2018 ([Galland et al., 2020](#_ENREF_62)). In addition to their high market value, tunas are also an important source of protein for developing countries, mostly in Africa, Asia and South America ([Allison et al., 2009](#_ENREF_2); [FAO, 2010](#_ENREF_50); [Galland et al., 2020](#_ENREF_62); [Weng et al., 2015](#_ENREF_144)). Also, tunas are considered to play an important ecological role due to their top-down influence over other species’ populations in the ecosystem ([Baum and Worm, 2009](#_ENREF_14); [Cox et al., 2002](#_ENREF_39); [Hinman, 1998](#_ENREF_67); [Juan-Jordá et al., 2011](#_ENREF_87); [Sibert et al., 2006](#_ENREF_126)). Due to the distinct transnational nature of tuna fisheries, tuna Regional Fisheries Management Organizations (RFMOs) that are formed by nations with fishing interests in large oceanic areas have been explicitly established to manage tuna and tuna-like fish and fisheries ([Ásmundsson, 2016](#_ENREF_6)). There are five tuna RFMOs: the International Commission for the Conservation of Atlantic Tunas, (ICCAT); the Indian Ocean Tuna Commission (IOTC); the Western and Central Pacific Fisheries Commission (WCPFC); the Inter‐American Tropical Tuna Commission (IATTC), and the Commission for the Conservation of Southern Bluefin Tuna (CCSBT). The tuna-RFMOs are responsible for assessing and managing tuna and tuna-like species, including skipjack, yellowfin, bigeye, albacore, Atlantic, Pacific and Southern bluefin tunas, as well as other non-tuna species such as billfishes and oceanic sharks ([ISSF, 2020](#_ENREF_83)). Nowadays, global tuna catches are composed of skipjack (57%), followed by yellowfin (29%), bigeye (8%), albacore (5%), and bluefin tuna (1%) ([FAO, 2020](#_ENREF_52); [ISSF, 2020](#_ENREF_83)). Tuna fishing fleets must travel long distances to search and catch high mobility and widely distributed tuna and billfish species ([FAO, 1994](#_ENREF_49); [Muhling et al., 2017](#_ENREF_101)), burning around 2.5 billion t of fuel every year (around 5% of the global fishing fuel consumption) ([Tyedmers and Parker, 2012](#_ENREF_135)), where up to 90% of the fuel consumption may be used searching and going to the fishing grounds ([Basurko et al., 2022](#_ENREF_11)).

The objective of this paper is to analyze the climate change and fishing impacts on biomass and body size of the world’s marine top predators and discuss their implications for global tuna fisheries. The mechanistic model SS-DBEM has been used to project climate and fishing-driven scenarios over commercial interest species which are divided into units (stocks) for assessment and management purposes. The target species are albacore (*Thunnus alalunga*, with 6 stocks), Atlantic (*Thunnus thynnus*, 2 stocks), Pacific (*Thunnus orientalis,* 1 stock) and Southern (*Thunnus maccoyii*, 1 stock) bluefin tunas,yellowfin (*Thunnus albacares*, 4 stocks), bigeye (*Thunnus obesus,* 4 stocks), skipjack (*Katsuwonus pelamis*, 5 stocks) and swordfish (*Xiphias gladius,* 7 stocks) ([ISSF, 2020](#_ENREF_83)).

# 2. Material and methods

A multi-species ecosystem model (hereafter called SS-DBEM; Fernandes et al., 2013, [Fernandes-Salvador and Cheung (2023)](#_ENREF_54)) which integrates a species-based model (DBEM, Dynamic Bioclimatic Envelope Model) ([Cheung et al., 2008a](#_ENREF_26); [Cheung et al., 2011](#_ENREF_27); [Cheung et al., 2008b](#_ENREF_29); [Cheung et al., 2009](#_ENREF_31)) with the size-spectrum approach (SS) ([Jennings and Collingridge, 2015](#_ENREF_84); [Jennings et al., 2008](#_ENREF_85)) was used in this study. This approach includes a large number of mechanisms and ecological processes such as population growth, movement, and dispersal of adults and larvae, as well as the ecophysiological effects of temperature, oxygen, and pH on body size, growth, mortality, and reproduction ([Cheung et al., 2013](#_ENREF_33)). The SS-DBEM model (**Fig. 1, Table 1**) provides spatially (at a 0.5 x 0.5º resolution) and temporally (yearly) resolved predictions of changes in species’ size, abundance and biomass ([Cheung et al., 2008a](#_ENREF_26); [Cheung et al., 2011](#_ENREF_27); [Cheung et al., 2008b](#_ENREF_29); [Cheung et al., 2009](#_ENREF_31); [Cheung et al., 2012](#_ENREF_32)) with consideration of competition ([Fernandes et al., 2013](#_ENREF_56)). The competition algorithm describes the resource allocation between different species co-occurring in a spatial unit (thereafter cell) by comparing the flux of energy (in biomass) that can be supported (estimated with the SS model) with the energy demanded by the species predicted to inhabit that cell (estimated with the DBEM model) ([Fernandes et al., 2013](#_ENREF_56)) (see **Fig. 1**). In addition, the environmental conditions are considered in the mechanisms and since different environmental conditions are provided by the biogeochemical models, species responses are also different spatially.

