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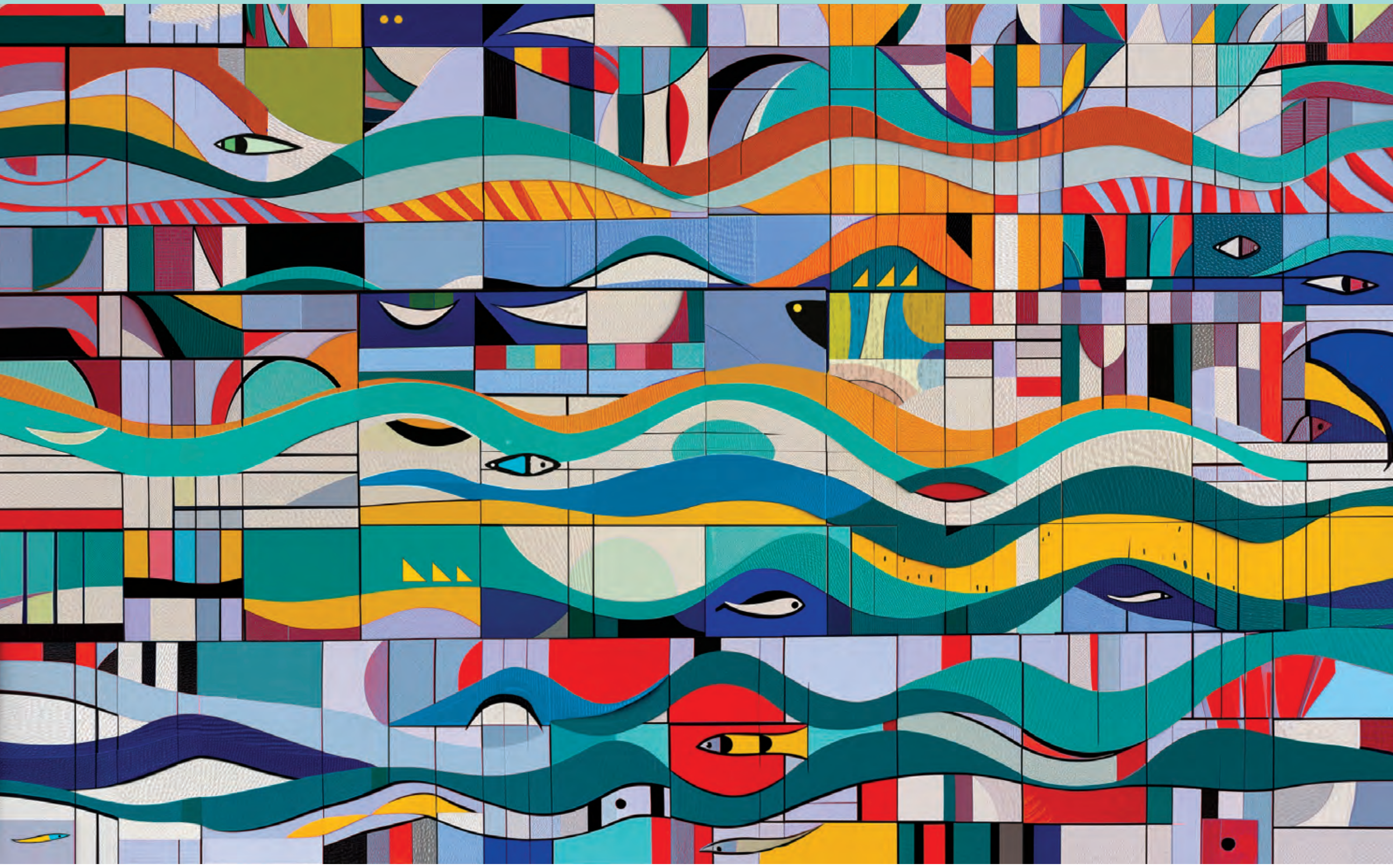
Projections to 2100 from the Fisheries and Marine Ecosystem Model Intercomparison Project



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Projections to 2100 from the Fisheries and Marine Ecosystem Model Intercomparison Project

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Preparation of this document

The preparation of this document started with a collaboration between FAO, the University of Tasmania (UTAS), and the Fisheries and Marine Ecosystem Model Intercomparison Project (FishMIP). Prof. Julia Blanchard (UTAS; FishMIP lead) and Dr Camilla Novaglio (UTAS; FishMIP co-coordinator) were appointed to produce a report on FishMIP climate change projections. The editors designed the structure and content of the Technical Paper and led writing, data analysis, incorporation of co-author contributions, and revisions, commissioning and addressing reviews with advice from Prof. Manuel Barange and Dr Tarûb Bahri (FAO Fisheries and Aquaculture Department).

To involve the FishMIP community, online meetings with members of FishMIP took place in 2022 and 2023 after a first draft was prepared. These were to discuss the overall contents and objectives of the Technical Paper that would provide synthetic information on marine ecosystem models and their outputs aimed primarily at policymakers and fisheries management: the paper was needed to support FAO's Climate Change Strategy and FAO's vision of a Blue Transformation. During these meetings, the structure of the Technical Paper and the chapters proposed by the editors were discussed and agreed upon. Moreover, a template for sub-sections was provided, and the lead authors and contributors for each section were identified. Experts submitted their first drafts in July 2023, and the draft Technical Report was presented and discussed at a meeting open to the whole FishMIP network. FishMIP international experts revised the draft Technical Report and the lead editors developed and wrote three additional chapters (in Part A). The main results were presented at the UN Ocean Decade Conference, Barcelona, in May 2024.

The Technical Report was peer-reviewed and comments and feedback provided by reviewers, and all contributing authors, were compiled and addressed. Once the final draft was approved language editing, formatting and layout were provided (see Acknowledgements).

Abstract

Climate change is posing serious risks to marine ecosystems and the fisheries they support. These rapid changes could undermine the effective fisheries management needed to achieve several of the UN Sustainable Development Goals, as well as FAO's Blue Transformation vision for a resilient, equitable and sustainable aquatic food systems.

Robust model projections are needed to help assess potential threats to fish biomass production associated with future climate change. This report presents projections from the Fisheries and Marine Ecosystem Model Intercomparison Project (FishMIP), an international network of researchers working towards understanding the long-term impacts of climate change on marine ecosystems and fisheries around the world. Using a state-of-the-art model ensemble, the projections estimate medium- and long-term potential losses and gains in the capacity of the world's marine ecosystems to produce fish[1] biomass.

FishMIP's future projections consider two possible future pathways under contrasting Intergovernmental Panel on Climate Change scenarios: 1) SSP1-2.6 is a 'low emissions' scenario, aiming for net-zero emissions after 2050 and less than 2 °C global atmospheric warming by 2100; and 2) SSP5-8.5 is a 'high emissions' scenario with emissions continuing to grow then peaking before the end of the century and leading to over 4 °C of global atmospheric warming by 2100.

Results reveal projected losses in fish biomass production in most places. By mid-century, declines > 10 percent are projected for most countries, particularly under the high emissions scenario (Figure 1). Declines continue to worsen towards the end of the century (e.g. > 30 percent in 48 countries and territories) under the high emissions scenario, which projects global warming of 3–4.0 °C. Some of the largest projected biomass declines are for countries that substantially rely on protein supply from aquatic foods (e.g. Solomon Islands, Federated States of Micronesia, Nauru, Portugal, Palau) or are top producers in terms of global marine fisheries production (e.g. China, Peru). End-of-century losses are greatly reduced under the low emissions scenario which projects global warming of 1.5–2 °C; changes stabilize between no change and a decrease of < 10 percent across 178 countries and territories. In a few cases, increases are projected under both scenarios. However, there is very low confidence in the direction of projected change where increases occur.

The report further describes how FishMIP-projected changes, and their associated uncertainties, are currently being used to help support a variety of regional vulnerability and risk assessment projects around the globe. FishMIP projections are being used to provide quantitative information for informing a variety of climate change risk and vulnerability assessments, including some case studies.

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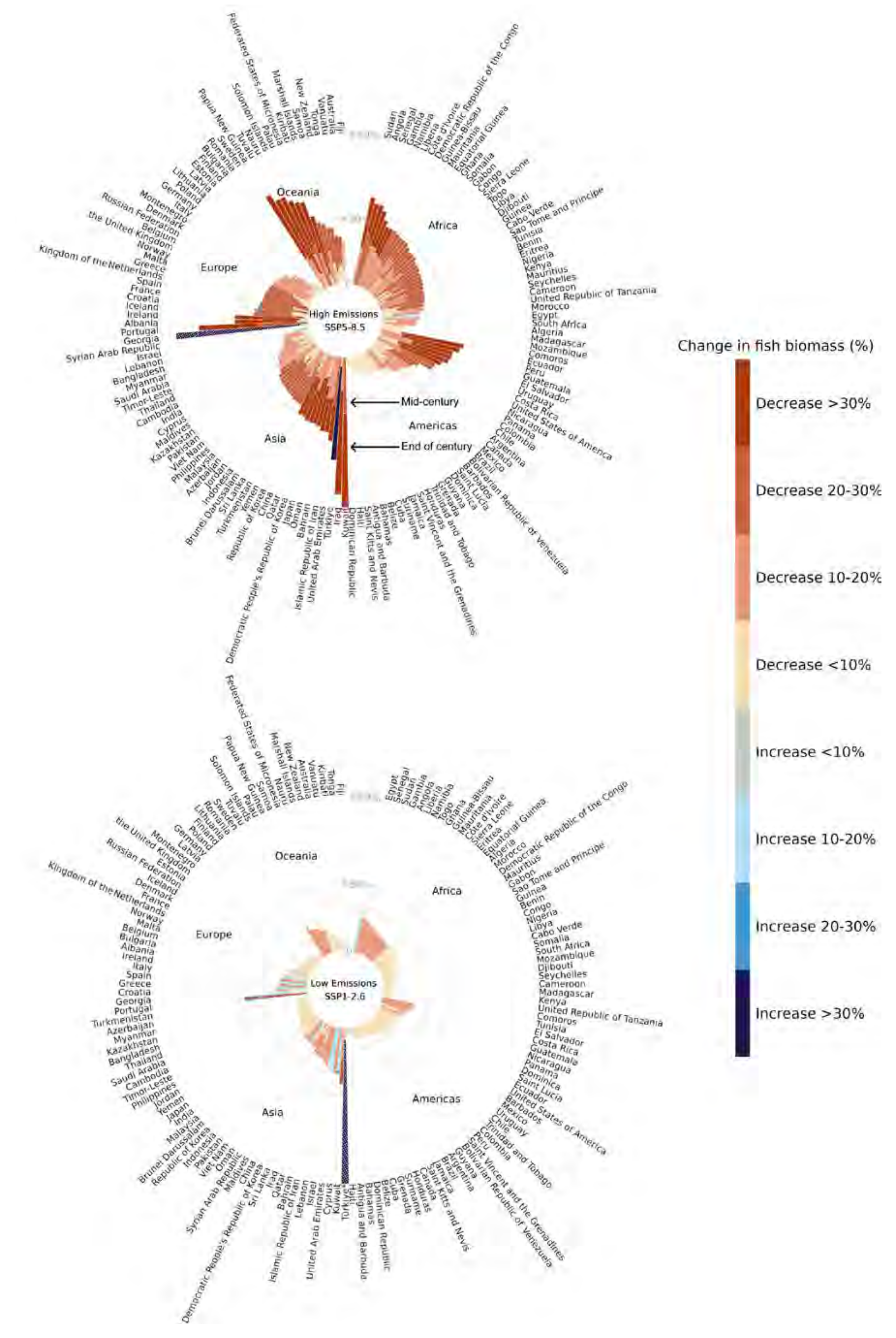
[1] The term 'fish' is employed broadly here, as fish typically dominate marine animal biomass between the size range used (10 g to 100 kg) for Part A projections – but this estimate also includes other marine animals that occupy that size range.

Information is provided on the key uncertainties and limitations of global ecosystem model projections, and on how these limitations are currently being tackled to improve the reliability of modelling outputs. This includes a description of FishMIP 2.0, the next phase of development of this international network which aims to build global capacity for advancing this research. FishMIP 2.0 offers a shared global approach for a wide range of communities and agencies to better understand the state of ecosystems, fisheries, and how to strategically respond to climate change.

The report concludes with recommendations for improving the accuracy of climate impact ensemble modelling for marine ecosystems and fisheries, including building capacity through provision of tools and training to enhance capabilities for meeting future policy needs. Among these is the inclusion of aquaculture in ecosystem models, and a combined analysis of land-sea modelling outputs for fully integrated assessments.

Figure 1. Trends in exploitable fish biomass across different countries under two climate scenarios



Notes: Model ensemble projections of changes in exploitable fish biomass (percentage) relative to the average biomass over the reference period (2005–2014) aggregated by administrative country (extended data disaggregated for countries and territories are provided in Table A4). Bars with stippling indicate low confidence in the projected direction of change (< 80% model agreement). The asterisk next to Türkiye denotes a greater value than shown in the figure (see Table A4). Projections capture ecosystems under climate change in the absence of fishing, and therefore represent changes in exploitable fish biomass. Light grey circles correspond to the level of variation in exploitable fish biomass (±10, 20, 30%)

Sources: Figure elaborated using: Flanders Marine Institute. 2019. Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM), version 11. https://doi.org/10.14284/386; countries' official names from https://www.fao.org/nocs/en.

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We also gratefully acknowledge all contributing global marine ecosystem modellers (listed in Table A6), regional modellers, coordinators, and members from the Fisheries and Marine Ecosystem Model Intercomparison Project. We thank the Intersectoral Impact Model Intercomparison Project cross-sectoral science and technical support teams for their roles in producing, coordinating, and maintaining input data and impact model output data.

Parts B and C of this report were written in parallel with the tenth anniversary FishMIP Special Issue on ‘Past and Future of Marine Ecosystems’ in Earth’s Future, organized by Julia Blanchard, Camilla Novaglio, Cheryl S. Harrison, Kelly Ortega-Cisneros, Kelsey Roberts and Tyler D. Eddy. We are grateful for the contributions of all editors, authors, coordinators, and reviewers (cited papers are listed Table A7).

Abbreviations

CMIP	Climate Model Intercomparison Project, phase 5 (CMIP5) and phase 6 (CMIP6)
ESM	earth system model
FishMIP	Fisheries and Marine Ecosystem Model Intercomparison Project
GFDL	Geophysical Fluid Dynamics Laboratory (Earth system model)
GFDL-ESM4	Geophysical Fluid Dynamics Laboratory Earth System Model version 4.1. This model version is used for Climate Model Intercomparison Project Phase 6 (CMIP6) simulations.
IPBES	Intergovernmental Platform for Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IPSL	Institute Pierre-Simon Laplace (Earth system model)
IPSL-CM6A-LR	Institute Pierre-Simon Laplace Climate Model 6A Low Resolution. This model version is used for Climate Model Intercomparison Project Phase 6 (CMIP6) simulations.
ISIMIP	Intersectoral Impact Model Intercomparison Project (https://www.isimip.org/)
NPP	net primary production
OSP	ocean system pathways
RCP	representative concentration pathways
SDGs	Sustainable Development Goals
SSP	Shared Socioeconomic Pathway
SST	sea surface temperature

Key messages

1. ***Global biomass projections highlight potential climate risks to fish production for nearly all regions of the world, including top producer countries and those with lower production but high reliance on aquatic foods. Actions to reduce hazards to marine ecosystems and fisheries from climate change impacts, and better understanding of associated uncertainties, urgently need to be addressed.***
    - Global projections of exploitable fish biomass show greater than 10 percent declines, particularly under the high emissions scenario, by mid-century for many regions of the world.
    - By the end of the century, under the high emissions scenario which projects global warming of 3–4.0 °C, declines worsen (e.g. 30 percent or greater in 48 countries and territories).
    - In contrast, under the low emissions scenario which projects global warming of 1.5–2 °C, changes stabilize between no change and a decrease of 10 percent or less across 178 countries and territories.
    - Notable declines include those for top fish producer nations, which worsen towards the end of the century under the high emissions scenario (e.g. greater than 30 percent for China) but stabilize under the low emissions scenario.
    - In waters outside national jurisdiction, end-of-the-century losses in exploitable fish biomass are highest (40 percent or greater) for Major Fishing Areas of the Northeast and Northwest Pacific Ocean, under the high emissions scenario. The latter registers the highest fisheries landings among all FAO Major Fishing Areas.

2. ***Lower emissions significantly reduce end-of-century losses for nearly all countries and territories compared to the high emissions scenario. This highlights the benefits of achieving net-zero emissions for fisheries and aquatic foods.***
    - A comparison of the losses projected under both scenarios by the end of the century reveals that lowering emissions has marked benefits for nearly all countries and territories.
    - This includes Small Island Developing States where people rely heavily on fisheries for food and income and where the ecological and socioeconomic risks posed by climate change are highest.
    - For example, among the Pacific Islands States, 68–90 percent of the extreme end-of-century losses projected under high emissions are averted by the low emissions scenario for Palau, Tuvalu, Nauru, the Federated States of Micronesia, and Solomon Islands.

3. ***Losses in fish biomass production in many regions have much higher levels of model confidence than the projected gains in a few countries. Regions with high uncertainties can help to prioritize where knowledge gaps and research advances are needed.***
    - Inter-model variability and agreement on the direction of change in exploitable fish biomass are used as a proxy for levels of confidence.

- There is very low confidence in the direction of projected change where steep increases are estimated (e.g. Arctic Ocean), and higher confidence in the direction of projected change in most of the regions where steep projected declines occur.
- At the regional scale, these projected changes do not capture uncertainties associated with more complex physical-ecological processes, highlighting where gaps in understanding need to be filled.

4. ***Improved accuracy is needed for processes associated with primary production; an important driver for projecting fish biomass changes.***
   - While Earth system models capture changes in temperature well, large differences exist between their estimates of net primary production, and biases with observational products exist.
   - Primary production and temperature variables are strong drivers of fish biomass estimates for many marine ecosystem models; differences in these inputs alone and under different ecological model assumptions result in wide inter-model variability in both the magnitude and direction of change. This is especially pronounced at regional scales.
   - To build more robust projections, accurate and comparable observational products are needed to improve Earth system and marine ecosystem models.

5. ***The marine ecosystem model ensemble does not include uncertainty associated with fisheries-management responses to climate change, and does not include risks from other drivers of change not represented in the models.***
   - The projections focus on the potential effects of climate change on exploitable fish biomass and do not include fishing.
   - Therefore the models do not simulate the potential for abrupt changes that may result from combinations of climate change, habitat deterioration, fishing pressure, pollution and other human factors.
   - To tackle missing drivers of change, new simulations are under development that capture the combined effects of past and future climate change and fishing activity.

6. ***FishMIP projections and their associated uncertainties offer the state-of-the art in climate change impact model projections for adaptation purposes.***
   - Projections are being used to help support a variety of regional vulnerability and risk assessment projects.
   - This quantitative information can be used to help guide adaptation planning and in discussions at local, national and regional levels.
   - Country-level estimates of losses associated with high emissions could support the development of Nationally Determined Contributions to reduce emissions.

7. ***To assist countries in achieving FAO's Blue Transformation vision of more resilient, equitable, and sustainable aquatic food systems, future FishMIP models will need to represent other ocean and coastal uses (i.e. beyond fisheries) to:***
   - Capture a more holistic view of managing marine natural resources in the face of climate change.
   - Inform trade-offs across sectors, including adaptive fisheries management and wider agri-food policies.
   - Address linkages with freshwater and terrestrial resource use (e.g. the reliance of aquaculture on both marine and terrestrial systems) to help support policy directions at the nexus of climate change, biodiversity, water and food security, and health.

Background

We are in a time of urgency: rising food insecurity, widening inequalities, mounting ecosystem degradation, and a climate crisis that is intensifying. To address this, the 2030 Agenda for Sustainable Development set universally agreed Sustainable Development Goals (SDGs) framed around contemporary challenges, such as hunger, climate change and biodiversity loss, and the Decade of Action called for accelerated solutions to deliver these goals (https://sdgs.un.org/goals). To help meet these goals, robust science-based knowledge is needed to create solutions that simultaneously meet the increasing human demand for food while reducing greenhouse gas (GHG) emissions and protecting ecosystems. Because agrifood systems rely on climate and environmental conditions, and changes to these conditions are already posing multiple threats, climate action is essential to achieve sustainable development.