*Table 1: Summary of mechanisms (with main equations and parameters) considered in SS-DBEM. For further details, check the associated references. The model code can be found in* [*Fernandes-Salvador and Cheung (2023)*](#_ENREF_54)*.*

|  |  |  |  |
| --- | --- | --- | --- |
| **Mechanism** | | **Equation** | **Parameters** |
| Growth=anabolims-catabolism ([Cheung et al., 2011](#_ENREF_27); [Pauly and Kinne, 2010](#_ENREF_111)) | | G = Hwa-kW H = g[O2] \* e−j1/T k = h[H+] \* e−j2/T | k= catabolism coefficient W=body weight α=anabolism exponent (0.5 to 0.95) W∞=asymptotic weight |
| Length-weight | | W = a \* Lb | W = weight L = length |
| Size-spectrum production (Fernandes *et al.*, 2013; Jennings *et al.*, 2008) | | P = exp (25.22 − E/kT) \* W0.76 | E = activation energy of metabolism T = temperature in Kelvin (°C + 273) k = Boltzmann's constant |
| Intrinsic population growth rate  (Hilborn & Walters, 1992) | | G = r \* A \* (1 − (A/KC)) | r = intrinsic rate of population increase KC = population carrying capacity A = the relative abundance |
| Larval recruitment  ([Cheung et al., 2008c](#_ENREF_30); [O'Connor et al., 2007](#_ENREF_104)) | | *-0.283\** | PLD = pelagic larvae duration T = surface temperature Tc = 15 C DM is the developmental type of larvae (0 lecithotrophic, 1 planktotrophic) N = number of cells where species occur |
| Larval dispersal  ([Cheung et al., 2008c](#_ENREF_30); [Hundsdorfer et al., 2003](#_ENREF_70)) | |  | D = diffusion parameter LAV = larvae recruitment (u, v) = velocity parameters |
| Adult movement | | cm/h | cm = centimetre h = hour |
| Natural mortality |  | | W∞ = asymptotic weight T = average water temperature in the animal's range K = von Bertalanffy growth parameter |
| Fishing mortality at MSY ([Fernandes et al., 2013](#_ENREF_56)) | | FMSY= R/4 | R=population intrinsic growth |

An initial distribution map with the probabilities of occurrences is needed in the SS-DBEM for each modeled species. Those initial distributions have been developed individually and acquired from [Erauskin-Extramiana et al. (2019)](#_ENREF_47) for tuna and swordfish target species. These distributions were estimated from the historical catch and effort information of the Japanese pelagic longline fleet with a combination of a presence/absence analysis and a Gaussian error distribution estimated using Generalized Additive Models (for further details see [Erauskin-Extramiana et al. (2019)](#_ENREF_47)). Initial distribution for the Pacific bluefin was obtained from the [Sea Around Us Project](file:///C:\Users\merauskin\AppData\Local\Microsoft\Windows\INetCache\Content.Outlook\MA80T0MI\www.seaaroundus.org) (SAUP, [www.seaaroundus.org](http://www.seaaroundus.org)) following the methodology from [Close et al. (2006)](#_ENREF_36). Based on this initial distribution, DBEM linked the species’ probability of occurrence with the environmental variables included in the model (sea surface and bottom temperature, coastal upwelling, salinity, sea-ice extent, depth and habitat types) ([Cheung et al., 2011](#_ENREF_27); [Fernandes et al., 2013](#_ENREF_56)) obtaining the preference range of environmental conditions for each species. Then, the model estimates changes in growth and life history traits in response to changes in temperature and oxygen concentration based on algorithms derived from growth and metabolic functions and empirical equations ([Cheung et al., 2011](#_ENREF_27); [Cheung et al., 2012](#_ENREF_32)). Using this information, the model predicts the size-frequency distribution for each species by grid cell using a size-structured ‘per recruit’ model. In the last stage, the model estimates the abundance and biomass within a cell based on the carrying capacity of a cell (given by the SS component of the model), density-dependent population growth, larval dispersal and adult migration ([Cheung et al., 2011](#_ENREF_27); [Cheung et al., 2008c](#_ENREF_30)).

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Descripción generada automáticamente*Figure 1: Schematic diagram of the SS-DBEM structure, defining the parameters used and the workflow of the model. Mechanisms included in each model and the climatic and fishing scenarios are described. Based on* [*Queirós et al. (2015)*](#_ENREF_121)*,* [*Fernandes et al. (2013)*](#_ENREF_56) *and* [*Cheung et al. (2011)*](#_ENREF_27)*.*

This study used the SS-DBEM to estimate the combined impact of climate change and fishing pressure on the main 7 commercial tuna species and swordfish due to their high commercial value and landings volume. The selected target species are albacore (*Thunnus alalunga*), Atlantic (*Thunnus thynnus*), Pacific (*Thunnus orientalis*) and Southern (*Thunnus maccoyii*) bluefin tunas,yellowfin (*Thunnus albacares*), bigeye (*Thunnus obesus*), skipjack (*Katsuwonus pelamis*) and swordfish (*Xiphias gladius*). We consider the trophic interaction of tunas with 11 species of non-commercial top predators (e.g. other billfish species…) for model improvement purposes as direct competitors of the resources. Species’ biological parameters information was obtained from [FishBase](file:///C:\Users\merauskin\AppData\Local\Microsoft\Windows\INetCache\Content.Outlook\MA80T0MI\www.fishbase.org) ([www.fishbase.se](http://www.fishbase.se)) and the Sea Around Us (SAUP, [www.seaaroundus.org](http://www.seaaroundus.org)) databases, and conducting an extensive literature review (see [**Supp. Mat. Table 1**](#SuppTab1)).

Stock assessment biomass estimations for target species ([Juan-Jordá et al., 2022](#_ENREF_86)) were used to be compared with SS-DBEM model biomass outputs at 1FMSY since there is no other data available with the required characteristics (e.g. long-term and ocean-wide fisheries independent surveys) to conduct a further validation process. The 1FMSY scenariowas selected due to its closeness to reality across stocks. The SS-DBEM model outputs were aggregated by RFMO to be comparable to management units (stocks) and rescaled with stock assessment biomass. A ‘stock’ is defined as a semi-discrete group of fish species populations with some definable attributes of interest for managers ([Begg et al., 1999](#_ENREF_15)). There are different stocks’ status definitions across RFMOs, and due to the lack of a standardized classification, the following [Arrizabalaga et al. (2012)](#_ENREF_5) definitions were used here: 1) “not overfished (B>BMSY) and not subject to overfishing (F<FMSY)” (in green); 2) “subject to overfishing (F>FMSY) OR overfished (B<BMSY)” (in yellow); and 3) “subject to overfishing (F>FMSY) AND overfished (B<BMSY)” (in red).

Two biogeochemical models were used to force the SS-DBEM; i) the global general circulation model IPSL-CM5 developed to study the long-term response of the climate system to natural and anthropogenic forcing ([Dufresne et al., 2013](#_ENREF_45)) and ii) the Model of Ecosystem Dynamics, nutrient Utilisation, Sequestration, and Acidification (MEDUSA), an intermediate complexity plankton model ([Yool et al., 2013](#_ENREF_145)). The Earth System Model IPSL includes an interactive carbon cycle, a representation of tropospheric and stratospheric chemistry, and a comprehensive representation of aerosols ([Dufresne et al., 2013](#_ENREF_45)). MEDUSA represents dissolved inorganic carbon and pCO2 in the ocean, allowing the calculation of air-sea CO2 fluxes and therefore, ocean acidification and its impact on ecosystem processes ([Yool et al., 2013](#_ENREF_145)). The environmental factors that forced the SS-DBEM model were the bottom (average of 15 m just above the sea floor) and surface (integration of first 15 m of the water column) temperature (ºC), pH ([H+]), O2 (in mol kg-1), salinity (PSU), ice coverage in the cell (%), total net primary production (total of the water column) (g C m-2 d-1), mixing layer depth (m), and advection (m s-1).

Climate change is formulated from projections of Greenhouse Gas emissions (different Representative Concentration Pathways, RCPs), and fishing scenarios which were defined as different levels of compliance with fishing mortality at the Maximum Sustainable Yield (FMSY). The two climate scenarios that represent high-, and low-range greenhouse gas emissions are (i) the mitigation scenario with 421 parts in a million (ppm) (RCP2.6) and (ii) the business-as-usual high emission scenario (936 ppm)(RCP8.5) by the year 2100 ([IPCC, 2013](#_ENREF_82)). The fishing effort scenarios were defined as 0 (no fishing), 0.8, 1.0, 1.2 and 1.5 times the fishing mortality at Maximum Sustainable Yield (FMSY) (thereinafter 0 FMSY, 0.8FMSY, 1.0FMSY, 1.2FMSY, and 1.5FMSY). The MSY is the highest average sustainable catch that can be continuously taken from a fish stock under average environmental conditions ([Hilborn and Walters, 1992](#_ENREF_66)). Values over 1-time FMSY mean that a fish stock is subject to overfishing. This approach has been used in previous research ([Fernandes et al., 2016](#_ENREF_58); [Mullon et al., 2016](#_ENREF_102)) and current international projects’ protocols ([Ferit, 2018](#_ENREF_53); [Fu et al., 2019](#_ENREF_61); [Hansen et al., 2019](#_ENREF_65)).

The SS-DBEM model outputs are provided at the species level for each spatial grid cell and later aggregated by each management unit (RFMO). The distribution, biomass and abundance of target species from 1980 to 2100 were projected and relative changes over time were estimated. Abundance and biomass were estimated for the mid- (2040-2050) and end-century (2090-2099) periods and compared with those to the reference period (2000-2010) to see the changes projected for the future. In addition, changes in the body size of target species were estimated using the ratio between the biomass and the abundance (ratio = biomass/abundance). When the values of the ratio are related to a reference period, positive changes (ratio > 1) indicate that bigger individuals are expected, while for negative values (ratio < 1), smaller individuals are predicted.

# 3. Results

## 3.1 Model biomass outputs comparison with stock assessment

Overall, the change in biomass estimated by the SS-DBEM model along the analyzed time period is higher than the stock assessment models for the main commercial tuna stocks (**Fig. 2**). Model trends are negative in all cases, whereas stock assessment trends are mostly negative, but some stocks also show some periods with biomass increases or positive trends, e.g. in response to implemented management plans. The comparison conducted showed mainly decreasing biomass trends for most tuna stocks (albacore in IOTC, bigeye in all its stocks, yellowfin in ICCAT, WCPFC and IOTC and skipjack in the IOTC), although with a different rate of change and variability (**Fig. 2**). Trends are similar at the beginning of the time series, but they differ after the first decade for albacore in the South Atlantic, bigeye West Pacific (WCFPC) and yellowfin in the East Pacific (IATTC). Trends from the model and stock assessment estimations differ substantially for albacore and skipjack in the North Atlantic (ICCAT) and south Pacific (WCPFC), where positive changes are estimated by the stock assessment studies, while the model has predicted negative impacts.

Diagrama

Descripción generada automáticamente*Figure 2: Biomass relative change (in %) for (a) SS-DBEM model outputs at 1FMSY (grey line), and (b) stock assessment models (blue line) for the main commercial tuna species stocks (as it is the unit used for assessment). The grey and blue lines represent the average across models and scenarios (in the case of SS-DBEM trends) and the shadow area represents the standard deviation as a measure of uncertainty (not available for all the stocks).* *The time series between 1990 and 2018 were compared, despite the limited availability of data for some stocks.*

## 3.2 Climate change and fishing impacts on the target species

The projected biomass change was estimated using the business-as-usual climatic projections and 1FMSY fishing pressure level as a baseline considering that it is the scenario that better represents the current situation and the future direction. No-fishing scenario (0FMSY) has also been represented in dashed lines showing the large difference between no-fishing and fishing scenarios (much higher than among climatic scenarios) (**Fig. 3**). The biomass is projected to be below the reference value (baseline scenario in the year 2000) for most of the species that are fished, with some exceptions: i) the Pacific bluefin tuna will be benefited if the environmental conditions are those predicted by MEDUSA model, ii) the Atlantic bluefin tuna seems to be benefited by mid-century although this pattern changes for the end-of-the-century maintaining the same level as in the historical period for IPSL outputs and decreasing further for those from MEDUSA; iii) bigeye, albacore and skipjack are projected to inverse their trends by 2100, being positively impacted under the “business-as-usual” climatic scenarios and exceeding the biomass present in the historical period. The Pacific bluefin showed very different trends depending on the biogeochemical model used, probably due to the decrease expected by the IPSL model in primary production but the slight increase projected by the MEDUSA model in the Pacific Ocean (see environmental trends in **Fig. 5 left column**) that benefits to the species. In addition, when environmental changes are those expected by MEDUSA some species seem to be more benefited under the high emission scenarios (RCP8.5) by the end of the century than with the RCP2.6 (i.e., albacore, bigeye, skipjack and Pacific bluefin tuna). Regarding the fishing effort, differences among fishing scenarios are generally small but huge compared with the no-fishing scenario (dashed line in **Fig. 3**).