To support the formulation and implementation of climate commitments from global to local levels, FAO developed the Climate Change Strategy 2022–2031, rooted in the best available science and the latest innovations, and advocating for evidence-based solutions to climate challenges. To strengthen climate policy and governance, and to trigger actions, this strategy emphasizes the importance of enabling the use of data, scientific information, and tools. These tools are essential for narrowing the knowledge gap on climate change risks to agrifood systems, monitoring and reporting climate vulnerability and risk, and balancing trade-offs between climate change and other SDGs (FAO, 2022a). Similarly, FAO's global roadmap to achieve food security without breaching the 1.5 °C threshold released after the 28th Conference of the parties to the United Nations Framework Convention on Climate Change (UNFCCC COP 28) set out actions, goals and milestones tailored to specific domains such as crops, livestock, fisheries and aquaculture. The roadmap also highlights the pivotal role of science and innovation and of robust science-policy interfaces for productivity enhancement and climate change solutions (FAO, 2023a).

The roadmap recognizes the current and future potential of fisheries and aquaculture to help sustainably meet global food demand. They have this role due to the high nutritional value of aquatic food, its relatively low GHG footprint, and the contribution of these sectors to national and local economies and livelihoods (Crona *et al*., 2023; FAO, 2023a). The roadmap also highlights actions that could contribute to the Blue Transformation agenda for fisheries and aquaculture, centred on better production, nutrition, environment, and life (FAO, 2022b). This includes the improvement of sustainable fishing practices through the use of innovative data and scientific information to help support ecosystem restoration and increase the resilience of fish stocks in the face of intensifying climate change impacts. Millions of livelihoods are at stake, and the need for adaptation strategies to cope with climate change impacts on fisheries was also expressed by the recently formed FAO sub-committee on fisheries management (COFI-FM). This body provides an intergovernmental platform for countries to discuss challenges and progress related to fisheries management as well as recommendations and policy advice: climate-resilient fisheries has been one of its key discussion items.

To better face these challenges, there is an urgent need for robust projections of climate change impacts on marine ecosystems and the fisheries they support (Barange *et al*., 2018). These projections are needed to inform vulnerability, adaptation, and mitigation planning for different nations and regions. Without improved model projections that appropriately capture ecosystem changes under future climate and human development scenarios, as well as an understanding of their associated uncertainties, evaluations of the risks and benefits of future seafood policy pathways may be misleading, potentially resulting in unanticipated threats to ecosystems, food security, and livelihoods.

Overview of FishMIP

The Fisheries and Marine Ecosystem Model Intercomparison Project (FishMIP; www.fishmip.org) was officially launched in 2013. It aims to address the challenges described above by bringing together the marine ecosystem modelling community and substantially advancing predictive modelling of marine ecosystems, thus providing more accurate advice for industry and governments, and enabling effective planning for adaptive and resilient seafood sectors under climate change. In 2024, FishMIP2.0 was established to increase the reliability of modelling projections and to answer a broader set of policy-related questions pertinent to food security and marine resource management, with climate change remaining the overarching theme (Blanchard *et al*., 2024; Novaglio *et al*., 2024).

Current work towards these aims includes:

1. Identifying regions where climate change is likely to pose hazards to marine ecosystems and the services they provide, and regions where projections from ecosystem models are highly uncertain and therefore require further investigation.

2. Benchmarking marine ecosystem models to help identify where improvements are needed, and achieving detailed validation against observations. Using novel big-data streams and modern statistical and mathematical approaches, FishMIP is developing new methods to test and advance the next-generation ensemble of global and regional ecosystem models and to compare model performance across key regions.

3. Integrating future projections of human and climate drivers of change: quantitative scenarios coupling climate and human pressures are being developed to provide a coherent picture of plausible futures. These scenarios will be used to pinpoint where adaptation, mitigation and climate-smart conservation are most urgently needed, and to identify the safe operating space for sustainable food and healthy ecosystems necessary for human wellbeing and biodiversity protection.

4. Integrating food-system climate vulnerability assessments by ensuring consistent methodologies across fisheries and aquaculture in climate impact models and by resolving missing linkages among marine and terrestrial food sectors. By strengthening international research and industry collaborations across land and sea sectors and by developing new analytical tools, outputs from FishMIP can be integrated with those from aquaculture and terrestrial agriculture modelling groups.

Marine ecosystem models use different assumptions and parameters to represent ecosystems, but to contribute to FishMIP they need to follow a standardized simulation protocol for conducting model experiments to assess climate change impacts in a consistent way across all regions (Blanchard *et al*., 2024; Tittensor *et al*., 2018). These are aligned with and contribute to wider climate impact modelling across sectors such as water, agriculture, and human health as part of the Intersectoral Impact Model Intercomparison Project (ISIMIP) (www.isimip.org; Warszawski *et al*., 2014; Frieler *et al*., 2024). This alignment is particularly important for understanding climate impacts on food systems as it enables consistent analysis of outputs across marine ecosystems and fisheries, and across agriculture models (Blanchard *et al*., 2017; Cinner *et al*., 2022).

Driven by outputs from Earth system models from two rounds of the Coupled Model Intercomparison Project (CMIP5 and CMIP6; Taylor *et al*., 2012; Eyring *et al*., 2016; https://wcrp-cmip.org/), FishMIP models produced projections of climate change impacts on marine ecosystems. CMIP uses a suite of Earth system models integrating complex atmosphere, ocean, land, ice, and biosphere dynamics to produce projections of climate variables (e.g. atmospheric and ocean temperature) and to understand their past and future changes. FishMIP work identified both regions where ocean biomass is likely to see marked changes by the end of the twenty-first century and regions of uncertainty in model projections – i.e. regions where models do not agree on the direction and/or magnitude of changes (Lotze *et al*., 2019; Tittensor *et al*., 2021). The focus of both CMIP5 and CMIP6 simulation rounds has been on the effects of climate change on ecosystems and the potential consequences for fisheries.

To date, the FishMIP model ensemble includes nine global models and more than 30 regional models. Projections for regional ecosystem models have been compared with global models for a small subset of different systems around the globe, such as the coasts of the United States of America and Southern Africa, the Mediterranean Sea, and shelf regions of Australia, New Zealand and Europe (Eddy *et al*., 2024). However, there is bias towards high-income countries in the geographical coverage of regional ecosystem models, and many are still under development. This means that most regions of the world do not have detailed regional models available, and underlines the importance of using global ecosystem models for providing the consistent country-level information that policymakers require.

FishMIP global projections inform climate-smart marine resource management and conservation on global and regional scales. They have played integral parts in the most recent synthesis reports from the Intergovernmental Panel on Climate Change (IPCC, 2019a,b, 2022) and the Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES, 2019). The global FishMIP ensemble contributed to the IPCC's *Special Report on the Ocean and Cryosphere in a Changing Climate* (2019) by providing future projections of fish distribution, size and biomass under different climate change scenarios. In the IPCC's *Sixth Assessment Report* (2022), global FishMIP projections elucidated the range of ecological responses to climate change in the future ocean. In the IPBES report (2019a), FishMIP introduced the value of model ensembles in understanding climate change effects on marine biodiversity, and highlighted climate-impact trajectories on marine ecosystems. For example, by 2100, the global ensemble mean marine animal biomass was projected to decline by between 3–23 percent (IPBES, 2019), largely driven by a combination of increasing water temperature and declining primary productivity, emphasizing the potential risk for ecosystem services including seafood supply and viable fisheries. FishMIP results have also been used to assess cross-sectoral food security and sustainability challenges, risks and uncertainties under climate change, highlighted in the IPCC *Special Report on Land* (2019b).

Now in its second decade, FishMIP 2.0 (www.fishmip.org) has more recently developed an integrative simulation framework that includes both climate and socioeconomic drivers of change (Blanchard *et al*., 2024), and modelling simulations of this kind are currently underway. This advance includes standardized global historical fishing effort inputs for models and better representation of coastal processes, which are of relevance to many of the world's fisheries (Blanchard *et al*., 2024; Ruane *et al*., 2016). Improvements also include the exploration of complex future climate and socioeconomic scenarios where multiple factors (e.g. market demand, management) simultaneously change to give rise to contrasting futures; these are very much needed for policy advice (Maury *et al*., 2024).

The advances described above permit FishMIP to work towards a detection and attribution framework that systematically assesses whether any observed declines in ecosystem biomass and/or catches are detectable from models – and, if they are, due to which combination of drivers (Blanchard *et al*., 2024; Novaglio *et al*., 2024). The inclusion of standardized past fishing changes allows for a formal assessment of model accuracy, which can provide decision-makers with measures of confidence for their regions. The detection of past ecosystem and fisheries changes will improve understanding of the relative and combined drivers of fishing and climate change, and of the scope for climate-resilient management measures. Future impact model projections under joint climate and ocean system socioeconomic pathways will enable testing of a range of future fisheries management scenarios, aligned with each of the Shared Socioeconomic Pathways, to determine the impacts associated with each of these pathways and the likelihood of sustainability targets being met. These important steps will enable the FishMIP community to move from model intercomparison towards a better understanding of the reliability of projections of significant ecosystem and fisheries damage under a suite of stressors, which are required to guide adaptation and mitigation strategies to achieve the SDGs and Blue Transformation (Blanchard *et al*., 2024; Novaglio *et al*., 2024).

How to use this report

There are three parts to this report:

PART A builds on previous FAO efforts (Barange *et al.*, 2018) and focuses on reporting FishMIP's most recent global model ensemble projections that bracket a range of possible future impacts by considering low and high emissions scenarios (see Part A Methodology). As a leading indicator for projected impacts of climate change on potential fish production under these scenarios, the focus is on projections of exploitable fish biomass (see Part A Methodology) for countries and territories, and for FAO Major Fishing Areas for areas outside of national jurisdiction.

PART B provides examples of how FishMIP ensemble projections have been and are being used to support policy and management in different regions of the world. This includes applications of global model ensemble results as well as comparisons with and further development of regional marine ecosystem models. While this is not a comprehensive list of all possible uses, examples show how projections can be used to help support climate risk, impact and vulnerability assessments, as well as to assist in the development of climate-resilient adaptive conservation and management plans.

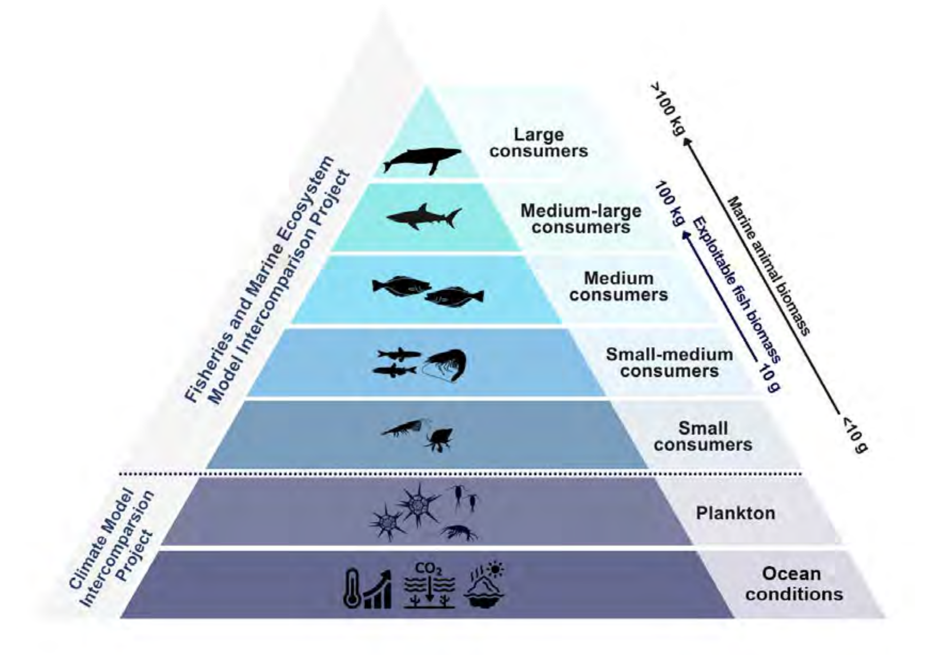
PART C focuses on current directions to improve marine ecosystem model ensembles and projections, including better quantification of model accuracy and uncertainties as well as inclusion of future socioeconomic scenarios in a coupled Earth system to socioecological framework.

Part A Methodology

A primary goal of FishMIP is to help project the potential long-term impacts of climate change on marine ecosystems, fisheries, and the benefits they provide to society. In this section, the methodological approach underpinning the global projections of climate change impacts presented in Part A is described.

To ensure consistency and comparability across all regions of the world, and across other sectors on land, FishMIP projections follow the standardized simulation experimental approach of the Inter-Sectoral Impact Model Intercomparison Project (Frieler *et al.*, 2024). This requires using a standardized set of possible future climate scenarios and Earth system models that produce relevant outputs on changing ocean conditions (temperature, oxygen, salinity, acidity, nutrients, primary productivity etc.). These, in turn, are connected to a diverse suite of global marine ecosystem models that collectively capture a range of plausible responses (e.g. changes in habitat, growth, reproduction, food-web interactions) to changing ocean conditions. It is the combination of these drivers and responses that gives rise to the projected distribution of biomass of marine animals in the ocean, and the potential fisheries they may be able to support (Figure 2).

Figure 2. Conceptual representation of the trophic and size coverage of the FishMIP model ensemble



Notes: The FishMIP global marine ecosystem ensemble consists of nine ecosystem models that use climate-related variables obtained from outputs of the Climate Model Intercomparison Project (e.g. changes in ocean conditions, phytoplankton, zooplankton) to capture a range of ecological responses, including changes in marine food webs, size-structure, and overall biomass. The FishMIP ensemble produces standardized outputs, such as total marine animal biomass and exploitable fish biomass. The latter is a proxy for the biomass available to fisheries, consisting of marine animals spanning the size range 10 g to 100 kg: this is typically dominated by fish, but is also inclusive of other animals such as crustaceans and cephalopods. Phylopic (https://www.phylopic.org/) icons were used to create this figure.

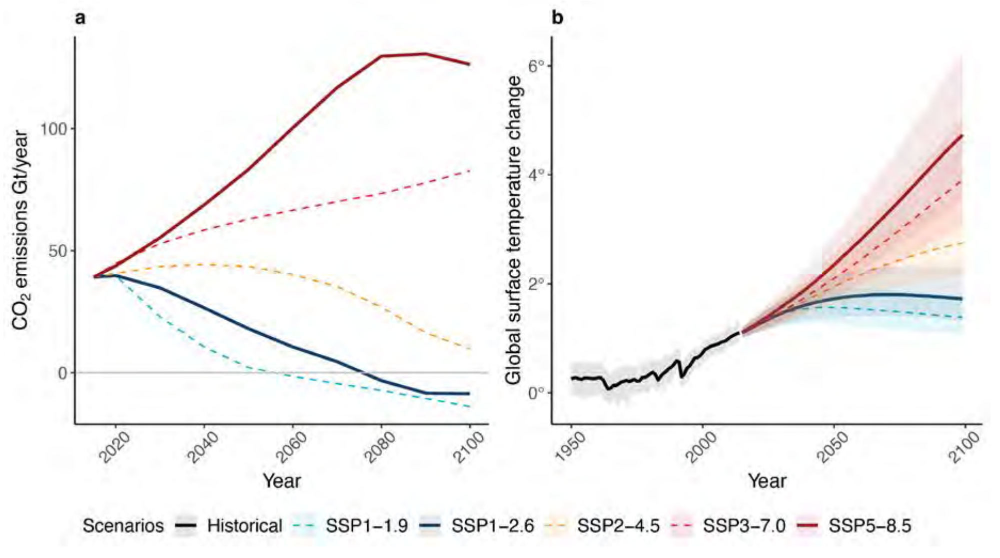
Source: Authors' own elaboration.

It is important to note that at the time of designing these simulations, standardized fishing driver data and future scenarios, for all regions of the world, were not yet available (see current and future work in Part C, which does include integration of standardized fishing drivers and scenarios). Therefore the projections in Part A of this report do not fully capture the range of all human impacts affecting marine ecosystems (e.g. fishing, pollution, habitat destruction), nor do they capture past and future fisheries management trajectories. However, as the state of the art in global ecosystem modelling, these projections can be used to indicate levels of risk and threat associated with the multifaceted effects of climate change on marine ecosystem production. This knowledge is highly relevant for developing science-based adaptive management systems that are responsive yet robust to climate changes.

FUTURE SCENARIOS

Two future climate scenarios are considered in this report: they bracket a range of possible future societal development pathways in terms of emissions. SSP1-2.6 is a 'low emissions' scenario in which net-zero emissions are achieved after 2050, leading to < 2.0 °C of global warming by 2100 relative to pre-industrial temperatures. SSP5-8.5 is a 'high emissions' scenario in which emissions continue to grow then peak before the end of the century, leading to > 4 °C of global warming by 2100 relative to pre-industrial temperatures (Figure 3, IPCC 2021). While other scenarios are also widely available (with the exception of SSP1-1.9), as shown by dashed lines in Figure 3, these contrasting emissions scenarios were considered the most appropriate as best- and worst-case scenarios (Frieler *et al.*, 2024).

Figure 3. Low and high emissions scenarios in terms of carbon dioxide (CO_2) emissions and surface temperature trajectories



Notes: a) Anthropogenic (human-caused) emissions trajectories for CO_2 from all sectors over the 2015–2100 period; and b) Global surface temperature changes relative to 1850–1900. Thick blue and red lines correspond to the low (SSP1–2.6) and high (SSP5–8.5) emissions scenarios used in Part A of this report. For more information on the scenarios considered, see IPCC (2021).

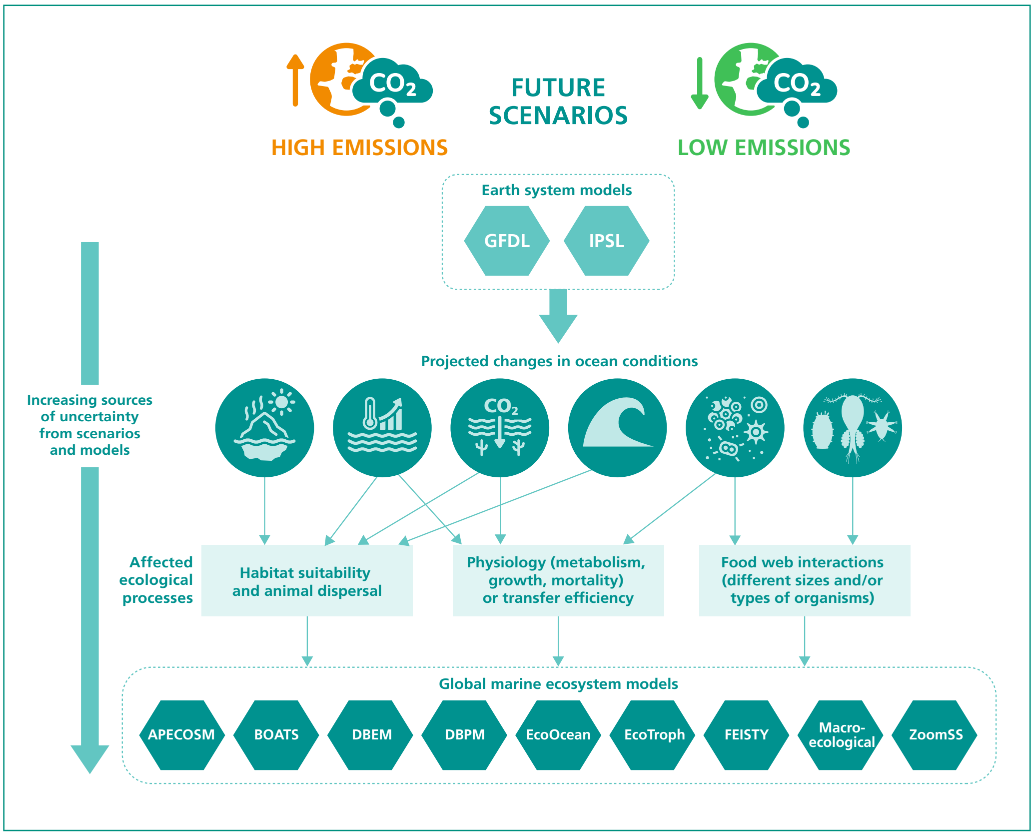
Sources: Figure adapted from IPCC. 2021. Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis.* Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–32, doi:10.1017/9781009157896.001. Data from IPCC Summary for Policymakers data archive.