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*Figure 3: Biomass relative change to the reference year 2000 (no changes illustrated with a dashed horizontal white line) for different climatic scenarios (RCP2.6 and 8.5) and biogeochemical models (IPSL, MEDUSA). Each line represents a model and climatic scenario being the marked continuous line the 1MSY scenario and the shaded area around the range among fishing scenarios (from 0.8FMSY to 1.5FMSY).*

## 3.3 Status and potential impacts on commercial stocks

Only two tuna species, skipjack and yellowfin, already represent 86% of main commercial tuna species ([FAO, 2020](#_ENREF_52); [ISSF, 2020](#_ENREF_83)), 93% if a third species is included (bigeye) (**Table 2**). Albacore, bigeye and swordfish are mainly fished in the Pacific Ocean (WCPFC and IATTC areas) followed by the Atlantic Ocean. Atlantic and Southern bluefin tunas are only caught in a limited area (the Atlantic Ocean (ICCAT) and South to 10ºS (CCSBT), respectively). WCPFC in the Pacific Ocean comprises the highest captures with around 55% of the total main commercial tuna and swordfish caught, whereas IOTC is the second with 21% of the total catches.

***Table 2****: Annual catch (1000 t) by species and RFMOs. Source: ISSF (reference year: 2020).*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Species** | **WCPFC** | **IATTC** | **IOTC** | **CCSBT** | **ICCAT** | **Percent (%)** |
| Swordfish | 26 | 14 | 33 | 0 | 28 | **1.8** |
| Atlantic bluefin tuna | 0 | 0 | 0 | 0 | 33 | **0.6** |
| Pacific bluefin tuna | 12 | 0 | 0 | 0 | 0 | **0.2** |
| Southern bluefin | 0 | 0 | 0 | 14 | 0 | **0.3** |
| Yellowfin | 690 | 241 | 432 | 0 | 133 | **27.4** |
| Bigeye | 130 | 98 | 74 | 0 | 74 | **6.9** |
| Albacore | 112 | 19 | 40 | 0 | 53 | **4.1** |
| Skipjack | 2045 | 348 | 547 | 0 | 266 | **58.7** |
| Total catch (1000 t) | 3015.0 | 720.0 | 1126.0 | 14.0 | 587.0 | **5462 t** |
| **Percent (%) by RFMO** | **55.2** | **13.2** | **20.6** | **0.3** | **10.7** |  |

The estimation of the catches at the MSY and stock status are represented in **Figure 4** ([CCSBT, 2017](#_ENREF_25); [ICCAT, 2014](#_ENREF_71); [ICCAT, 2017](#_ENREF_72); [ICCAT, 2018](#_ENREF_73); [ICCAT, 2019](#_ENREF_74); [ICCAT, 2020a](#_ENREF_75); [ICCAT, 2020b](#_ENREF_76); [ICCAT, 2020c](#_ENREF_77); [IOTC, 2017](#_ENREF_78); [IOTC, 2018](#_ENREF_79); [IOTC, 2019a](#_ENREF_80); [IOTC, 2019b](#_ENREF_81); [WCPFC, 2018](#_ENREF_139); [WCPFC, 2019](#_ENREF_140); [WCPFC, 2020a](#_ENREF_141); [WCPFC, 2020b](#_ENREF_142); [WCPFC, 2020c](#_ENREF_143)). Currently reported catches are 5.46 million t, whereas it has been estimated that 6.37 million t (14.3% more) could be achieved if all the stocks would be fished at MSY levels (**Fig. 4**). 67% of the stocks are fished close to their MSY, while 17% are in recovery or requiring overfishing to be addressed (southern bluefin tuna, bigeye in the eastern Pacific, and albacore and bigeye in the Indian Ocean). The remaining 10% of the stocks are overfished and currently subject to overfishing and therefore require urgent actions (bigeye in the Atlantic, bluefin in the Pacific and yellowfin in the Indian Ocean). There are also two stocks of bluefin in the Atlantic Ocean (East and West) where estimates of biomass base reference points are not reliable. In summary, 85% of the target species catch come from stocks that are well managed and in a healthy status, however, some stocks are still being harvested over their fishing mortality value at MSY (five over 30 stocks, 17%). The other 80% (25 stocks) are below, at MSY level, or unknown.

Gráfico, Gráfico de rectángulos

Descripción generada automáticamente *Figure 4: Mosaic plot of the main commercial tuna species and swordfish at the maximum sustainable yield (MSY, in million t). Colors represent the status category of the stocks (in the legend) by RFMOs (in white) based on our three groups’ classification.*

On average across scenarios, stocks are projected to decrease by 36% their potential biomass by mid-century (**Fig. 5 lower box**) compromising around 2.1 million t of the current catches (**Table 1**). The highest decreases are shown by the Indian Ocean albacore and yellowfin stocks and bigeye in ICCAT with a reduction of up to 43%. The skipjack is also projected to decrease in the same magnitude in the Atlantic Ocean by 2100. Overall, the biomasses are projected to decrease more in the Indian and Atlantic Oceans (42 and 39%, respectively), while positive changes are expected for the bluefin in the Pacific Ocean by 2100. However, the two bluefin stocks in the Pacific represent less than 1% of all this ocean’s catches (**Table 1**).

Body size is projected to have a larger decrease by mid-century (15%) than by the end-of-the-century (7%) (**Fig. 5 upper box**). Size changes show similar patterns and intensity across RFMOs, where smaller individuals are expected. The largest decrease by 2050 corresponds to albacore in ICCAT and bigeye in ICCAT and IATTC (22%), while by 2100, the largest estimated decrease corresponds to the bluefin in the West Pacific (24%). The only exceptions correspond to a size increase of 5% for the Pacific bluefin and yellowfin in IATTC, and for skipjack and yellowfin in the WCPFC (in 8.5 and 10%, respectively).