MODEL UNCERTAINTY

FishMIP uses an ensemble modelling approach to help quantify a range of sources of uncertainty (Willcock *et al.*, 2020, 2023). An ensemble, or group of models, is used to capture a range of plausible mechanisms driving changes in marine ecosystem processes (Willcock *et al.*, 2020, 2023). Our approach captures three main sources of uncertainty: scenario uncertainty, Earth system model uncertainty, and marine ecosystem model uncertainty. This is done by considering two contrasting possible emissions scenarios, for each of which outputs from two contrasting CMIP6 Earth system models are used: one developed by the Geophysical Fluid Dynamics Laboratory (GFDL), the other by the Institute Pierre-Simon Laplace (IPSL). Together these two Earth system models provide a range of projected changes in ocean physics and chemistry that drive primary and secondary production in different ways but produce a common set of outputs that can be used by FishMIP global marine ecosystem models.

Currently, nine global marine ecosystem models contribute to FishMIP (Appendice Table A1). Each is based on different assumptions and has a unique way of conceptualizing marine ecosystems and fisheries. Together FishMIP global marine ecosystem models capture a range of ecological processes and structural complexities (Table A1), ranging from the combined effects of temperature, salinity, and oxygen on species spatial distributions, growth, mortality and reproduction to how the effects of temperature and phytoplankton affect the flow of energy through simplified global marine food-webs (see Figure 4). Regional-scale marine ecosystem models also contribute to FishMIP, but these are only available for certain parts of the world and are therefore not part of the country-level analysis in Part A (see Parts B and C, Table A2).

Figure 4. Schematic diagram to illustrate the flow of information used by the FishMIP global marine ecosystem model ensemble capturing a range of scenario and model uncertainties.



Notes: Two future scenarios, capturing different possible future societal pathways in terms of emissions, are simulated with two selected Earth system models. The Earth system models capture different assumptions about how physical and biogeochemical processes interact to shape our planet. The Earth system models produce a wide range of outputs which each global marine ecosystem model can draw on to model ecological consequences. Because each ecosystem model also has its own specific set of mechanisms and assumptions, a range of plausible pathways for ecological consequences on biomass production can be accounted for. The ensemble as a whole therefore captures a range of quantifiable uncertainties associated with the selected future societal scenarios, Earth system, and ecosystem processes. Not all global marine ecosystem models use all variables shown; the links shown are for illustrative purposes. For more information on the core structure, processes, and variables used by each global ecosystem model see Table A1.

Sources: Authors' own elaboration.

As described above, uncertainties associated with the effects of fishing and other direct human drivers, the effects of benthic habitat changes, changes in fisheries management or fisheries adaptation scenarios, either in past or future, are not accounted for. Therefore the results in this report should be interpreted as an indication of the potential level of climate change risk,[2] and to help identify hotspots which warrant further regional-scale investigation (see Part C).

PROJECTED MODEL OUTPUTS

The use of a standardized protocol is key to producing outputs that can be compared across models. FishMIP models produce a range of outputs (Table A3). Multiple projections across models enable these outputs to be combined into an ensemble which captures the cross-model average, or most likely value, as well as the range across models (e.g. inter-model variability, here captured by standard deviation across models). The latter provides information on the level of confidence in the magnitude and direction of change in the projected trends across models. Further metrics, including the ensemble median and the range of projections across models (minimum, maximum), and the level of model agreement in terms of direction of projected changes are also provided (see Table A4).

All nine global marine ecosystem models can produce estimates of total marine animal biomass (g/m^2 of fish and other ocean animals) in the absence of fishing (Tittensor *et al.*, 2021; Lotze *et al.*, 2019). Relative changes in total marine animal biomass are the focus of different FishMIP studies, including those considered in Part B of this report. To focus more closely on the component of marine animal biomass relevant for fisheries, we use the sum of total biomass of marine animals spanning in size from 10 g to 100 kg, which is broadly representative of the size range dominated by fish; referred to as *'exploitable fish biomass'* produced by six of the global marine ecosystem models (Figure 2). Relative changes in exploitable fish biomass are the focus of Part A of this report because fish and other marine species within this size range (10 g to 100 kg) support fisheries – and, therefore, the achievement of food security, economic and livelihood goals.

This report focuses on how changes in exploitable fish biomass – without fishing – would fluctuate from past to future, under contrasting future emissions scenarios that translate to changes in many physical-ecological processes influencing ecosystem productivity. This differs from how present-day fish biomass, which has been affected by fishery removals and other factors, would change in future. Changes in fish biomass without fishing represent changes in ocean carrying capacity – or, in other words, what the biomass would be if it resulted from physical-ecological processes only.

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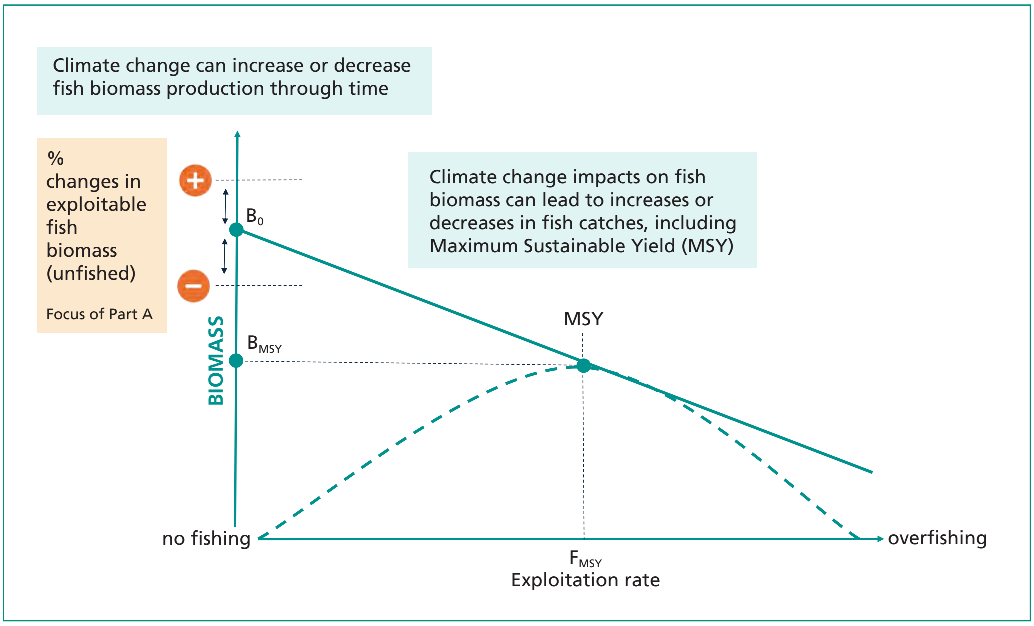
[2] Where risk is defined as the potential for adverse consequences (Reisinger *et al.*, 2020).

In fisheries science, there is a closely related concept of B_0, or unfished biomass at equilibrium (often prior to fishing). Therefore, the projected changes in exploitable fish biomass can be broadly conceptualized as the fluctuations around an aggregate B_0 as driven by climate change. These projections have important consequences for potential fisheries production and management. For example, if unfished biomass decreases, and if fishing mortality rates are at levels consistent with maximum sustainable yield (MSY), fisheries catch could also decrease and the expected level of B_{MSY} (which is roughly half of B_0) would be lower (Figure 5). Knowledge of how B_0 may change could be used to help inform adaptative fisheries management. Due to the variety of feedbacks involved, the compounded and relative effects of climate change and fishing can be challenging to disentangle, even in simplified marine ecosystems models (e.g. Lindmark *et al*., 2022), and therefore would require careful and systematic consideration in the context of a model ensemble.

Figure 5. Idealized illustration of how changes in exploitable fish biomass relate to concepts used to inform fisheries management reference points



Notes: B_0 refers to average unfished biomass at equilibrium. MSY refers to maximum sustainable yield, which is the long-term maximum yield at (equilibrium). F_{MSY} is the fishing mortality (exploitation) rate that is consistent with producing MSY. B_{MSY} is the corresponding biomass that occurs at MSY. While these theoretical concepts are typically used at stock level, here they represent an aggregate biomass. These values will typically exhibit a wide range of variability depending on the species, size, age, life history etc. of the fish included.

Sources: Authors' own elaboration.

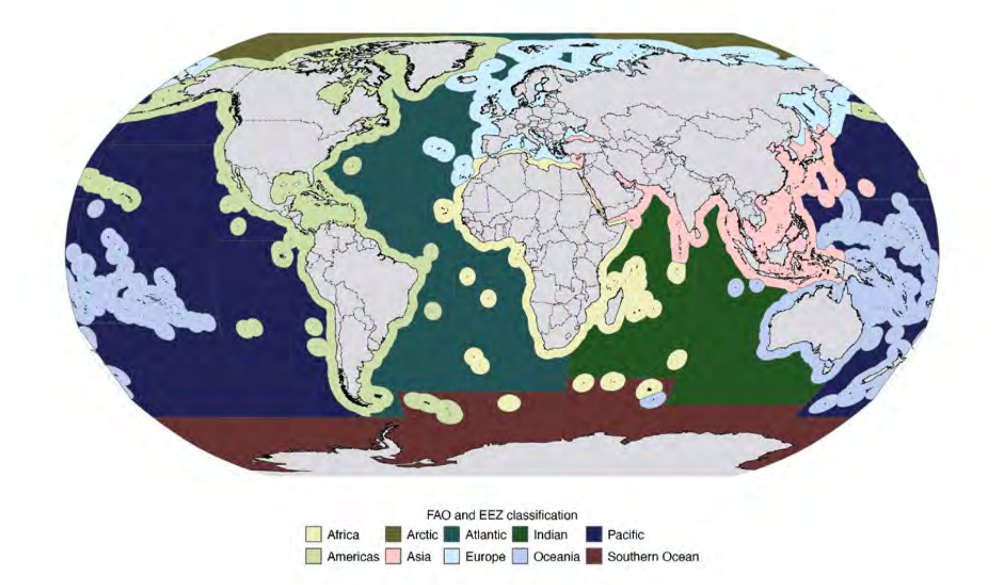
Why use exploitable fish biomass rather than catches? So far, only two global marine ecosystem models have produced IPCC scenario simulations with historical fishing and future projections held constant at 2015 fishing levels (Table A3). At the time of carrying out the simulations standardized global historical fishing inputs were not yet available as part of that protocol, and thus the assumptions about past spatio-temporal changes in fishing differed. To robustly capture an ensemble mean +/- inter-model variability requires a greater number of marine ecosystem models, for robustly assessing climate change risks and model uncertainties. Additional variables which have been produced by a smaller set of models are described in Table A3.

REPORTING RESULTS BY COUNTRIES AND TERRITORIES

Because projections are globally gridded they can be aggregated into larger geographical units corresponding to countries and territories as well as FAO Major Fishing Areas (see Figure 6).

Projections are visualized as either geographical patterns of change (e.g. global or regional maps, with a resolution of 1 latitudinal x 1 longitudinal degree) or trajectories (e.g. annual trends by region). Both types of visualizations present projections as percentage change relative to a reference period rather than as absolute values. Projections include a historical period (e.g. 1950–2014) and a future scenario period (e.g. 2015–2100); the latter relates to the time period for the future climate scenarios according to CMIP6 (IPCC, 2021). For gridded maps, we show four panels consisting of the two future emissions scenarios and two time periods: mid-century (2041–2050) and end of century (2091–2100), both relative to the final 10 years (2005–2014) of the historical period. To provide a global and regional fisheries context, fisheries landings were added to the maps using data from FAO FishStatJ (https://www.fao.org/fishery/en/topic/166235).

Figure 6. Map of regions for analysing and reporting projections



Notes: Waters under national jurisdiction grouped by continent (lighter colours: Africa, Asia, Americas, Europe, Oceania), and FAO Major Fishing Areas grouped by ocean (dark colours: Arctic, Atlantic, Indian, Pacific and Southern Oceans). Note that the 200 nautical miles line for Antarctica is not shown, as projections for this area are discussed at the ocean level. Special disclaimer for Sudan and South Sudan: Final boundary between the Republic of Sudan and the Republic of South Sudan has not yet been determined. Special disclaimer for Jammu and Kashmir: Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties.

Sources: Map elaborated using: FAO. 2020. Geo Server. In: Food and Agriculture Organization of the United Nations. www.fao.org/figis/geoserver/web/; Flanders Marine Institute. 2019. Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM), version 11. https://doi.org/10.14284/386; FAO Statistical Areas for Fishery Purposes. In: FAO Fisheries and Aquaculture Department. www.fao.org/fishery/area/search/en.

FAO countries' and territories' names were considered in all figures of Part A, except for Figure 1 and 8, and for Table 1 where the sovereign country was considered instead (https://www.fao.org/nocs/en) without any detail on territories. For High Seas regions outside waters under national jurisdiction, maps and trajectories were analysed using FAO Major Fishing Areas within the Atlantic, Indian, Pacific, Arctic and Southern Oceans (Figure 6).

PART A. PROJECTED CLIMATE CHANGE IMPACTS ON MARINE ECOSYSTEMS IN FISHING REGIONS

Chapter A.1 Global overview

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Global fisheries and aquaculture animal production reached 185 million tonnes in 2022, and 89 percent of this was used for human consumption. Aquatic animal foods consumption has increased at an annual rate of 3 percent between 1961 and 2021, which is almost double the rate of annual population growth (FAO, 2024). In 2022, the fisheries and aquaculture primary production sector employed about 62 million workers, and aquatic animal products constituted an important food commodity, traded worldwide (FAO, 2024). The marine fisheries component played an important role, with a global fishing fleet of about 4.9 million vessels contributing around 80 million tonnes of fish and marine animals (FAO, 2024).

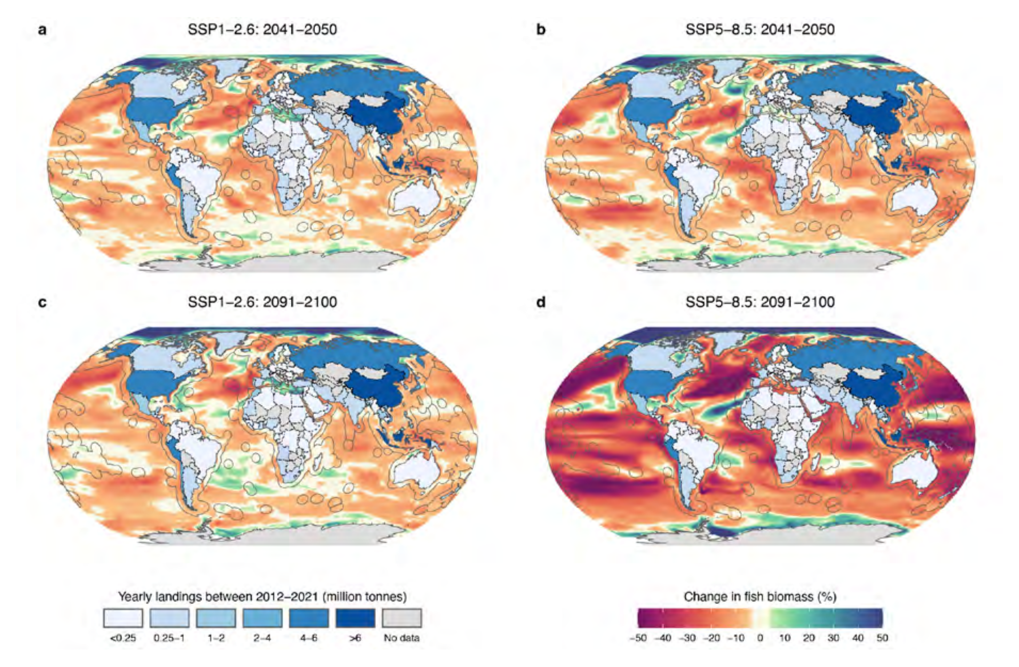
Understanding the climate risks to fisheries resources is critical for many millions of people who rely on fisheries for food and livelihoods (Scherrer *et al*., 2024). Future scenario projections from ensemble models are increasingly being used to help understand these risks (Barange *et al*., 2018; Boyce *et al*., 2022; Lotze *et al*., 2019; Tittensor *et al*., 2018). Such projections have been used to inform international bodies such as FAO, the IPCC and IPBES. The most recent FishMIP ensemble projections for total marine animal biomass have highlighted that a high emissions scenario may disproportionately affect coastal nations, which are responsible for a large fraction of global marine capture fisheries and include nations facing socioeconomic and nutritional challenges (Boyce *et al*., 2020; Bryndum-Buchholz *et al*., 2023; Tittensor *et al*., 2021). This pattern still holds when considering exploitable fish biomass (marine animals between 10 g and 100 kg). Global trajectories in exploitable fish biomass show mid-century (2041–2050) ensemble mean decreases of about 5 percent (+/- 1.6 percent inter-model variability) and 7 percent (+/- 1.6 percent inter-model variability) relative to 2005–2014, under the low and high emissions scenarios respectively (Table 1). By the end of the century, these decreases intensify to about 21 percent (+/- 6.1 percent inter-model variability) under the high emissions scenario, but stabilize at around 7 percent (+/- 3.1 percent inter-model variability) under low emissions, with a clear separation of trends between the two scenarios. By the end of the century, this suggests that the low emissions scenario results in 68 percent less in losses than the high emissions scenario. Decreases are more evident at temperate latitudes under the low emissions scenario, and at both temperate and tropical latitudes under the high emissions scenario (Figure 7). Geographical locations of losses and gains in exploitable fish biomass are similar between the middle and the end of the century for the low emissions scenario, but the intensity of the changes is amplified under the high emissions scenario.

TABLE 1.

Ensemble mean percentage change in exploitable fish biomass and standard deviation (sd), as well as model agreement (agr) in the direction of change by mid-century (2041–2050) and end of century (2091–2100) compared to the reference decade (2005–2014), under the low and high emissions scenarios. Values are reported for the globe and waters under national jurisdiction of the seven countries with the largest 2022 fish catches. Values in bold indicate significant difference in the two scenarios' projections in terms of end-of-century changes (2091–2100) relative to the reference period (2005–2014) ($p < 0.05$, Wilcox statistical test).

Country and the globe	Mid century SSP1-2.6			Mid century SSP5-8.5			End century SSP1-2.6			End century SSP5-8.5		
	mean	sd	agr	mean	sd	agr	mean	sd	agr	mean	sd	agr
Global	-5.3	1.6	100	**-6.9**	1.6	100	-6.7	3.1	100	**-21**	6.1	100
China	-11.9	3.1	100	-11.3	4.4	100	-9.1	3.8	100	**-30.9**	12.1	100
India	-7.2	3.5	100	**-8.7**	2.5	100	-9.3	3.8	100	**-19.6**	8.1	90
Indonesia	-8.7	6.6	90	**-12.4**	6.3	100	-9.1	5.7	100	**-24.9**	12.3	100
Peru	-6	5.7	80	**-10**	7.1	90	-8.3	6.5	100	**-37.3**	20.4	100
Russian Federation	-2	2.9	70	**-4.1**	4.1	80	-5.1	4.6	90	**-19.7**	11.9	100
United States of America	-8.4	4.1	100	**-11.1**	6.5	100	-9.6	3.4	100	**-28.9**	12.9	100
Viet Nam	-10.1	4.1	100	-11.6	4.2	100	-8.4	5	100	**-22.7**	9	100

Figure 7. Percentage change in exploitable fish biomass



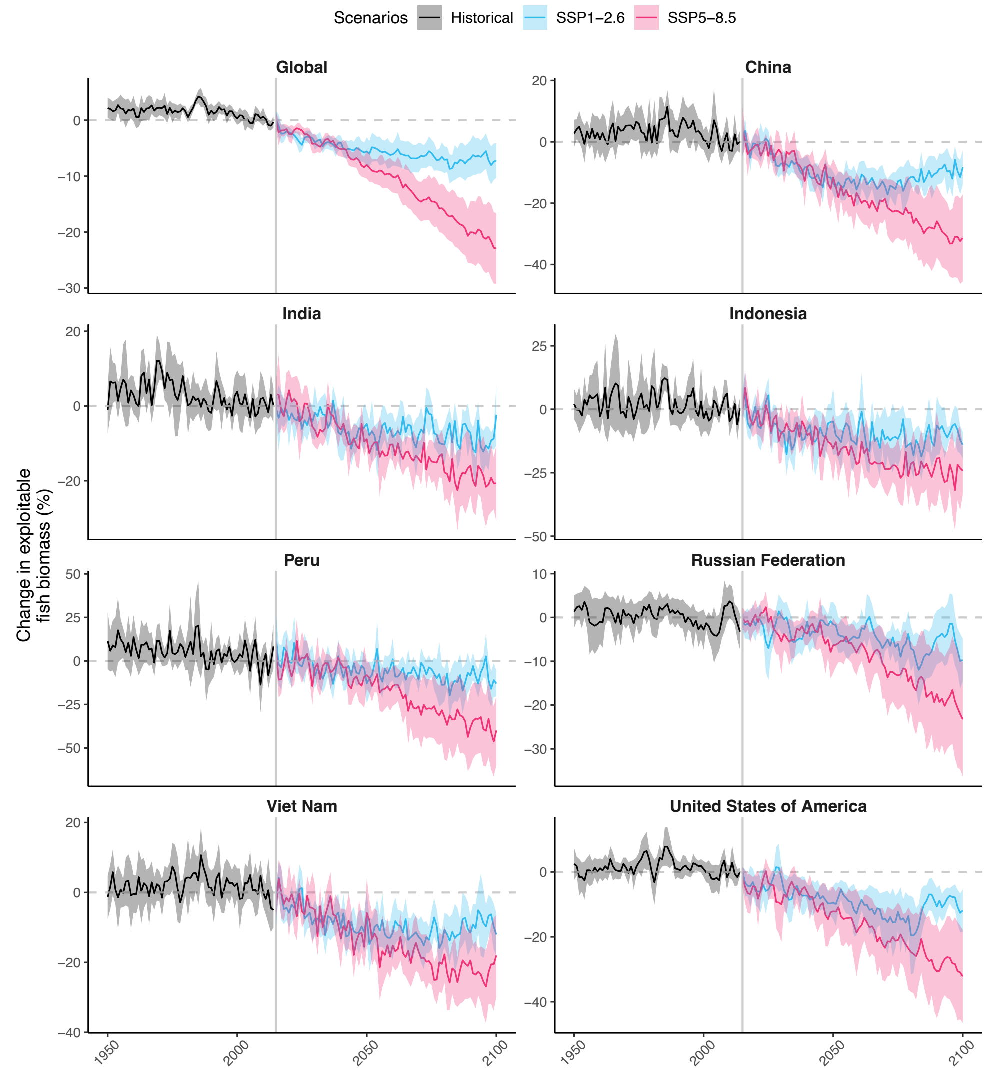
Notes: In the ocean, model ensemble projects the change (percentage) in exploitable fish biomass between 2005–2014 and 2041–2050 (a,b) or 2091–2100 (c,d) under the low emissions (a,c) and the high emissions (b,d) scenarios. Projections capture ecosystems under climate change but in an unfished state. On land, mean annual fisheries catches over the period 2012–2021 are shown by country.

Sources: Maps elaborated using: FAO. 2020. Geo Server. In: Food and Agriculture Organization of the United Nations. www.fao.org/figis/geoserver/web/; Flanders Marine Institute. 2019. Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200 NM), version 11. https://doi.org/10.14284/386; FAO. 2023. Fishery and Aquaculture Statistics. Global production by production source 1950–2021 (FishStatJ). www.fao.org/fishery/en/statistics/software/fishstatj.

By the end of the century, across both emissions scenarios, the seven countries with the largest fish catches which between them accounted for 48 percent of global marine captures in 2022 – i.e. China, India, Indonesia, Peru, the Russian Federation, Viet Nam and the United States of America (FAO, 2024) – will likely experience losses in exploitable fish biomass (Figure 8 and Table 1, 90–100 percent model agreement in direction of change across all countries). The magnitude of losses is much larger under the high emissions scenario than under the low emissions scenario by the end of the century. Losses in exploitable fish biomass are visible by mid-century and further grow by the end of the century under the high emissions scenario; part of these losses, though not all, are avoided under the low emissions scenario (53–78 percent reduction in losses across the seven countries). Countries showing the strongest decline under high emissions – and thus which have the greatest benefit associated with lower emissions by the end of the century – are China (31 percent and 9 percent loss under the high and low emissions scenarios respectively), Peru (37 percent and 8 percent loss under the high and low emission scenarios respectively) and the United States of America (29 percent and 10 percent loss under the high and low emissions scenarios respectively) (Figure 8).

These projections focus exclusively on the impacts of climate change; in other words, they assume ecosystems are not undergoing any fishing pressure or any other human drivers of change (e.g. pollution, seafloor habitat loss). In addition, marine ecosystem models are by their nature simplified, and may fail to capture nonlinearities. It is likely that once the cumulative effects of climate change and human resource use are considered, changes in exploitable fish biomass will be larger and almost definitely more complex across the many different fished species. Consideration of this mixed set of drivers – i.e. climate change and fishing – is a key next step for FishMIP, as is detailed in Part C of this technical paper. These projections also suggest that actions to reduce hazards to marine ecosystems and fisheries from climate change impacts, and better understanding of associated uncertainties, urgently need to be addressed.

Figure 8. Trends in exploitable fish biomass for the globe and the top seven major marine capture fisheries producers.



Notes: Model ensemble projected trends in exploitable fish biomass for the globe and waters under national jurisdiction of the top seven countries with the largest 2022 fish catches (FAO. 2024. The *State of World Fisheries and Aquaculture 2024*. Blue Transformation in action. Rome, FAO. https://doi.org/10.4060/cd0683en). Change is expressed as the percentage change in exploitable fish biomass relative to the average biomass over the reference period (2005–2014). Historical projections (1950–2014) are shown in black, while future projections under the low emissions (SSP1–2.6) and high emissions (SSP5–8.5) scenarios are respectively shown in blue and red. Shaded areas indicate standard deviation (across-models uncertainty). The vertical line sets the start of future projections in 2015, and the horizontal line shows no changes compared to the reference period. Note that the y-axis varies across plots to highlight trends for each country. Projections capture ecosystems under climate change in the absence of fishing, and therefore represent changes in potential biomass.

Sources: Figure elaborated using Flanders Marine Institute. 2019. Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM), version 11. https://doi.org/10.14284/386.

Chapter A.2 Projections for countries, territories, and high seas

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Climate action that is tailored to different contexts and realities is most effective, and nations planning and adopting innovative solutions to foster the resilience of agrifood systems rely on country-specific, as well as local, information and scientific knowledge (FAO, 2022a). Such knowledge is key to address climate change challenges in hotspots of human vulnerability found particularly in West, Central and East Africa, South Asia, Central and South America, Small Island Developing States, and the Arctic, where the ecological and socioeconomic risks that climate change poses are highest (FAO, 2022a; IPCC, 2022).

While FishMIP global projections of exploitable fish biomass help to highlight broad patterns of change in the ocean, country-level projections can be analysed to identify fisheries and ecosystem gains and losses to help guide the future of national economies, livelihoods and food security, and the climate actions needed to best overcome expected challenges. At the global scale, projections of exploitable fish biomass show widespread declines under both emissions scenarios by mid-century (on average 7 percent and 5 percent for high and low emissions scenarios respectively; Figure 8 and Table 1) that draw further apart by the end of the century (21 percent and 7 percent, for high and low emissions scenarios respectively). However, patterns within waters under national jurisdiction reveal considerable variation across the globe. These patterns are the focus of the next sections, which are organized by continental regions.

Among their important societal implications, the country- and territory-level patterns of change identified in the next sections raise concerns on equity outcomes. There are some developed countries and territories which might benefit from climate change in terms of increased exploitable fish biomass (some countries and territories of Europe, the east coast of the United States of America, and northern Canada). However, most developing countries and territories – which tend to have a greater dependence on and benefit from fish protein, vitamins and essential fatty acids than their richer counterparts (FAO, 2023b; 2022c; Crona *et al.*, 2023) – face the risk of being further disadvantaged as fish biomass in their national jurisdictions declines (Blanchard *et al.*, 2017; Boyce *et al.*, 2020; Bryndum-Buchholz *et al.*, 2023; Cinner *et al.*, 2022).

SECTION A.2.1 COUNTRIES AND TERRITORIES IN ASIA

Aquatic foods and the activities relating to them are of key importance for food security, economies and livelihoods in Asia (here including parts of the Middle East). Countries and territories of Asia are the world's main fisheries and aquaculture producers, together accounting for about 70 percent of global aquatic food production in 2022 (FAO, 2024). Asia has the largest fishing fleet, and about 85 percent of the world's fishers and fish-farmers were located in this region in 2022 (FAO, 2024). In some Asian nations, such as Cambodia, Bangladesh and Indonesia, fish and other aquatic foods contribute at least half of the total intake of animal protein (FAO, 2024). Any future change in exploitable fish biomass may therefore threaten the wealth and wellbeing of people living in Asia.

Most Asian countries and territories (60 percent) show significant declines in exploitable fish biomass under both scenarios by mid-century (Tables 2 and A4). Under the high emissions scenario, declines of up to 22 percent (+/- 23 percent, with 100 percent model agreement; United Arab Emirates) are projected by mid-century, and declines of up to 39 percent (-/+ 19 percent, with 100 percent model agreement; United Arab Emirates) are projected by the end of the century. Even worse trends are projected for Iraq (63 percent +/- 7.5 percent) and Kuwait (69 percent +/- 4 percent): the latter pair show high model agreement (100 percent), but results were only available for 3 and 4 out of the 10 models, respectively. Exceptions to end-of-century declines exist for only a few countries and territories in the west of the continent, where the percentage change in biomass is either increasing or not significantly different from zero (Türkiye, Israel, Lebanon, Syrian Arab Republic; inter-model variation includes 0 percent change and low model agreement of 50–80 percent on the direction of change, Table A4). These increasing (for Türkiye) and apparently stable trends are characterized by low levels of confidence (high inter-model variability and low model agreement on direction of change) (Figures 9 and 10). For Türkiye, distinct trends compared to other countries and territories are also due to divergent directions of change in exploitable fish biomass in its waters under national jurisdiction in the Black Sea (increase) and in the Mediterranean Sea (decrease) (Figure 9).

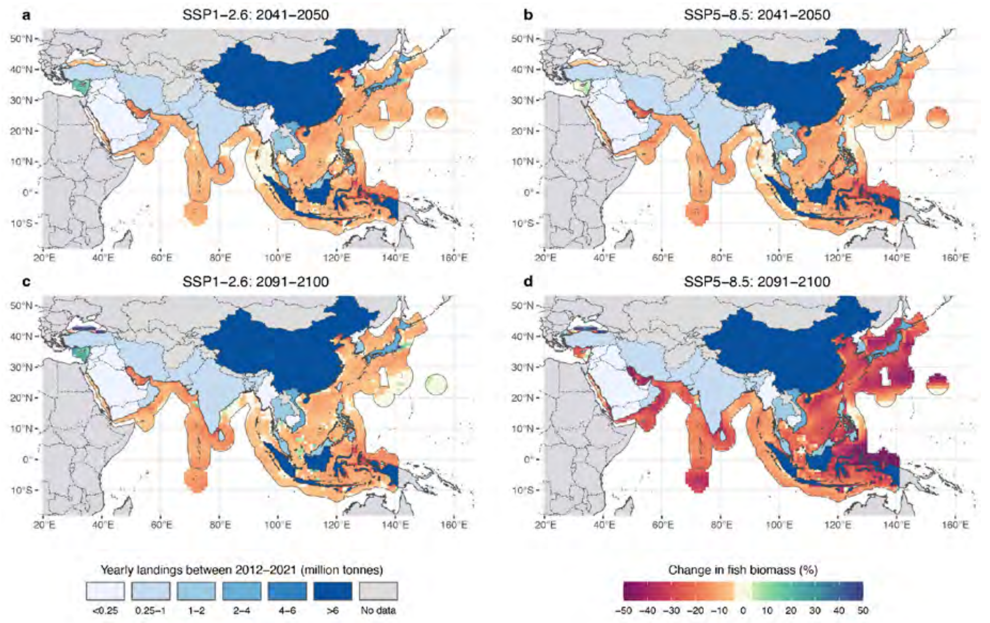
For most countries and territories, under the high emissions scenario, declines relative to the reference period (2005–2014) intensify by the end of the century compared to mid-century, while the pattern is stable if not reversed under the low emissions scenario. For example, projected end-of-century declines exceed 30 percent for China, Democratic People's Republic of Korea and Japan under high emissions but are around 10 percent under low emissions (Table 2). The outlook for this broad region is of particular concern for countries and territories that are heavily reliant on fish for protein (FAO, 2024) and where population growth (Samir and Lutz, 2017) could pose risks to per capita fish supply in the absence of adaptation strategies. These combined trends further throw into question the future ability of marine ecosystems to meet local demand for aquatic foods.

TABLE 2.

Ensemble mean percentage change in exploitable fish biomass and standard deviation (sd), as well as model agreement (agr) in the direction of change by mid-century (2041–2050) and end of century (2091–2100) compared to the reference decade (2005–2014), under the low and high emissions scenarios. Values are reported for waters under national jurisdiction of the ten most negatively impacted countries in Asia (ranked by end-of-century mean change under the high emissions scenario, extended data disaggregated for countries and territories are provided in Table A4. Values in bold indicate significant differences between the two scenarios' projections ($p < 0.05$, Wilcox statistical test) for both mid- and end-of-century estimates.

Country	Mid century SSP1-2.6			Mid century SSP5-8.5			End century SSP1-2.6			End century SSP5-8.5		
	mean	sd	agr	mean	sd	agr	mean	sd	agr	mean	sd	agr
Kuwait	-14.1	4.5	100	**-25.6**	4.9	100	-24.6	6.4	100	**-69**	4.1	100
Iraq	-8.4	4	100	**-15.4**	6.9	100	-14.7	4.4	100	**-63**	7.5	100
United Arab Emirates	-18.7	24	100	**-22.2**	23	100	-19.9	23.6	100	**-38.7**	19.2	100
Islamic Republic of Iran	-15	21.4	100	**-18.8**	19.5	100	-17.1	20.9	100	**-34.9**	14.1	100
Bahrain	-15.8	2.9	100	**-19.4**	2.3	100	-15.3	4.9	100	**-34.7**	7.4	100
Oman	-11.1	7.7	90	-13.9	6.7	100	-10.4	8.3	90	**-33**	13.7	100
Japan	-7.8	4.9	100	-9.8	5.5	90	-7	5.1	100	**-32.4**	14.7	100
Democratic People's Republic of Korea	-5.3	9.1	70	**-10.4**	10.4	80	-13.5	7.8	100	**-32.3**	26.1	90
Qatar	-14.8	25.8	90	**-16.6**	25	100	-14.8	25.2	100	**-32.2**	22.3	100
China	-11.9	3.1	100	-11.3	4.4	100	-9.1	3.8	100	**-30.9**	12.1	100

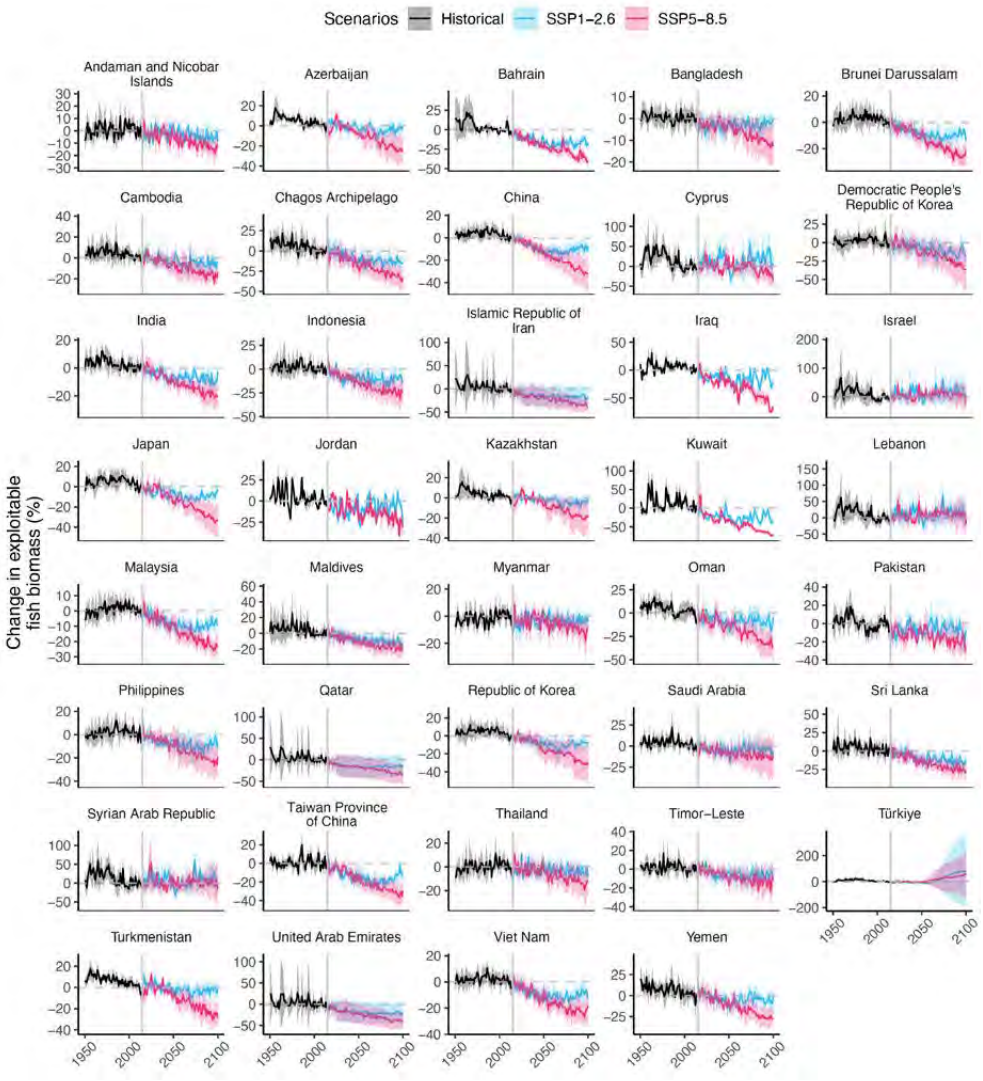
Figure 9. Percentage change in exploitable fish biomass for countries and territories in Asia



Notes: In the ocean, model ensemble projects the change (percentage) in exploitable fish biomass between 2005–2014 and 2041–2050 (a,b) or 2091–2100 (c,d) under the low emissions (a,c) and high emissions (b,d) scenarios for Asia. Projections capture ecosystems under climate change in the absence of fishing, and therefore represent changes in exploitable fish biomass. On land, mean annual fisheries catches by country over the period 2012–2021 are shown.

Sources: Map elaborated using: FAO. 2020. Geo Server. In: Food and Agriculture Organization of the United Nations. www.fao.org/figis/geoserver/web/; Flanders Marine Institute. 2019. Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM), version 11. https://doi.org/10.14284/386; FAO. 2023. Fishery and Aquaculture Statistics. Global production by production source 1950–2021 (FishStatJ). www.fao.org/fishery/en/statistics/software/fishstatj.

Figure 10. Trends in exploitable fish biomass for countries and territories in Asia



Notes: Model ensemble projections of changes in exploitable fish biomass (%) relative to the average biomass over the reference period (2005-2014) for countries and territories in Asia. Historical projections (1950-2014) are shown in black, while future projections under the low emissions (SSP1-2.6) and high emissions (SSP5-8.5) scenarios are shown in blue and red, respectively. Shaded areas indicate standard deviation (across-models uncertainty). The vertical line sets the start of future projections, and the horizontal line shows no changes compared to the reference period. Note that the y-axis varies across plots to highlight trends for each country. Projections capture ecosystems under climate change in the absence of fishing and therefore represent changes in exploitable fish biomass.

Sources: Figure elaborated using: Flanders Marine Institute. 2019. Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM), version 11. https://doi.org/10.14284/386; countries and territories official names from https://www.fao.org/nocs/en.

SECTION A.2.2 COUNTRIES AND TERRITORIES IN THE AMERICAS

The Americas (Latin America and the Caribbean, North America) are the world's second-largest fisheries and aquaculture producer after Asia, with the United States of America being the sixth country worldwide in terms of marine fisheries production in 2022 (FAO, 2024). However, most fishers and fish-farmers are concentrated in Latin America and the Caribbean, where small-scale fisheries are deeply linked to the history and culture of communities and are a valuable source of income and food (FAO, 2024; de Oliveira Leis *et al*., 2019).