Temperature changes projected are similar across RFMOs (slightly higher in the CCSBT and ICCAT (13.1 and 12.7% of increase by 2100, respectively)), as well as the intensity of changes across biogeochemical models (see the left column in **Fig. 5**). However, on average, MEDUSA projects worldwide 1ºC more than IPSL. The rate of change in primary production is much more heterogeneous than in temperature across biogeochemical models. IPSL estimates a 30% higher primary production at the beginning of the time series (the reference year 2000), but it suffers a stronger overall worldwide decrease than MEDUSA (10% vs 2.5% by 2100, respectively). Differences are also found in the primary production by RFMO areas: both biogeochemical models project a consistent decrease in the Atlantic Ocean (ICCAT, 15.7%). A similar decrease is also projected in the IOTC (17.6%) but only by IPSL, whilst the MEDUSA projects less than a 5% of change by 2100. IPSL projects positive changes in IATTC and ICCAT primary production before 2020, becoming negative after this year. No changes (around 1%) are projected by MEDUSA along the time series in CCSBT and IATTC, being positive values expected in the WCPFC (2.5% on Mapa

Descripción generada automáticamenteaverage).

*Figure 5: Averaged body size ratio (the biomass divided by the abundance, upper box) and biomass (lower box) change (y-axis) in percentage (%) related to the reference period (2000-2010) in bars (x-axis) across scenarios for each RFMO in the world map for main commercial tuna species and swordfish. RFMOs are ICCAT in the Atlantic, IATTC and WCPFC in the Pacific, IOTC in the Indian Ocean and CCSBT across three oceans but mainly placed in the Indian.* *The left column plots represent the rate of change (in %) of the temperature (in red) and primary production (in blue) for the two biogeochemical models by RFMO. Data available* [*here*](https://zenodo.org/record/7550751#.Y8k02RfMKUk)*.*

# 4. Discussion

Most target species (Atlantic and Southern bluefins, albacore, bigeye and swordfish) are projected to decrease in biomass and size, comprising 2.1 million t of current catches. Only the Pacific bluefin seems to be benefited in the future under projected environmental changes increasing biomass in the whole ocean and size proxy in the east (IATTC). However, this species’ catches represent less than 1% of the total Pacific catches. The size increase is also expected for the two tropical species (yellowfin and skipjack) in the west Pacific Ocean, where productivity is going to maintain or decrease less than in other oceans.

Changes in species biomass are mainly driven by the level of fishing pressure (no-fishing vs fishing), where the no-fishing scenario predicts much higher biomasses than any other fishing scenario. However, when the fishing magnitude is maintained within the range of current levels (between 0.8FMSY and 1.2FMSY), changes are mainly driven by climate change (the overall increase in temperature and the decrease in primary production). The increasing temperature affects the distribution of the species, that look for optimal environmental conditions as well as growth, due to an increased metabolic rate that has, as a consequence, smaller individuals. The different impacts among oceans can be explained mainly due to differences in the projected primary production that affect to the biomass of higher trophic levels that can be supported in each cell.

## 4.1 Biomass trends comparison

The comparison between the stock assessment and SS-DBEM biomass outputs at the 1FMSY fishing scenario provides insight into the mechanisms that may affect tuna populations. Survey and stock assessment data can provide a way of validating model outputs ([Simpson et al., 2011](#_ENREF_127)). For example, the SS-DBEM model has been previously compared in the North-East Atlantic where high-quality data on species distribution from scientific surveys are available ([Fernandes et al., 2020a](#_ENREF_57); [Fernandes et al., 2020b](#_ENREF_60); [Queirós et al., 2018](#_ENREF_120)). It must be considered that fisheries surveys tend to focus on species of interest life history, and are designed to provide a geographical and temporal snapshot of their status ([Fernandes et al., 2013](#_ENREF_56)), while stock assessment use model closed population dynamics ([Begg et al., 1999](#_ENREF_15)). Those more accurate data are useful for comparison purposes being cautious about the interpretations of the model performance due to structural and parameter uncertainties ([Fernandes et al., 2013](#_ENREF_56)). However, the different nature of data sources (catches in stock assessment and modeled biomass in the SS-DBEM), the mechanisms and equations used, and the outputs analyzed in this study, make the comparison very limited for model validation purposes.

Here, the comparison conducted between the model outputs and main commercial tuna species stock assessment biomass estimations showed similar decreasing trends in most of the stocks. A few of them differ substantially (i.e. western skipjack and albacore in ICCAT and albacore in the Pacific Ocean). The results showed that although fishing at a sustainable level, the environmental changes projected a higher decreasing biomass rate than those estimated by stock assessment models. Those models’ estimations are based on fishing pressure without directly considering the environmental effects, allowing for biomass increases when fishing mortality decreased in response to management plans or fishery dynamics (as was the case of North Atlantic albacore, [Anonimous (2020)](#_ENREF_3)). However, the SS-DBEM assumed constant historical fishing mortality around FMSY, selected due to its closeness to the current fishing level in most of the stocks which, in addition to climate change effects, predicted consistent and substantial decreases of biomass over the last two decades. However, longer datasets should be compared to be completely sure that the spin-up and model initialization process effect is not affecting the model results in the period analyzed.

## 4.2 Tuna and swordfish stock projections

Our results in the projected biomass decrease for the target species are aligned with other studies’ results which projected high trophic level species biomass and catch potential drop under climate change ([Cheung et al., 2009](#_ENREF_31); [Fu et al., 2019](#_ENREF_61); [Lotze et al., 2019](#_ENREF_97); [Petrik et al., 2020](#_ENREF_116); [Sumaila et al., 2011](#_ENREF_131)). Other studies also projected a high decrease in the large pelagic functional group (13.9% ±0.7% for TL>4) although this group is related to the highest degree of projection uncertainty ([Petrik et al., 2020](#_ENREF_116)). The water warming and the overall decrease in the primary production affect to the low trophic level biomass available to higher trophic level species in each grid cell. This directly impacts the total supported biomass of the target species. The difference in the biomass estimations projected by the two biogeochemical models (MEDUSA and IPSL) are based on the different mechanisms and forcings that each model use having, as a result, large primary production estimation differences ([Bopp et al., 2013](#_ENREF_20)). In general, higher biomass levels seem to be projected by the MEDUSA model than IPSL, probably due to the lower environmental change rates (lower decrease in primary production and the lower temperature increase). In some species (i.e. Atlantic and Southern bluefins and swordfish), projected biomasses with fishing pressure forced by MEDUSA are above the biomass projected by IPSL without fishing, which highlights the importance of the biogeochemical model used to force the SS-DBEM and remarks the importance of the models’ comparison or ensembles.

Species responses to climatic and fishing scenarios are heterogeneous, both, across species and along the time series. The highest difference between projected biomass trends comes from the fishing pressure; the biomass is an order of magnitude higher in no-fishing scenarios than in scenarios where fishing is considered. Projected biomasses are also higher with lower fishing pressure in all of the species which may help increase species’ resilience to climate change ([Cheung et al., 2017](#_ENREF_28); [Fernandes et al., 2016](#_ENREF_58); [Travers et al., 2010](#_ENREF_134)). The higher increase projected under RCP8.5 for both tropical tuna species (yellowfin and skipjack) may be due to their greater affinity with warmer tropical and subtropical regions compared with other tuna species ([Muhling et al., 2017](#_ENREF_101)) becoming better candidates to expand their distribution and being benefited with the water warming. However, the strong primary production decrease projected by IPSL negatively affects their biomass. The same pattern has been found in albacore, which has been projected to expand their northern and southern limits and decrease in temperate areas ([Erauskin-Extramiana et al., 2019](#_ENREF_47)). We hypothesize that this species may be benefited from the higher latitudinal areas’ productivity ([Bopp et al., 2013](#_ENREF_20)) as well as the advantages of a warmer waters proximity where they must migrate to spawn ([Kailola et al., 1993](#_ENREF_88)) when the primary production maintains the current levels. However, when a decrease in productivity is expected (by IPSL), the albacore may also be negatively affected. For the other species, there is not a clear trend, except for the Atlantic bluefin tuna, for which the high GHG emission scenario will affect negatively its biomass. Bluefins are among the tuna species with the most advanced endothermic capabilities and are therefore the most cold‐tolerant ([Korsmeyer and Dewar, 2001](#_ENREF_91)). Our results agree with other studies where temperature-induced reductions in its habitat in the tropical and sub-tropical Atlantic have been projected under the RCP8.5 ([Muhling et al., 2017](#_ENREF_101)). The Pacific bluefin is the only species that seems to be benefited from the end-of-century increasing biomass in the whole Pacific Ocean. These results from some species could be a consequence of an improvement in the habitat conditions that seem to be beneficial for these specific species or due to adaptation mechanisms. The environmental conditions in this ocean change less than in others, even increasing slightly the primary production (in the case of MEDUSA). But this can be only a temporal benefit if the suitable conditions continue moving and produce a species distribution shift ([Fernandes et al., 2017](#_ENREF_59)). The projected change is more positive for both periods (by 2050 and 2100) in the East than in the West Pacific for bluefin. This difference between the areas inside the same ocean may be driven by a shift in the species distribution. This is a similar pattern found in yellowfin tuna in the Pacific Ocean, where an Eastward shift is expected in the future under business-as-usual climate change and acidification scenarios, increasing the abundance in the East Pacific while decreasing in the West ([Nicol et al., 2022](#_ENREF_103)).

In this study, an average decrease in main commercial tuna species size of 15% has been projected by 2050, which is supported by other studies where the reduction in body size or change in the size-length frequency driven by fishing and climate change has also been reported ([Baudron et al., 2014](#_ENREF_13); [Bianchi et al., 2000](#_ENREF_18); [Dulvy et al., 2004](#_ENREF_46); [Erauskin-Extramiana et al., 2017](#_ENREF_48); [Genner et al., 2010](#_ENREF_63); [Queirós et al., 2018](#_ENREF_120); [Sáenz-Arroyo et al., 2005](#_ENREF_122)). Physiological and evolutionary mechanisms could produce these life-history patterns of decrease in body size, increase in the proportion of small-sized species, young age classes and earlier maturation ([Audzijonyte et al., 2016](#_ENREF_7); [Daufresne et al., 2009](#_ENREF_41); [Lindmark et al., 2022](#_ENREF_96)). Warmer waters may increase the metabolic rate and fasten the growth of the individuals, having, as a consequence, individuals of smaller sizes ([Audzijonyte et al., 2016](#_ENREF_7); [Baudron et al., 2014](#_ENREF_13); [Cheung et al., 2012](#_ENREF_32); [Daufresne et al., 2009](#_ENREF_41); [Genner et al., 2010](#_ENREF_63); [Perkins, 2022](#_ENREF_113); [Pomeranz et al., 2021](#_ENREF_118); [Queirós et al., 2018](#_ENREF_120)). Although explicit adaptation mechanisms have not been included in the SS-DBEM, changes in the environmental conditions directly affect to the growth rates and maximum lengths, leading to different population productivity (changes in abundances and biomass) and sizes.

The main strength of the SS-DBEM is that the combination of those two approaches provides spatially and temporally resolved species biomass, abundance and size predictions, considering a wide range of effects of ecological interactions ([Fernandes et al., 2013](#_ENREF_56)). However, this approach also has some limitations and uncertainties attached. The Earth System Models are one of the main uncertainties’ sources, because their coastal resolution is not high enough to capture the dynamics and, as a consequence, primary production is sub-estimated in those areas ([Steinacher et al., 2010](#_ENREF_129)). The SS-DBEM model limitations mainly come from the assumptions made to simplify the complex ecosystem dynamics into equations ([Fernandes et al., 2013](#_ENREF_56)). In the Size Spectrum component, the relationship between abundance and the size classes (both on a logarithmic scale) in the cell is linear, which can be not followed in reality ([Blanchard et al., 2011](#_ENREF_19)). Regarding the DBEM component ([Cheung et al., 2009](#_ENREF_31)): (i) it is assumed that current distributions represent habitat preferences of the species and are in equilibrium, (ii) estimates of population and dispersal parameters are obtained using indirect methods due to the lack of accurate parameters availability (see [Cheung et al. (2008c)](#_ENREF_30)), (iii) only one parameter value is considered by species although differences could be found among ocean basins ([Kolody et al., 2016](#_ENREF_90)), (vi) trophic interactions are modeled using theory and empirical data which is a simplification of the complexity among species but avoids the requirement of large and detailed data about the species-specific predatory interactions and, (v) model does not explicitly consider phenotypic or evolutionary adaptations of the species. Observations suggest that evolutionary processes and adaptations occurred with high frequency but they do not seem to change the absolute climate tolerance of the species ([Parmesan, 2006](#_ENREF_109)). The next steps in the model development would be the inclusion of other top predators or species in the model such as chondrichthyans, marine mammals, mollusks and crustaceans, and also adding explicit adaptation and evolutionary mechanisms.