Countries and territories of North and South America show wide variation in projected changes in exploitable fish biomass (Tables 3 and A4). By mid-century, geographical patterns (Figure 11) and trends (Figure 12) are similar under the low emissions and high emissions scenarios, with slightly stronger decreases under the high emissions scenario. Even by mid-century, declines of over 10 percent are projected for some Small Island Developing States in the region (e.g. Saint Lucia, Barbados, Dominica), all highly reliant on fisheries (FAO, 2024). By the end of the century, geographical patterns remain similar under the low emissions scenario, but changes are strongly exacerbated under the high emissions scenario (Figure 11). Under high emissions, end-of-century losses are greater than 20 percent across the ten most affected countries (Table 3), including Ecuador and Peru (losses of 39-37 percent +/- 19-20 percent), the latter contributes nearly six percent of global capture production of aquatic animals (FAO, 2024). While small increases or no change are projected in a small set of areas within waters of national jurisdiction (e.g. south vs. north Brazil, east vs. west vs. northern United States of America and Canada), these are associated with high levels of spatial variability which are balanced out by declines at the country level (Figure 11). Furthermore, at the country and territory level, increasing trends (and no change) are accompanied by high inter-model variability (Figure 12) and low levels of model confidence (< 60 percent model agreement on direction of change, Table A4).

The United States of America, which is today one of the world's largest producers and importers of aquatic animal products (FAO, 2024), ranks seventh in terms of projected end-of-century losses of exploitable fish biomass (29 percent +/- 13 percent) under high emissions, which could lead to a reduction in fish supply. Likewise, there are strong declines in exploitable fish biomass for other countries and territories in Central and South America, such as Guatemala, El Salvado, Uruguay, Costa Rica, Nicaragua, Panama, Colombia. This poses additional challenges for Latin America and the Caribbean, where coastal populations are projected to increase by 42 percent and 48 percent by 2050 relative to 2010 levels, under SSP1-2.6 and SSP5-8.5 respectively, before population growth slows down towards the end of the century (Merkens *et al*., 2016).

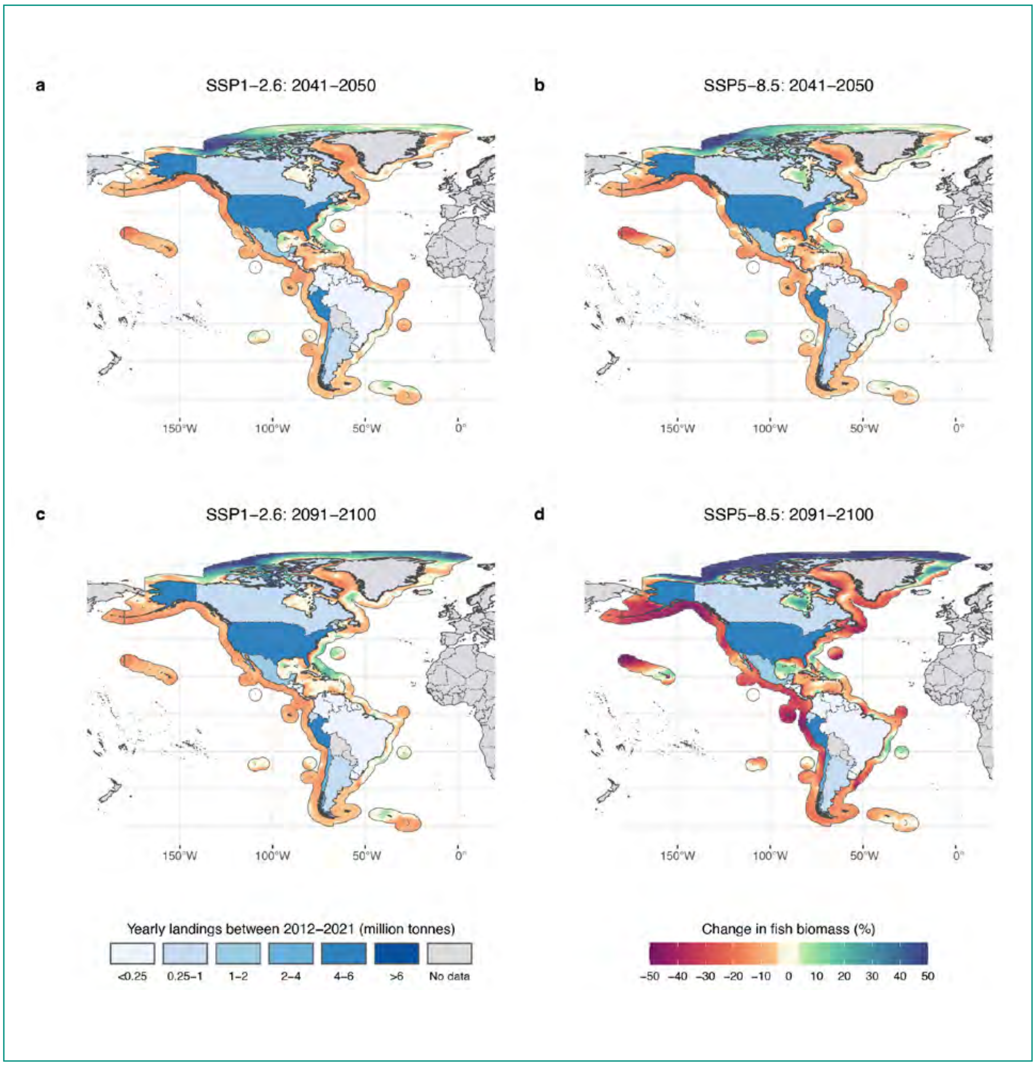
Many trends show a difference between the scenarios considered (e.g. all countries in Table 4; Figure 12). As with some countries and territories of Asia, the lower emissions scenario has a stabilizing effect on both geographical patterns and trends of change between mid- and end of the century.

TABLE 3.

Ensemble mean percentage change in exploitable fish biomass and standard deviation (sd), as well as model agreement (agr) in the direction of change by mid-century (2041–2050) and end of century (2091–2100) compared to the reference decade (2005–2014), under the low and high emissions scenarios. Values are reported for waters under national jurisdiction of the ten most negatively impacted countries in the Americas (ranked by end-of-century mean change under the high emissions scenario, extended data disaggregated for countries and territories are provided in Table A4). Values in bold indicate significant differences between the two scenarios' projections ($p < 0.05$, Wilcox statistical test) for both mid- and end-of-century estimates.

Country	Mid century SSP1-2.6			Mid century SSP5-8.5			End century SSP1-2.6			End century SSP5-8.5		
	mean	sd	agr	mean	sd	agr	mean	sd	agr	mean	sd	agr
Ecuador	-7.5	5.8	90	-9.5	6.7	90	-9.6	6.1	100	**-38.9**	18.9	100
Peru	-6	5.7	80	**-10**	7.1	90	-8.3	6.5	100	**-37.3**	20.4	100
Guatemala	-13.3	13.3	90	-15	10.8	100	-13	6.4	100	**-34.8**	18.5	100
El Salvador	-14.3	16.2	90	-14.6	12.5	100	-12.6	8.6	100	**-34.7**	22.2	100
Uruguay	-5.5	4.6	90	**-9**	7.9	90	-9	8.1	80	**-34**	18.9	100
Costa Rica	-13.2	16.4	80	-9.8	14.5	80	-13.6	12.8	100	**-31.4**	26.9	90
United States of America	-8.4	4.1	100	**-11.1**	6.5	100	-9.6	3.4	100	**-28.9**	12.9	100
Nicaragua	-11.9	16.6	70	-12.2	12.9	90	-10.8	11.5	80	**-28.6**	22.1	100
Panama	-9	13.3	70	-8.3	10.9	70	-10.6	10.1	90	**-22.3**	20.6	80
Colombia	-7.2	13.1	70	-6.7	8	80	-8.5	9.5	70	**-20**	19.6	90

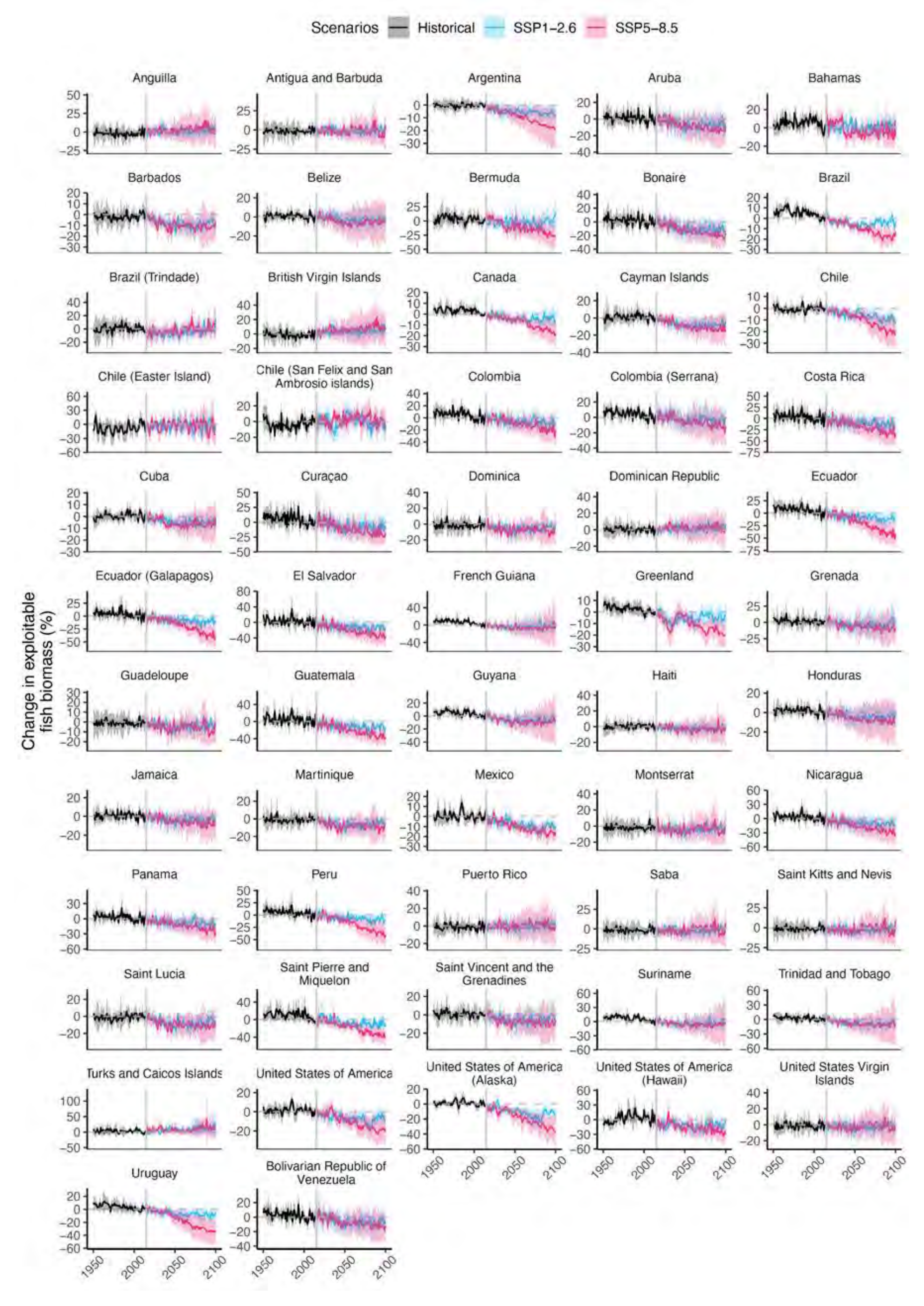
Figure 11. Percentage change in exploitable fish biomass for countries and territories in the Americas



Notes: In the ocean, model ensemble projects change (percentage) in exploitable fish biomass between 2005–2014 and 2041-2050 (a,b) or 2091–2100 (c,d) under the low emissions (a,c) and the high emissions (b,d) scenarios for the Americas. Projections capture ecosystems under climate change in the absence of fishing, and therefore represent changes in exploitable fish biomass. On land, mean annual fisheries catches by country over the period 2012–2021 are shown.

Sources: Map elaborated using: FAO. 2020. Geo Server. In: Food and Agriculture Organization of the United Nations. www.fao.org/figis/geoserver/web/; Flanders Marine Institute. 2019. Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM), version 11. https://doi.org/10.14284/386; FAO. 2023. Fishery and Aquaculture Statistics. Global production by production source 1950–2021 (FishStatJ). www.fao.org/fishery/en/statistics/software/fishstatj.

Figure 12. Trends in exploitable fish biomass for countries and territories in the Americas



Notes: Model ensemble projections of changes in exploitable fish biomass (percentage) relative to the average biomass over the reference period (2005–2014) for countries and territories in the Americas. Historical projections (1950–2014) are shown in black, while future projections under the low emissions (SSP1–2.6) and high emissions (SSP5–8.5) scenarios are shown in blue and red respectively. Shaded areas indicate standard deviation (across-models uncertainty). The vertical line sets the start of future projections, and the horizontal line shows no changes compared to the reference period. Note that the y-axis varies across plots to highlight trends for each country. Projections capture ecosystems under climate change in the absence of fishing, and therefore represent changes in exploitable fish biomass.

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SECTION A.2.3 COUNTRIES AND TERRITORIES IN EUROPE

Europe is the world's third largest fisheries and aquaculture producer after Asia and the Americas but has the lowest share of employment in the primary sector of fisheries and aquaculture across continents (FAO, 2024). In 2022, the European Union's (EU) marine fishing etc. marine fishing fleet and total catch (about 3.4 million tonnes) saw a reduction compared to recent years, but the value of landings increased (https://ec.europa.eu/eurostat/statistics-explained). Spain, Denmark and France were the top producers and Spain, Italy, France and Greece had the highest shares of employment in the EU fisheries industry, which provided jobs to about 160 000 people (https://ec.europa.eu/eurostat/web/products-eurostat-news/-/edn-20201016-3).

In Europe, by mid-century, model ensemble projections reveal a mixture of responses under both high emissions and low emissions scenarios (Tables 4 and A4). While some increases are projected for very high latitudes (e.g. Russian Federation) and in the Eastern Mediterranean Sea (e.g. Greece, Italy and Malta), particularly under the high emissions scenario (Figure 13), aggregated trends reveal declines for most countries and territories under both scenarios (Figure 14). Under the low emissions scenario, even by mid-century, declines are most marked for countries including Portugal, Ireland, and Spain (see Table 4); while increases are most evident in the Russian Federation and Albania (Figures 13 and 14). By 2100, under high emissions, declines worsen and exceed 21 percent for the top ten most affected countries in European waters, with the largest decline projected for Portugal (exceeding 50 percent +/- 9 percent), in part due to very high losses projected for the Azores (Table A4, Figure 13). There is scope for losses to be reduced by more than 100 percent for many regions (e.g. Albania, Greece, Malta, Italy) under the low emissions scenario compared to the high emissions scenario (Figures 13 and 14, Table A4).

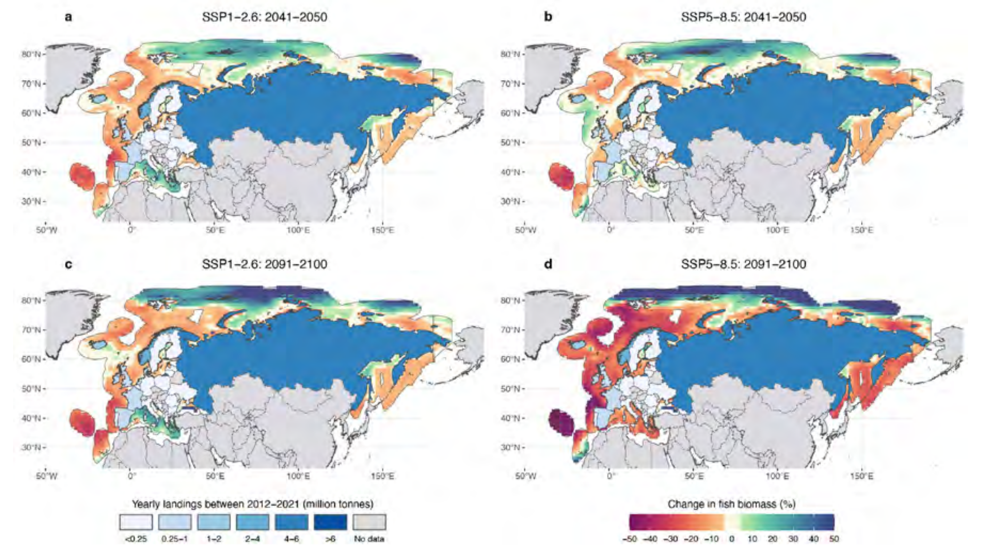
There is a widening of inter-model variability under the high emissions scenario by the end of the century for some countries and territories (e.g. Latvia, Finland, Poland, the Russian Federation, Sweden; Figure 14). This is accompanied by low model agreement in terms of direction of change in some Nordic regions, where some increases in exploitable fish biomass are projected (Table A4). This indicates that these projected increases are accompanied by very low model confidence in the direction of change (a pattern also seen for a number of tropical locations in other regions).

TABLE 4.

Ensemble mean percentage change in exploitable fish biomass and standard deviation (sd), as well as model agreement (agr) in the direction of change by mid-century (2041–2050) and end of century (2091–2100) compared to the reference decade (2005–2014), under the low and high emissions scenarios. Values are reported for waters under national jurisdiction of the ten most negatively impacted countries in Europe (ranked by end-of-century mean change under the high emissions scenario, extended data disaggregated for countries and territories are provided in Table A4. Values in bold indicate significant differences between the two scenarios' projections ($p < 0.05$, Wilcox statistical test) for both mid- and end-of-century estimates.