## 4.3 Implications to fisheries management

Tunas and billfish are the main large pelagic commercial species and represent an economically important contribution to many nations ([Brill and Hobday, 2017](#_ENREF_23)) particularly in developing countries ([Fernandes, 2018](#_ENREF_55); [Lauria et al., 2018](#_ENREF_92)). Due to their commercial value (they are the world’s most valuable fish ([Galland et al., 2020](#_ENREF_62); [Juan-Jordá et al., 2011](#_ENREF_87))) and the consequent high demand, tuna and their relatives’ biomass have declined by 52% in the past ([Juan-Jordá et al., 2011](#_ENREF_87)). The World Bank and FAO ([Bank et al., 2009](#_ENREF_8)) estimated that global overfishing may cost roughly 50 billion USD a year. Here, it is shown that currently, 85% of the main commercial tuna species’ total catch comes from healthy stocks in terms of abundance. However, the Pacific bluefin tuna, and one yellowfin and bigeye stocks are overfished; resulting in that 10% of the total catch is coming from overfished stocks.

Skipjack and yellowfin accounted for more than 75% of the total tuna cans generating the highest revenues, but at the individual species level, the three bluefins - Atlantic, Pacific, and Southern - are the most highly prized by consumers ([Collette et al., 2011](#_ENREF_37); [Galland et al., 2020](#_ENREF_62)). Abruptly raising landings can generate economic loss due to market response to fish prices ([Sun et al., 2019](#_ENREF_132)). Larger body-size fish tend to be scarce and more valuable ([Sun et al., 2019](#_ENREF_132); [Zimmermann and Heino, 2013](#_ENREF_146)). Therefore, the decreasing body size due to overfishing or climate change impacts can lead to lower prices and reduced revenues ([Sjöberg, 2015](#_ENREF_128)). The only tuna stock which is expected to increase both, biomass and size is the Pacific bluefin, although, its catches comprise less than 1% of the total.

This study shows a larger impact of climate scenarios than fishing efforts considering current and recent fishing pressure worldwide. However, when the no-fishing scenario is included, much higher biomass is projected for all target species which agrees with other studies that explored wider ranges of fishing pressure scenarios estimating that fishing can have a higher impact than climate change ([Barange et al., 2010](#_ENREF_9); [Barange et al., 2014](#_ENREF_10); [Brander, 2007](#_ENREF_22); [Holsman et al., 2019](#_ENREF_69); [Merino et al., 2010a](#_ENREF_98)). Efforts to mitigate and adapt to climate change should be planned together with international management collaborations to ensure the future viability of marine resources ([Baudron et al., 2020](#_ENREF_12); [Palacios-Abrantes et al., 2020](#_ENREF_106); [Poulain et al., 2018](#_ENREF_119)) and social aspects ([Ommer et al., 2013](#_ENREF_105)). Many studies show the economic and ecological benefits of fishing levels below MSY ([Da-Rocha and Mato-Amboage, 2016](#_ENREF_40); [Merino et al., 2015](#_ENREF_100); [Shephard et al., 2013](#_ENREF_125); [Voss et al., 2014](#_ENREF_137)) which improves fish stocks’ resilience to climate change impacts ([Fernandes et al., 2013](#_ENREF_56); [Fernandes et al., 2016](#_ENREF_58)).

Adaptation tools need to be proposed and evaluated ([Poulain et al., 2018](#_ENREF_119)). For example, the fishing industry can adapt by (i) inducing reductions of captures through increasing the value of their products (increase revenue through sustainable certifications ([Council, 2002](#_ENREF_38))), (ii) reducing fuel use (reduce costs), and (iii) reducing the time at sea with higher digitalization and route optimizations ([Granado et al., 2021](#_ENREF_64)). Modern fisheries heavily depend on fossil fuels ([Pauly et al., 2003](#_ENREF_110)) and its price increases are likely to continue pushing the fishing industry to improve fuel efficiency to remain profitable ([Daw et al., 2009](#_ENREF_42)). In addition, the performance of the fishing fleets has decreased, mainly due to the coastal stocks decline ([Pauly et al., 2003](#_ENREF_110); [Watson and Pauly, 2001](#_ENREF_138)) and the increasing effort that fleets must be done searching target species ([Parker et al., 2018](#_ENREF_107); [Tyedmers et al., 2005](#_ENREF_136)). Like other sectors of the economy, fisheries would be required to mitigate the carbon footprint ([Sumaila et al., 2011](#_ENREF_131)). Strategies to improve the short- and long-term performance of the industry and decrease fuel consumption should include behavioral (i.e. reducing vessel speed while steaming and using more selective fishing times and locations [Abernethy et al. (2010)](#_ENREF_1)), technological and managerial efforts ([Parker et al., 2018](#_ENREF_107)). Route optimization methods offer an opportunity for the fisheries industry to enhance its economic and ecological sustainability by reducing costs and environmental impacts ([Granado et al., 2021](#_ENREF_64)). I.e. a win-win for industry and the environment ([Granado et al., 2021](#_ENREF_64); [Pauly et al., 2003](#_ENREF_110)). However, the most effective improvement to fisheries’ energy performance will come as a result of rebuilding stocks where they are depressed and reducing over-capacity ([Parker and Tyedmers, 2015](#_ENREF_108)). Despite sparse studies of climate change impacts on large predators, it should not be a limitation to taking action to mitigate and adapt the fisheries sector to future potential changes ([Sumaila, 2019](#_ENREF_130)).