Country	Mid century SSP1-2.6			Mid century SSP5-8.5			End century SSP1-2.6			End century SSP5-8.5		
	mean	sd	agr	mean	sd	agr	mean	sd	agr	mean	sd	agr
Portugal	-21.3	10.2	100	-23	6.8	100	-27.7	4.9	100	**-50.2**	8.9	100
Albania	10.3	6.6	100	**4.7**	9	67	11.3	6.8	100	**-33.7**	8.8	100
Ireland	-12.1	7.1	100	**3.4**	11.4	60	-9.1	5.1	100	**-33.6**	6.1	100
Iceland	-5.3	5.5	90	**-1.2**	10.8	60	-5	8.5	70	**-25.1**	9.2	100
Croatia	-7	9.3	70	-7.3	9.8	80	-13.6	18.2	60	**-24.6**	15.5	100
France	-5.6	3.2	100	**-7.8**	4.3	100	-6.2	4.2	100	**-23.1**	11.2	100
Spain	-11.7	11.5	100	**0.3**	5	60	-12.4	7.4	100	**-22.7**	14.8	90
Kingdom of the Netherlands	-3.9	3.7	90	**-7.4**	4.5	100	-7.1	6.3	80	**-22**	12	100
Greece	12.8	6.9	90	**-0.2**	6.7	60	10.7	11.4	80	**-21.8**	11.3	100
Malta	3.8	15.6	50	0.5	17.5	60	8.9	31.4	50	**-21.8**	12.5	90
Norway	-5.9	3.4	100	-3.9	6.7	80	-7.9	7.4	90	**-21.3**	7.6	100

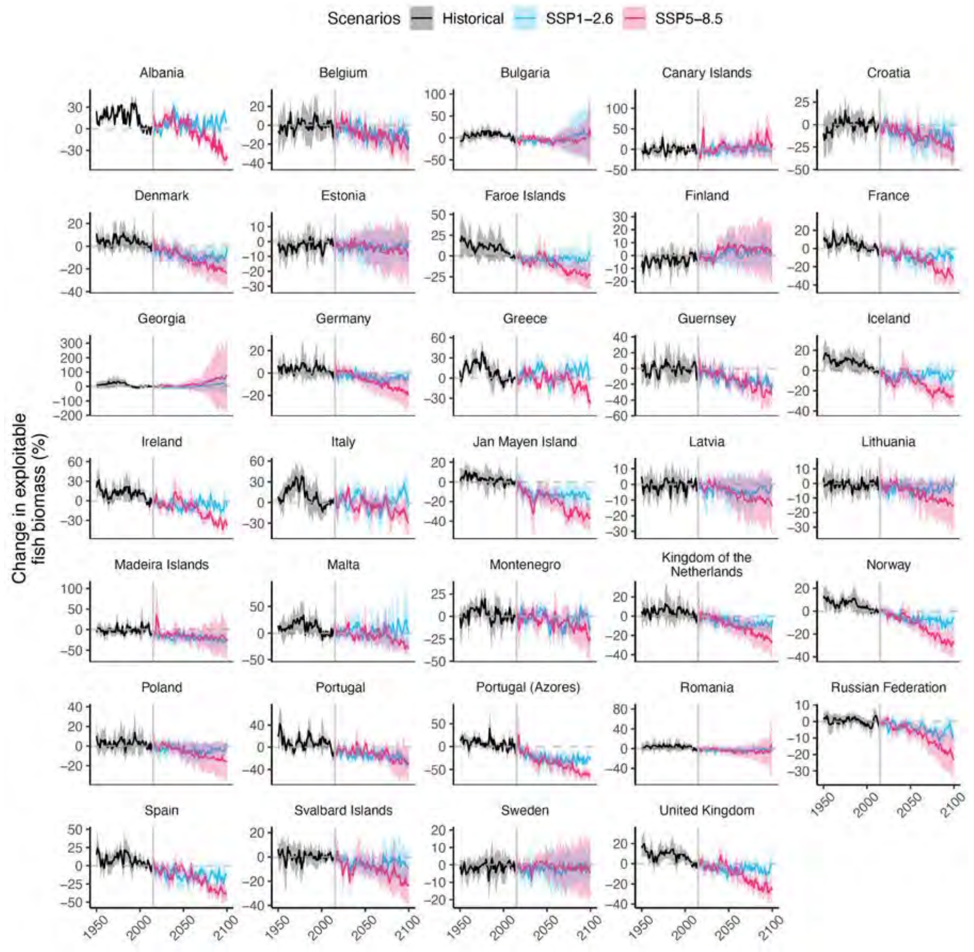
Figure 13. Percentage change in exploitable fish biomass for countries and territories in Europe



Notes: In the ocean, model ensemble projects change (percentage) in exploitable fish biomass between 2005–2014 and 2041-2050 (a,b) or 2091–2100 (c,d) under the low emissions (a,c) and the high emissions (b,d) scenarios for Europe. Projections capture ecosystems under climate change in the absence of fishing, and therefore represent changes in exploitable fish biomass. On land, mean annual fisheries catches by country over the period 2012–2021 are shown.

Sources: Map elaborated using: FAO. 2020. Geo Server. In: Food and Agriculture Organization of the United Nations. www.fao.org/figis/geoserver/web/; Flanders Marine Institute. 2019. Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM), version 11. https://doi.org/10.14284/386; FAO. 2023. Fishery and Aquaculture Statistics. Global production by production source 1950–2021 (FishStatJ). www.fao.org/fishery/en/statistics/software/fishstatj.

Figure 14. Trends in exploitable fish biomass for countries and territories in Europe



Notes: Model ensemble projections of changes in exploitable fish biomass (percentage) relative to the average biomass over the reference period (2005–2014) for countries and territories in Europe. Historical projections (1950–2014) are shown in black, while future projections under the low emissions (SSP1–2.6) and high emissions (SSP5–8.5) scenarios are shown in blue and red respectively. Shaded areas indicate standard deviation (across-models uncertainty). The vertical line sets the start of future projections, and the horizontal line shows no changes compared to the reference period. Note that the y-axis varies across plots to highlight trends for each country. Projections capture ecosystems under climate change in the absence of fishing and therefore represent changes in exploitable fish biomass.

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SECTION A.2.4 COUNTRIES AND TERRITORIES OF AFRICA

In Africa, the fisheries and aquaculture sectors support coastal communities and provide important sources of nutrition, including protein and micronutrients (Crona *et al*., 2023; Golden *et al*., 2021; Hicks *et al*., 2019). More than 40 percent of the world's non-motorized vessels are located in Africa, where employment in the fishing industry has seen steady growth (FAO, 2024); and in countries and territories such as Sierra Leone, Ghana and Mozambique, aquatic foods contribute half or more of the total animal protein intake (FAO, 2022c).

In Africa, most countries and territories are expected to experience declines in exploitable fish biomass, except those in the northern part of the continent and around some southeastern and southwestern islands (e.g. Morocco, Réunion and Mauritius). These declines, coupled with Africa having the highest human population growth rate among major areas and the high reliance of coastal communities on domestic markets, translate into potential risks for food security (Figure 15; Samir and Lutz, 2017). Under the high emissions scenario, losses exceed 29 percent for the top ten most impacted countries by the end of the century (Table 5), indicating growing ecosystem changes and an increasing widening of differences across countries and territories if actions to mitigate and adapt to climate change are not taken. Lowering emissions reduces changes in, and stabilizes, ecosystems and their productivity as well as across-country differences (Figure 16; Tables 5 and A4). For many countries and territories around the continent, losses are reduced under the low emissions scenario than under the high emissions scenario. For example, by the end of the century, losses shift from 39 percent (+/- 14 percent) under the high emissions scenario to 5 percent (+/- 15 percent) under the low emissions scenarios for Angola; from 38 percent (+/- 13 percent) to 9 percent (+/- 8 percent) for Senegal; and from 41 percent (+/- 7 percent) to 12 percent (+/- 5 percent) for Sudan (Table 5, Figure 16). All of these countries already face substantial food insecurity risks.

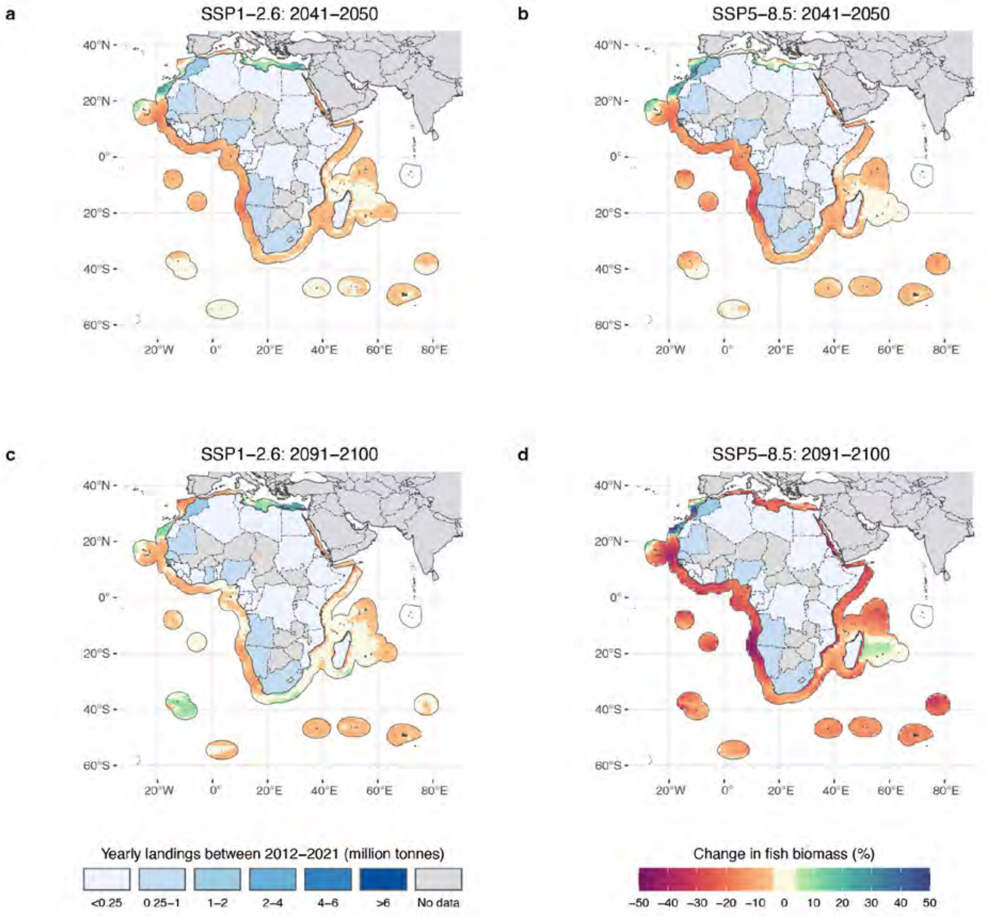
Trends are significantly different across the two scenarios for most countries and territories (e.g. all countries listed in Table 5). However, for countries and territories in the Indian Ocean (e.g. Comoros, Mauritius, Réunion, Madagascar, Mozambique), across-model uncertainties increase by the end of the century, particularly under the high emissions scenario (Figure 16).

TABLE 5.

Ensemble mean percentage change in exploitable fish biomass and standard deviation (sd), as well as model agreement (agr) in the direction of change by mid-century (2041–2050) and end of century (2091–2100) compared to the reference decade (2005–2014), under the low and high emissions scenarios. Values are reported for waters under national jurisdiction of the ten most negatively impacted countries in Africa (ranked by end-of-century mean change under the high emissions scenario, extended data disaggregated for countries and territories are provided in Table A4. Values in bold indicate significant differences between the two scenarios' projections ($p < 0.05$, Wilcox statistical test) for both mid- and end-of-century estimates.

Country	Mid century SSP1-2.6			Mid century SSP5-8.5			End century SSP1-2.6			End century SSP5-8.5		
	mean	sd	agr	mean	sd	agr	mean	sd	agr	mean	sd	agr
Sudan	-15.1	6.2	100	**-17.8**	6.4	100	-12.2	5.4	100	**-41**	6.8	100
Angola	-13.8	8.5	100	**-24.6**	10	100	-4.7	15.4	70	**-38.6**	14.3	100
Senegal	-16	7.4	100	-20.4	6.7	100	-8.7	7.8	90	**-38.5**	12.8	100
Gambia	-14.2	7	100	-19.2	6.2	100	-7.2	6.3	100	**-36.3**	11.8	100
Namibia	-12.2	12.4	100	**-18.8**	14.6	100	-9.2	15.4	60	**-32.7**	20.4	100
Côte d'Ivoire	-10.7	4.3	100	**-15.9**	7.8	100	-5.7	2.5	100	**-30.1**	10.6	100
Liberia	-13.2	5.3	100	**-17**	5	100	-9.7	4	100	**-30.1**	11.2	100
Democratic Republic of the Congo	-9.4	4.9	100	**-15.4**	7.8	100	-4.6	6.3	60	**-29.9**	9.2	100
Guinea-Bissau	-11.1	7	90	-14.7	7.7	90	-5.5	7.8	90	**-29.3**	12.8	100
Mauritania	-10.7	6.2	90	-13.2	5.6	100	-8.7	6.4	90	**-28.7**	12.6	100
Equatorial Guinea	-9.8	5.6	100	**-17.4**	9	100	-4.3	7.6	60	**-28.6**	9.8	100

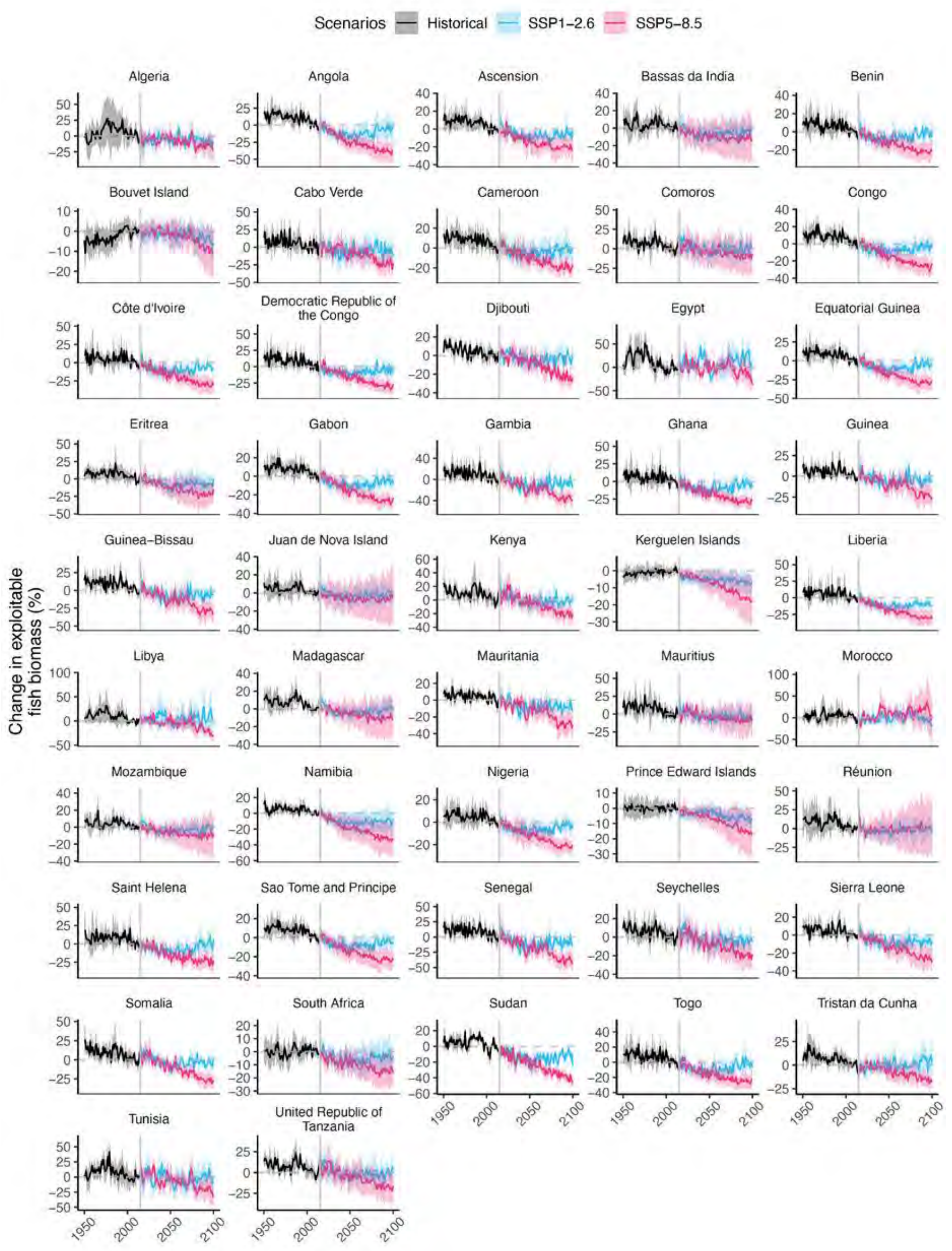
Figure 15. Percentage change in exploitable fish biomass for countries and territories in Africa



Notes: In the ocean, model ensemble projects mean change (percentage) in exploitable fish biomass between 2005–2014 and 2041-2050 (a,b) or 2091–2100 (c,d) under the low emissions (a,c) and the high emissions (b,d) scenarios for Africa. Projections capture ecosystems under climate change in the absence of fishing, and therefore represent changes in exploitable fish biomass. On land, mean annual fisheries catches by country over the period 2012–2021 are shown.

Sources: Map elaborated using: FAO. 2020. Geo Server. In: Food and Agriculture Organization of the United Nations. www.fao.org/figis/geoserver/web/; Flanders Marine Institute. 2019. Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM), version 11. https://doi.org/10.14284/386; FAO .2023. Fishery and Aquaculture Statistics. Global production by production source 1950–2021 (FishStatJ). www.fao.org/fishery/en/statistics/software/fishstatj.

Figure 16. Trends in exploitable fish biomass for countries and territories in Africa



Notes: Model ensemble projections of changes in exploitable fish biomass (percentage) relative to the average biomass over the reference period (2005–2014) for countries and territories in Africa. Historical projections (1950–2014) are shown in black, while future projections under the low emissions (SSP1–2.6) and high emissions (SSP5–8.5) scenarios are shown in blue and red respectively. Shaded areas indicate standard deviation (across-models uncertainty). The vertical line sets the start of future projections, and the horizontal line shows no changes compared to the reference period. Note that the y-axis varies across plots to highlight trends for each country. Projections capture ecosystems under climate change in the absence of fishing, and therefore represent changes in exploitable fish biomass.

Sources: Figure elaborated using: Flanders Marine Institute. 2019. Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM), version 11. https://doi.org/10.14284/386; countries and territories official names from https://www.fao.org/nocs/en.

SECTION A.2.5 COUNTRIES AND TERRITORIES IN OCEANIA

Some of the most pronounced losses in exploitable fish biomass globally are evident for Oceania (Tables 6 and A4), a region that faces numerous other climate hazards and risks (e.g. sea-level rise, loss of freshwater resources, intensified extreme events, climate-related health hazards; Kumar *et al*., 2020; Martyr-Koller *et al*., 2021; UNDP, 2024). By mid-century, the most negatively affected countries and territories (> 15 percent decline) under the high emissions scenario include Palau, Papua New Guinea, Solomon Islands, the Federated States of Micronesia, and Samoa (Figures 17 and 18). By the end of the century under the high emissions scenario, average declines reach high levels of concern. Extreme losses (> 40 percent) are projected for the following Small Island Developing States: Papua New Guinea, Tuvalu, Nauru, Solomon Islands, Palau, and the Federated States of Micronesia (Table 6). Declines of 26 percent are projected for New Zealand and Tonga with 100 percent model agreement on direction of change (Table 6, Table A4). Concerning end-of-century declines (29-33 percent) are projected for Kiribati, Marshall Islands, and Samoa but with lower levels of model confidence (80-90 percent model agreement on direction of change). The projections are incredibly worrying for a region that is heavily reliant on fish production.

Significant differences between the two scenario trajectories occurs by the end of the century for all countries and territories (Figure 18, Table A4). The only exceptions are the Northern Marianas Islands (United States of America), the Pitcairn Islands (the United Kingdom of Great Britain and Northern Ireland), Guam (United States of America), Johnston Atoll and Wake Island (United States of America), all of which have high inter-model variability and low model agreement on the direction of change (Table A4). Overall – and for most countries and territories in this region – losses are much reduced under the low emissions scenario. The greatest reduction in losses is for Kiribati, with > 90 percent of losses eliminated under the low emissions scenario. Similarly, for Australia and New Zealand 78 percent and 71 percent of losses associated with high emissions are averted under a lower emissions scenario. For Pacific Islands States, 68–90 percent of the extreme end-of-century losses projected under high emissions are averted for Palau, Tuvalu, Nauru, the Federated States of Micronesia, and Solomon Islands.

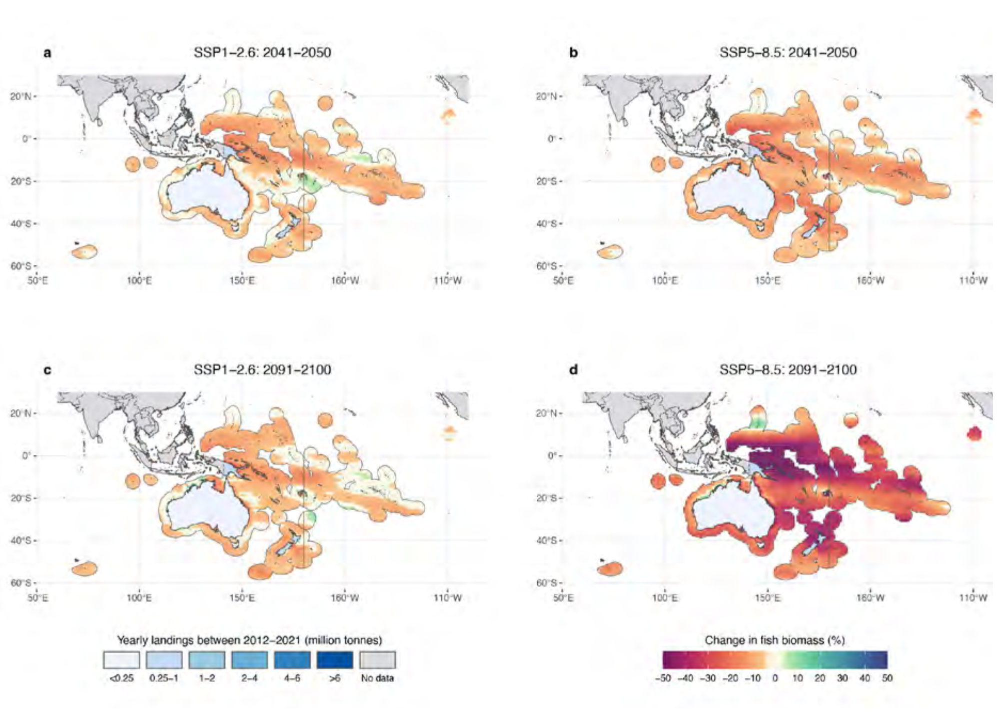
By the end of the century, declines are accompanied by uncertainty for some of the Pacific Island Countries and Territories (e.g. Vanuatu, Samoa, Fiji), especially under the high emissions scenario. For Samoa, Vanuatu, and Fiji while there is high inter-model variability on the magnitude of change, there is reasonable confidence associated with the direction of change (at least 80 percent agreement model, Table A4).

TABLE 6.

Ensemble mean percentage change in exploitable fish biomass and standard deviation (sd), as well as model agreement (agr) in the direction of change by mid-century (2041–2050) and end of century (2091–2100) compared to the reference decade (2005–2014), under the low and high emissions scenarios. Values are reported for waters under national jurisdiction of the ten most negatively impacted countries in Oceania (ranked by end-of-century mean change under the high emissions scenario, extended data disaggregated for countries and territories are provided in Table A4). Values in bold indicate significant differences between the two scenarios' projections ($p < 0.05$, Wilcox statistical test) for both mid- and end-of-century estimates.

Country	Mid century SSP1-2.6			Mid century SSP5-8.5			End century SSP1-2.6			End century SSP5-8.5		
	mean	sd	agr	mean	sd	agr	mean	sd	agr	mean	sd	agr
Papua New Guinea	-12.5	8.8	100	**-16.5**	9.4	100	-11.3	13.3	90	**-50.5**	19.3	100
Tuvalu	-15	6.7	100	-15	6.5	100	-12.1	6.3	100	**-46.5**	21.3	100
Nauru	-8	3.2	100	-6.9	4.5	100	-4.7	6.6	70	**-46.4**	18	100
Solomon Islands	-13.2	6.3	100	-16.3	12.9	100	-12.9	11.5	100	**-43.5**	25.1	100
Palau	-12.8	16.4	80	**-20.1**	12.1	100	-13.1	12.9	90	**-41.6**	23.7	100
Federated States of Micronesia	-10.9	10.9	90	**-15.6**	7.5	100	-9.3	9	90	**-40.7**	23.9	100
Kiribati	-5	2.4	100	-4.8	5.8	80	-2.6	4.1	80	**-33.2**	17.7	90
Marshall Islands	-6.1	11	50	**-10.5**	7.7	90	-8	6	100	**-29.7**	24.8	80
Samoa	-10.9	8.2	100	**-15.5**	12.4	100	-9.6	8.2	100	**-28.7**	26.6	90
New Zealand	-5.8	2.9	90	**-9.7**	2.5	100	-7.5	4.2	90	**-26.5**	7.3	100

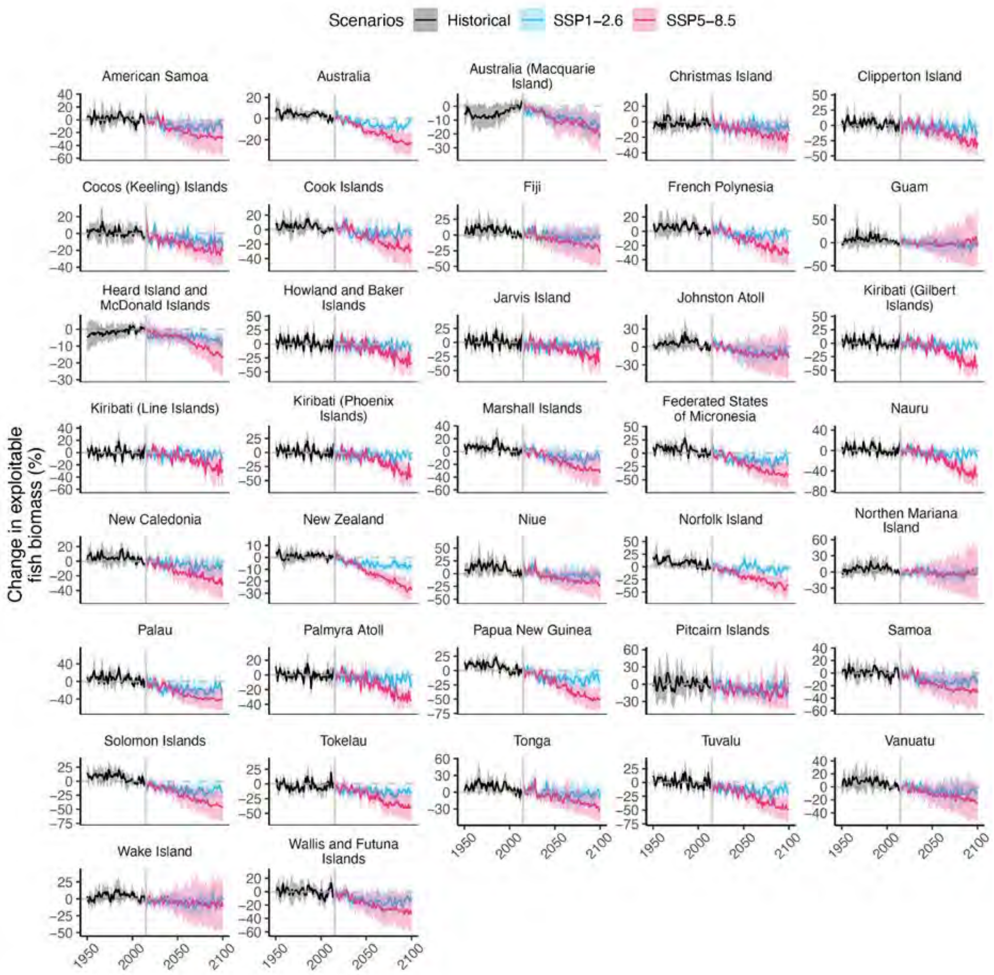
Figure 17. Percentage change in exploitable fish biomass for countries and territories in Oceania



Notes: In the ocean, model ensemble projects mean change (percentage) in exploitable fish biomass between 2005–2014 and 2041-2050 (a,b) or 2091–2100 (c,d) under the low emissions (a,c) and the high emissions (b,d) scenarios for Oceania. Projections capture ecosystems under climate change in the absence of fishing, and therefore represent changes in exploitable fish biomass. On land, mean annual fisheries catches by country over the period 2012–2021 are shown.

Sources: Map elaborated using: FAO. 2020. Geo Server. In: Food and Agriculture Organization of the United Nations. www.fao.org/figis/geoserver/web/; Flanders Marine Institute. 2019. Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM), version 11. https://doi.org/10.14284/386; FAO. 2023. Fishery and Aquaculture Statistics. Global production by production source 1950–2021 (FishStatJ). www.fao.org/fishery/en/statistics/software/fishstatj.

Figure 18. Trends in exploitable fish biomass for countries and territories in Oceania



Notes: Model ensemble projections of changes in exploitable fish biomass (percentage) relative to the average biomass over the reference period (2005–2014) for countries and territories in Oceania. Historical projections (1950–2014) are shown in black, while future projections under the low emissions (SSP1–2.6) and high emissions (SSP5–8.5) scenarios are shown in blue and red respectively. Shaded areas indicate standard deviation (across-models uncertainty). The vertical line sets the start of future projections, and the horizontal line shows no changes compared to the reference period. Note that the y-axis varies across plots to highlight trends for each country. Projections capture ecosystems under climate change in the absence of fishing, and therefore represent changes in exploitable fish biomass.

Sources: Figure elaborated using: Flanders Marine Institute. 2019. Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM), version 11. https://doi.org/10.14284/386; countries and territories official names from https://www.fao.org/nocs/en.

SECTION A.2.6 HIGH SEAS AGGREGATED BY FAO MAJOR FISHING AREAS

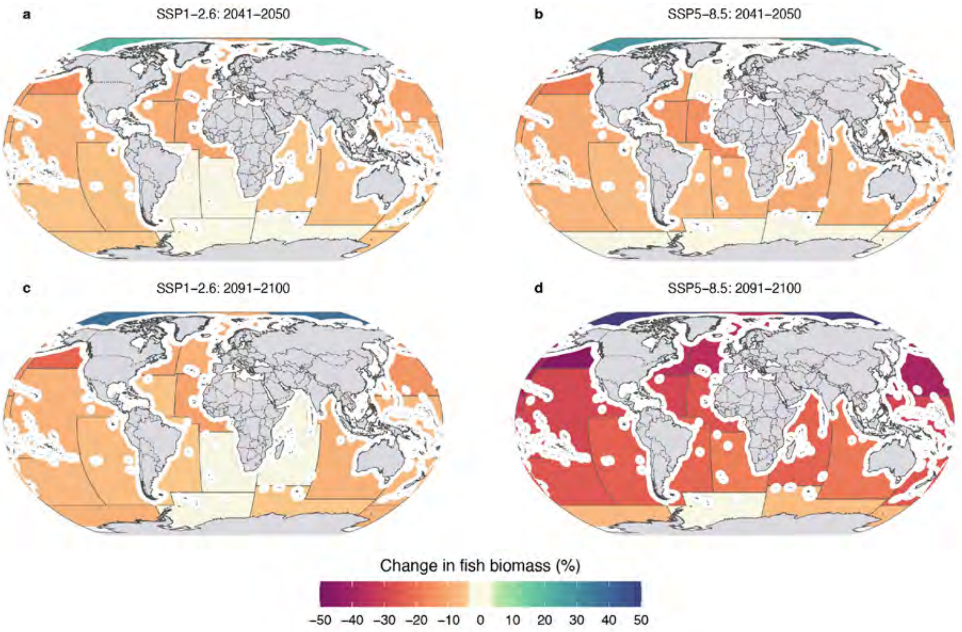
Much of the global ocean lies outside of countries' jurisdiction, which creates many challenges and opportunities for effective management of resources and climate adaptation. This section reports on the FishMIP climate projections for areas beyond national jurisdiction, by FAO Major Fishing Areas in each major ocean: the Pacific, Indian, Atlantic, Arctic and Southern Ocean (Figures 19 and 20; Table 7).

TABLE 7.

Ensemble mean percentage change in exploitable fish biomass and standard deviation (sd), as well as model agreement (agr) in the direction of change by mid-century (2041–2050) and end of century (2091–2100) compared to the reference decade (2005–2014), under the low and high emissions scenarios for FAO Major Fishing Areas. Note that the Mediterranean and Black Sea FAO Major Fishing Area is not included as its waters lie within countries' and territories' national jurisdictions. Values in bold indicate significant difference in the two scenarios' projections by mid- and end- of century ($p < 0.05$, Wilcoxon rank-sum statistical test).

FAO Major Fishing Area	Mid century SSP1-2.6			Mid century SSP5-8.5			End century SSP1-2.6			End century SSP5-8.5		
	mean	sd	agr	mean	sd	agr	mean	sd	agr	mean	sd	agr
Pacific, Northeast	-14.9	6.2	100	-18.1	10.4	100	-22.9	9.6	100	**-46.1**	24.4	100
Pacific, Northwest	-10.7	6.2	100	-14.8	**7**	100	-13.6	6.3	100	**-39.5**	14.9	100
Pacific, Western Central	-7	8.4	90	-8.9	6.5	90	-7.2	6.9	90	**-29.5**	22.9	100
Pacific, Eastern Central	-7.6	3.2	100	-9.4	**3.2**	100	-8.2	4.7	100	**-28.9**	7.2	100
Pacific, Southwest	-5.4	2.2	100	-7.7	**2.6**	100	-7	5.5	90	**-25.4**	7.8	100
Pacific, Southeast	-5.8	2.8	100	-6.8	3.3	100	-6.5	3.6	100	**-24**	8	100
Pacific, Antarctic	-4.2	4.3	80	-3.1	3.7	90	-8.4	8.3	90	-7	10.4	80
Atlantic, Northeast	-8.9	6	100	-0.9	**8.6**	50	-8.6	9.4	80	**-35.1**	7.5	100
Atlantic, Northwest	-10.7	4.1	100	-11.7	2.9	100	-10.3	4.8	100	**-35.1**	11.3	100
Atlantic, Western Central	-8.8	8.4	80	-12.9	**10.2**	90	-5.3	4.9	90	**-29.2**	10	100
Atlantic, Eastern Central	-10.7	5.3	100	-14.2	**4.8**	100	-11.1	7.6	100	**-25.9**	13	100
Atlantic, Southwest	-3.4	2.4	80	-6.8	**3.1**	100	-4.4	4.2	90	**-22.6**	9.4	100
Atlantic, Southeast	-3.2	2.2	90	-7.6	**2.8**	100	-2.7	3.4	80	**-18.1**	9.5	100
Atlantic, Antarctic	-0.5	3.3	80	0.1	3.1	50	-3.1	6.8	70	-1.4	10.4	60
Indian Ocean, Western	-4.5	4.2	100	-9.7	**4.5**	100	-3.3	6.8	70	**-23.2**	8.4	100
Indian Ocean, Eastern	-5.4	3.7	100	-7.5	**3.5**	100	-8.2	5.1	100	**-19.2**	9.9	100
Indian Ocean, Antarctic	-2.1	3.9	80	-2.2	4	80	-4.3	4.4	90	**-6.2**	8.4	80
Arctic Sea	20.7	44.2	70	27.6	52.5	90	37.8	67	70	97.8	181	90

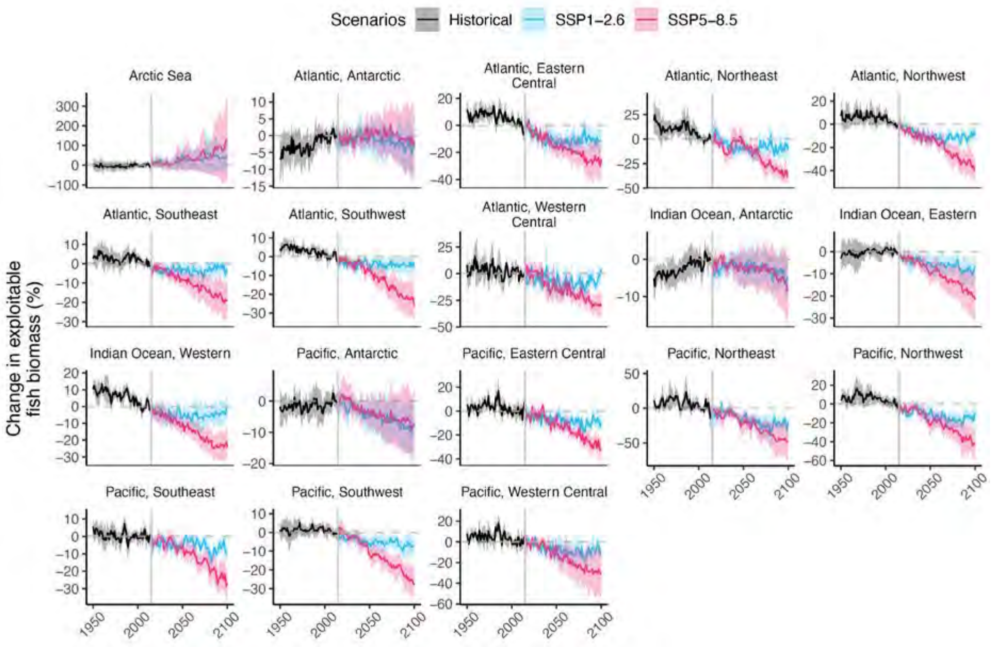
Figure 19. Percentage change in exploitable fish biomass for waters outside national jurisdiction, aggregated into FAO Major Fishing Areas



Notes: Model ensemble projects change (percentage) in exploitable fish biomass between 2005–2014 and 2041-2050 (a,b) or 2091–2100 (c,d) under the low emissions (a,c) and the high emissions (b,d) scenarios for High Seas FAO Major Fishing Areas. Projections capture ecosystems under climate change in the absence of fishing, and therefore represent changes in exploitable fish biomass.

Sources: Maps elaborated using: FAO. 2020. Geo Server. In: Food and Agriculture Organization of the United Nations. www.fao.org/figis/geoserver/web/; Flanders Marine Institute. 2019. Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM), version 11. https://doi.org/10.14284/386; FAO Statistical Areas for Fishery Purposes. www.fao.org/fishery/area/search/en.

Figure 20. Trends in exploitable fish biomass for high seas aggregated by FAO Major Fishing Areas



Notes: Model ensemble projections of changes in exploitable fish biomass (percentage) relative to the average biomass over the reference period (2005–2014) for High Seas FAO Major Fishing Areas. Historical projections (1950–2014) are shown in black, while future projections under the low emissions (SSP1–2.6) and high emissions (SSP5–8.5) scenarios are shown in blue and red respectively. Shaded areas indicate standard deviation (across-models uncertainty). The vertical line sets the start of future projections, and the horizontal line shows no changes compared to the reference period. Note that the y-axis varies across plots to highlight trends for each country. Projections capture ecosystems under climate change in the absence of fishing, and therefore represent changes in exploitable fish biomass.

Sources: Figure elaborated using: FAO Statistical Areas for Fishery Purposes. In: FAO Fisheries and Aquaculture Department. www.fao.org/fishery/area/search/en.

The *Pacific Ocean* registers the highest fisheries landings among all ocean areas, amounting to some 46 million tonnes in 2022. The Northwest Pacific and the Western Central Pacific are the first and second most productive FAO Major Fishing Areas, with respective total landings of about 18.6 million tonnes and 14 million tonnes in 2019 (FAO, 2024).

In the Pacific High Seas FAO regions, high losses are evident by mid-century under both scenarios in the Northwest Pacific (11-15 percent, +/- 6-7 percent), where fisheries catches are the highest. Losses are much worse by the end of the century (40 percent, +/- 15 percent) under the high emissions scenario (Figure 20). These losses are reduced by over 50 percent under the low emissions scenario. Similar patterns are projected by the end of the century in the Northeast, Central and South Pacific.

In recent years, the *Atlantic Ocean* has seen an overall decreasing trend in marine fisheries catches, with the total catch amounting to 20 million tonnes in 2022. Despite this, the Northeast Atlantic is the fourth most productive FAO Major Fishing Area (FAO, 2024).

By mid-century, the North Atlantic Ocean faces a mixture of responses in terms of exploitable fish biomass, with more spatially variable outcomes under the high emissions scenario than under the low emissions scenario (Figures 19 and 20). The most extreme losses are projected for the Northwest Atlantic, with mean ensemble losses of 12 percent (+/- 3 percent) by mid-century and 35 percent (+/- 11 percent) by the end of the century under the high emissions scenario. Under the low emissions scenario, 71 percent of these end-of-century losses are averted. A similar situation is shown across all Atlantic FAO regions under the high emissions scenario (albeit with high levels of inter-model variability), particularly for the Southeast, Eastern Central, and Northeast Atlantic, which currently sees the bulk of fisheries catches.

The *Indian Ocean* has shown a steady increase in catches in recent years, and registered 11.8 million tonnes in 2022 (FAO, 2024). In the Western and Eastern Indian Ocean, where much of the world's tuna fishing takes place (FAO, 2024), losses range from 5–10 percent by mid-century under both scenarios and 19–23 percent (+/- 8–10 percent) by the end of the century under the high emissions scenario (Figure 20). For the Western Indian Ocean, low emissions result in reduced losses between mid- and end-of century and a slightly upward trend in exploitable fish biomass. This region also shows a clear separation by around 2070 between the low and high emissions scenarios, highlighting the potential long-term benefits of climate action to reduce impacts (Figure 20). For the Eastern Indian Ocean, declines continue even under the low emissions scenario, but with losses reduced by around 60 percent compared to the high emissions scenario (albeit associated with large across-model uncertainty) by the end of the century.