# 5. Conclusions

1) The fish stocks are projected to decrease their global potential productivity by 36% on average across scenarios by 2050. These stocks affected by reduced productivity represent 2.1 million t of the current catch worldwide. The results suggest that high trophic level species will be more impacted by climate change than by fishing pressure under the assumption that they remain nearby their MSY levels or current fishing pressure, but that the biomass would be much higher without fishing.

2) Five species; Atlantic and Southern bluefins, swordfish, bigeye and albacore are estimated to decrease in biomass and size, being the bluefins the highest-value commercial species. These species represent almost a third of the landings in the Atlantic Ocean and 10% in the Pacific Ocean.

3) Tuna and swordfish body size are expected to decrease by 15% by 2050, being the largest decrease for the bluefin in the West Pacific (24%). The exceptions correspond to a size increase of 5% for the Pacific bluefin and yellowfin in IATTC, and for skipjack and yellowfin in the WCPFC (in 8.5 and 10%, respectively). Fish price and demand are partially driven by body size and therefore, climate change and fishing can potentially reduce revenues for the fishing industry even for the catch of stocks that are estimated to increase productivity.

4) Adaptation measures to the changing climate should be adopted by the fishing industry by increasing the value of fish through sustainability certifications and reducing fuel consumption and time at sea with higher digitalization. Reducing fuel consumption can be also considered a mitigation measure for climate change since it comprises 5% of the total globally fishing used fuel amount and would reduce CO2 emissions.

**CODE AVAILABILITY**

The code of the SS-DBEM model used in this study can be found in the following link in [ZENODO](https://zenodo.org/record/7548113#.Y8kw5RfMKUk) with the associated doi: [10.5281/zenodo.7548113](https://doi.org/10.5281/zenodo.7548112)

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# Supplementary Material

The Von Bertalanffy growth function coefficients from different studies were averaged for each species after discarding the two smallest and highest values found in the literature, using [FishBase](file:///C:\Users\gchust\AppData\Local\Microsoft\Windows\INetCache\Content.Outlook\JKACK3NC\www.fishbase.org) data as an individual source of information and represented by the average of the observations. The trophic levels and maximum Standard Lengths (SL) were updated according to [SAUP](file:///C:\Users\gchust\AppData\Local\Microsoft\Windows\INetCache\Content.Outlook\JKACK3NC\www.seaaroundus.org) data (downloaded in January 2019).

*Supp. Mat. Table 1: Parameters updated in the SS-DBEM model for each target species. \*Species lengths in cm.*

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **TaxonKey** | **Taxon Name** | **Common Name** | **Linf\*** | **VBonK** | **t0** | **lwA** | **lwB** | **TL** | **MaxLenTL\*** | **CommonL\*** | **R** |
| 600089 | Acanthocybium solandri | Wahoo | 250.00 | 0.34 | -0.31 | 0.003 | 3.19 | 4.26 | 250 | 300 |  |
| 600006 | Coryphaena hippurus | Common dolphinfish | 210.00 | 1.41 | -0.07 | 0.05 | 2.75 | 4.37 | 210 | 290 |  |
| 600077 | Istiophorus platypterus | Indo-Pacific sailfish | 348.00 | 0.11 | -0.87 | 0.04 | 2.63 | 4.5 | 386 | 200 | 1.04 |
| 600107 | Katsuwonus pelamis | Skipjack tuna | 81.31 | 0.54 | -0.88 | 0.005 | 3.22 | 4.43 | 120 | 290 | 0.96 |
| 601072 | Lampris guttatus | Opah | 203.40 | 0.2 | 0 | 0.03 | 3.00 | 4.22 | 200 | 270 |  |
| 601042 | Lepidocybium flavobrunneum | Escolar | 203.40 | 0.08 | -1.29 | 0.01 | 3.00 | 4.34 | 244 | 200 |  |
| 600216 | Makaira nigricans | Atlantic blue marlin | 500.00 | 0.32 | -0.25 | 0.007 | 2.96 | 4.49 | 500 | 165 | 0.44 |
| 603915 | Tetrapturus angustirostris | Shortbill spearfish | 233.40 | 0.44 | -0.21 | 0.0005 | 3.83 | 4.5 | 230 | 160 |  |
| 600223 | Tetrapturus audax | Striped marlin | 420.00 | 0.26 | -0.34 | 0.02 | 3.06 | 4.58 | 420 | 150 | 0.26 |
| 600220 | Tetrapturus pfluegeri | Longbill spearfish | 257.40 | 0.36 | -0.25 | 0.01 | 3.00 | 4.4 | 282 | 170 |  |
| 600142 | Thunnus alalunga | Albacore | 118.48 | 0.24 | -1.37 | 0.03 | 2.80 | 4.3 | 155 | 180 | 0.45 |
| 600143 | Thunnus albacares | Yellowfin tuna | 175.74 | 0.43 | 0.33 | 0.02 | 2.98 | 4.41 | 265 | 150 | 0.79 |
| 600144 | Thunnus atlanticus | Blackfin tuna | 107.95 | 0.33 | -0.39 | 0.02 | 3.02 | 4.35 | 120 | 190 |  |
| 600145 | Thunnus maccoyii | Southern bluefin | 210.60 | 0.16 | -0.27 | 0.02 | 3.06 | 3.87 | 272 | 100 |  |
| 600146 | Thunnus obesus | Bigeye tuna | 239.53 | 0.20 | -0.53 | 0.02 | 2.90 | 4.49 | 250 | 120 | 0.55 |
| 614290 | Thunnus orientalis | Pacific bluefin tuna | 303.20 | 0.10 | -0.92 | 0.01 | 3 | 4.21 | 333 | 70 |  |
| 600147 | Thunnus thynnus | Northern bluefin tuna | 313.72 | 0.11 | -0.65 | 0.02 | 2.93 | 4.45 | 458 | 100 | 0.39 |
| 600148 | Thunnus tonggol | Longtail tuna | 144.98 | 0.32 | -0.36 | 0.01 | 3.00 | 4.5 | 161 | 72 | 0.43 |
| 600226 | Xiphias gladius | Swordfish | 269.34 | 0.096 | -1.99 | 0.01 | 3.21 | 4.53 | 505 | 80 | 0.83 |