Highly uncertain projections exist across the Southern Ocean, which shows mixed responses (Figure 19 and 20). The Atlantic Antarctic FAO Major Fishing Area shows little or no decline in exploitable fish biomass under both low and high emissions scenarios by the end of the century (1–3 percent reduction, +/- 7–10 percent inter-model variability, 60–70 percent model agreement on direction of change), while the Antarctic Indian and Pacific Major Fishing Areas show declines of 2–4 percent (+/- 4 percent) by mid-century and 4–8 percent (+/- 4–10 percent) by the end of the century that are not significantly different across scenarios for the Pacific Antarctic Major Fishing Area (Figure 20, Table 7). However, higher-resolution maps show the most marked decreases in lower latitudes and increases near the continent (e.g. Figure 7); this may be due to highly variable estimates of sea-ice reduction in Earth system models, which in turn affects primary production, salinity, oxygen, temperature etc., but for which high levels of uncertainty remain a challenge (Murphy *et al.*, 2024). Greater variation occurs in the high emissions scenario by the end of the century (Figure 20), when both extreme losses and gains could pose risks to marine resources, due to the potential restructuring of ecosystems and/or a race to exploit resources.

In the *Arctic* High Sea FAO region, uncertainty is at its highest level across the global projections (Figure 20). This is the only region for which the ensemble mean shows a spatially uniform increase. But it is critical to highlight the extremely high variation across models, driven by underlying differences in inputs from the two Earth system models used to force FishMIP models (Tittensor *et al.*, 2021; Mason *et al.*, 2024). The combination of extreme increases with such high uncertainties makes this a region of very high risk, where ecosystem structure and function may change drastically, leading to changes in ecosystem services.

Chapter A.3 Uncertainties and limitations of projections

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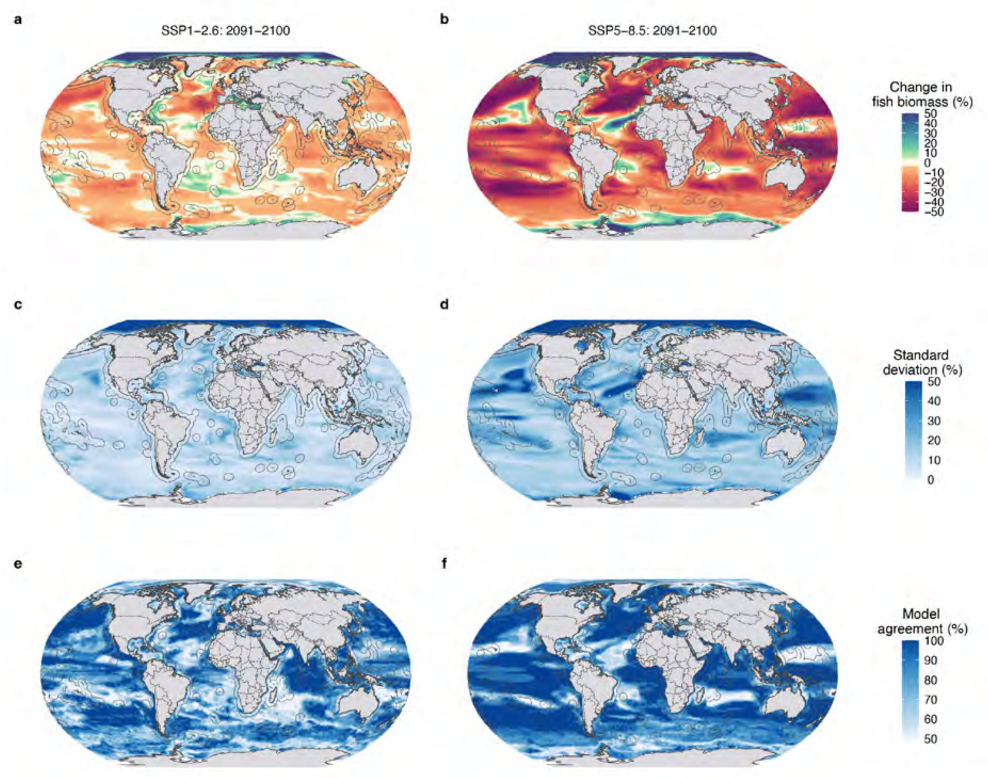
SECTION A.3.1 HIGH UNCERTAINTIES INDICATE KNOWLEDGE GAPS FOR KEY REGIONS

Inter-model variability of FishMIP ensemble projections in exploitable fish biomass reveals regions where confidence in projections is low or high (Figure 21). For example, inter-model variability is particularly high in the Arctic, where exploitable fish biomass is expected to steeply increase under both the low and high emissions scenarios by 2100 (Figure 21). However, models do not agree on the magnitude of the increase in this area, with some projecting a much higher increase than others (see also Bryndum-Buchholz *et al*., 2019). By 2100, other regions of high inter-model variability under the high emissions scenario include the Central Pacific and Indian Ocean, and waters along the coast of Northwest Africa and Antarctica. Generally, these regions also show increases in exploitable fish biomass over time, but the degree of inter-model variability exceeds the magnitude of change.

The level of model agreement (Figure 21) provides an additional measure of the level of confidence in the projected change. When the projected mean percentage changes are closer to zero, there is low agreement across models in the direction of change (< 80 percent) (which explains, for example, the pattern in the Southern Pacific, Atlantic, and Indian Ocean regions under the low emissions scenario). Notably, most of the regions where steep projected declines occur – which include much of the global ocean under the high emissions scenario – also show high agreement (> 90 percent) across models on the direction of change. In contrast, where steep increases occur (e.g. Arctic, Southern Ocean) there is low model agreement on the direction of change.

These results have far-reaching implications. First, they highlight the need to improve understanding of the sources of uncertainty in model projections overall and for key regions. This is to improve both the reliability of climate impact estimates and their utility for decision-making, and consequently to increase their uptake for policy advice. Second, they call for policies and operational fisheries management approaches that are flexible and that can be updated in the future as more information and certainty is gained. In line with recommendations from the IPCC's *Sixth Assessment Report* (IPCC, 2022), these results are directing the focus of the next steps in modelling efforts. To understand and reduce the uncertainty of FishMIP projections and tackle its main sources, steps are being taken towards improving understanding of the temperature dependence of biological processes (Section A.3.2), and of the advances in climate model inputs that are needed to reduce uncertainty (Section A.3.3). In addition, progress is being made on integrating fishing in all marine ecosystem models and standardizing fishing activity inputs, improving the representation of coastal processes (e.g. finer spatial resolution and riverine inputs), and developing inter-model accuracy assessment frameworks (Chapter C.1).

Figure 21. Inter-model variability and agreement of FishMIP projections



Notes: a) and b): In the ocean, model ensemble projects change (percentage) in exploitable fish biomass between 2005–2014 and the 2090s under the low and high emissions scenarios respectively. Projections capture ecosystems under climate change but in an unfished state. c) and d): Inter-model variability calculated as the standard deviation relative to the mean of the percentage change in exploitable fish biomass (a,b) under the low emissions and the high emissions scenarios respectively. e) and f): Model agreement as a measure of the agreement in the direction (increase or decrease) of projected changes (a,b) across FishMIP models under the low emissions and the high emissions scenarios respectively. One hundred percent represents all models indicating the same direction of change, and 50 percent represents half the models indicating one direction of change and half indicating the opposite.

Sources: Maps elaborated using: FAO. 2020. Geo Server. In: Food and Agriculture Organization of the United Nations. www.fao.org/figis/geoserver/web/; Flanders Marine Institute. 2019. Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM), version 11. https://doi.org/10.14284/386; FAO. 2023. Fishery and Aquaculture Statistics. Global production by production source 1950-2021 (FishStatJ). www.fao.org/fishery/en/statistics/software/fishstatj.

SECTION A.3.2 IDENTIFYING MAIN SOURCES OF UNCERTAINTY

Over the past three decades a wide range of ecosystem models of different structural forms have been developed, and each model takes a unique perspective in how it represents marine ecosystems. These perspectives extend from models that use a species distributional basis to project future ecosystems, through to models based primarily on trophic or size interactions (Tittensor *et al.*, 2018). The suite of models that make up the FishMIP ensemble has helped build knowledge of potential impacts on global marine ecosystems resulting from a wide diversity of processes and interactions. However, it also results in high uncertainty of ensemble projections.

Key contributors to such uncertainty include differences in how marine ecosystem models:

- **i)** Represent living organisms, their interactions, and movement.
- **ii)** Represent the effect of temperature (and other physical factors) on marine organisms (Heneghan *et al*., 2021; Lindmark *et al*., 2022).
- **iii)** Integrate forcing variables from Earth system models, such as plankton or primary production.

Model uncertainty (pertinent for points i–iii above), also called structural uncertainty, is associated with the choices made during model development and implementation (Payne *et al*., 2016). Coll *et al.* (2020) have shown that different representations of key ecological processes within marine ecosystem models cause significant inter-model variability, which can be of the same order of magnitude as the model uncertainty derived from the use of different Earth system models to force the marine models, or different climate change scenarios (Lotze *et al*., 2019; Tittensor *et al*., 2021). Structural uncertainty reflects the fragmented understanding of ecological and other dynamics characterizing marine ecosystems and their functioning. At present, by calculating the mean projection across an ensemble of models, structural uncertainty is addressed by implicitly assuming that each modelling perspective is equally valid. This ensemble approach represents the current collective knowledge and is therefore more powerful than any single approach considered separately. Until the ecological and modelling community clarifies unknown aspects of marine systems, this inclusive approach is the most sensible when informing climate policy.

Other important sources of uncertainty include:

- **iv)** Adoption of different approaches to integrating fishing in global and regional models, as well as a lack of standardized fishing inputs in the models. This is critical given that fishing is a major driver of marine ecosystem change and a key factor determining the resilience of marine ecosystems to climate change impacts.
- **v)** Inadequate representation of coastal processes, where the majority of fishing takes place. This is due to, for example, the use of climate inputs with a resolution that is too coarse to capture local-scale physical processes and coastal dynamics, including omitting riverine and sediment exchanges at land-ocean interfaces (and other processes on smaller scales) which regulate primary production patterns and benthic detritus fluxes. In addition, benthic habitats and their changes (e.g. reefs) are seldom considered in global and regional FishMIP models. However, exceptions exist where dynamical change in these habitats is represented explicitly, or implicitly via parameterized relationships between specific model groups.
- **vi)** Historical projections based on climate model inputs that do not capture actual historical events, such as specific El Niño years, that may have affected fisheries catches.
- **vii)** Limited knowledge or absence of relevant empirical monitoring data, such as fishery-independent biomass estimates. There is also high uncertainty associated with spatialized fisheries catches for some regions of the world. Both types of data are critical to validate ecosystem models.
- **viii)** The absence of a standardized model evaluation framework, which can be used to test the ability of models to reproduce past ecosystems and their changes, to understand the sources of disagreement across models and to guide model improvement.

SECTION A.3.3 TACKLING KEY UNCERTAINTIES: ECOLOGICAL RESPONSES TO WARMING

Temperature drives biological rates and influences ecological interactions that govern the productivity, abundance, and spatial range of species. It is also among the variables most accurately projected by Earth system models. Yet uncertainty exists with respect to the functional dependence of biological processes on temperature and their representation in ecosystem models.

Theoretical arguments and experimental evidence as synthesized and encapsulated by the Metabolic Theory of Ecology (Brown *et al.*, 2004) suggest that over a limited range of temperatures metabolic and other biological rates for similarly sized species scale positively and exponentially with temperature. However, additional evidence indicates that the steepness of the temperature dependence may differ between biological rates at the individual level (Englund *et al.*, 2011; Rall *et al.*, 2012), scale negatively with body mass within each species (Killen, Atkinson and Glazier, 2010), and vary further according to phylogeny and species-specific traits beyond body mass. Across larger temperature spans, biological rates typically exhibit dome-shaped temperature-dependence (Pörtner and Peck, 2010), with rates depressed at upper and lower temperature extremes and peaking at an optimum. Variation in curve shape is also significant across species and only partly understood.

In practice, food web and ecosystem models used to project climate impacts have typically adopted only one type of temperature-dependence assumption (Woodworth-Jefcoats, Blanchard and Drazen, 2019), but in doing so have neglected a potentially large source of structural uncertainty. Food web projections are sensitive to the temperature-dependence assumption (Lindmark *et al.*, 2022; Reum *et al.*, 2024), and accounting for variation in assumptions can impart uncertainty into projections that, in some instances, may exceed that associated with climate scenarios (Reum *et al.*, 2020). In the absence of a strong rationale for adopting specific assumptions, ensemble methods (either single-model or multi-model) should capture a range of plausible temperature assumptions when feasible to better represent this uncertainty in projections.

Structural uncertainty within and among models results from a lack of information on which biological rates are temperature-dependent and the nature of such dependencies, or their interaction with other drivers such as salinity, oxygen levels or ocean pH. There are some common approaches to modelling temperature-dependent metabolic (Brown *et al.*, 2004) and aerobic (Thornton and Lessem, 1978; Woodworth-Jefcoats, Blanchard and Drazen, 2019) rates, as well as a number of other approaches (Moisan, Moisan and Abbott, 2002). Alternatively, cumulative thermal experience (e.g. degree days) may be a better determinant of developmental rates or growth through distinct life history stages than the current temperature.

Ultimately, a combination of empirical studies and innovative modelling approaches are needed to tackle uncertainties around warming. Empirical studies could help reduce uncertainty surrounding model parameters (e.g. thermal tolerances, temperature-dependent rates). Innovative modelling approaches should aim to better represent the uncertainty in thermal responses, particularly in instances where laboratory experiments do not exist (which is the case for most species).

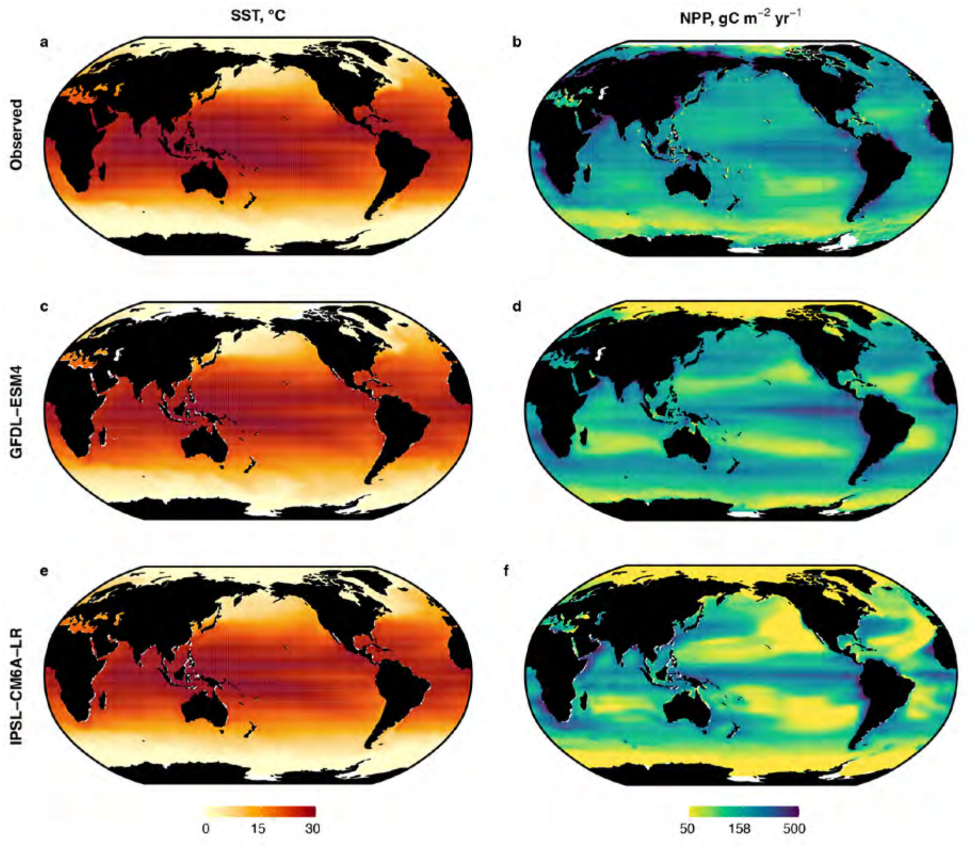
At the most basic level, thermal habitat preferences and ranges are still not well understood for many marine species, nor is the adaptive capacity of species in the face of a rapidly changing environment. Improved understanding is needed to enhance the realism of projections. Thermally driven range shifts are already occurring (Pinsky *et al.*, 2013) and are likely to have major consequences for fishery-dependent communities. Furthermore, the emergence of novel thermal habitats is expected under high emissions scenarios. This poses critical concerns for regions facing compounded climate hazards, such as Small Island Developing States, where people rely heavily on fish for food and income (Bell *et al.*, 2021; FAO, 2024).

SECTION A.3.4 FURTHER CLIMATE MODEL IMPROVEMENTS NEEDED TO REDUCE UNCERTAINTY

Of all the physical and biogeochemical variables that are used by FishMIP models, among the most uncertain are those related to lower trophic-level biomass and production, e.g. chlorophyll (Fu *et al*., 2022; Laufkötter *et al*., 2015; Séférian *et al*., 2020), net primary production (Figure 22; Bopp *et al*., 2013; Kwiatkowski *et al*., 2020), export production (Laufkötter *et al*., 2015; Séférian *et al*., 2020), and zooplankton biomass (Petrik *et al*., 2022). For example, 40–50 percent of the total uncertainty in projections of net primary production from 2015–2100 arises from Earth system model uncertainty across global and regional scales (Frölicher *et al*., 2016). As for marine ecosystem models, Earth system models' structural uncertainty arises from the different ways in which they represent the physical and biogeochemical components of the ocean and in how those representations are parameterized.

As primary production is the base of the marine food chain, this uncertainty alone can account for much of the total uncertainty in projections with marine ecosystem models which use nutrient or lower trophic-level inputs from Earth system models. While both the Earth system models used in FishMIP produce similar patterns for observed global sea surface temperature, for net primary production there are much greater differences between the models, as is also the case when the models are compared with observations (Figure 22). As detailed in previous sections, there is also large uncertainty in marine ecosystem model responses to changes in lower trophic-level inputs when forced with a single Earth system model (Heneghan *et al*., 2021), which could be compounded when forced by multiple models.

Figure 22. Selected Earth-system model variables compared with observations



Notes: Comparison of observations with modelled variables from two contrasting CMIP6 Earth system models from the Geophysical Fluid Dynamics Laboratory (GFDL) and Institute Pierre-Simon Laplace (IPSL) that are used by FishMIP to drive global and regional marine ecosystem model ensembles. Observed a) sea-surface temperature and b) net primary production (NPP); sea-surface temperature from c) GFDL-ESM4 and e) IPSL-CM6A-LR Earth system models; and net primary production from d) GFDL-ESM4 and f) IPSL-CM6A-LR. For NPP, the colour bar gradients are plotted in log-space and the numerical values are provided in original units.

Sources: Maps elaborated using: Observed primary production from the Ocean Productivity lab, averaged across four satellite products from 2003–2019. Observed sea-surface temperature from NOAA Optimum Interpolation SST V2 (Reynolds, R.W., Rayner, N.A., Smith, T.M., Stokes, D.C. and Wang, W. 2002. An improved in situ and satellite SST analysis for climate. Journal of Climate, 15(13), 1609–1625.), averaged from 1961–2020. ESM primary production and sea-surface temperatures were averaged from 1970–2000. While unfortunately the time-averaged observational products were not available for the exact same time period as the ESM variables, the maps are visually comparable as large-scale geographic patterns. They also reveal large differences in geographical patterns for NPP between the two ESMs, which are directly comparable.

For progress to be made in the refinement of biogeochemical components of Earth system models, and to give marine ecosystem modellers a better understanding of Earth system model strengths and limitations, there needs to be: i) clear understanding of the differences between biogeochemical sub-models, ii) required climate variables provided from a wider range of Earth system models, and iii) further assessment of these variables. Fostering stronger links between FishMIP and the Ocean Model Intercomparison Project could help to meet these needs. This would allow marine ecosystem modellers to determine whether the ecosystem processes they want to study are reflected in the structure of the biogeochemical sub-models, as promoted by Kearney *et al.* (2021). The second need could be satisfied with the provision of a number of additional Earth system model variables, such as grazing rates, and mortality rates by plankton groups (e.g. phytoplankton and zooplankton by size classes). Providing these outputs would help meet the third need, which could include comparison of modelled rates to those of laboratory and field studies, thereby contributing additional metrics for model refinement beyond the standard satellite estimates of chlorophyll. Furthermore, model development needs to advance beyond validation of single variables (e.g. fishery catches, see Section C.1.1) to consider how well models capture emergent properties, such as the size and trophic structure of marine communities, and relationships between physical and ecological variables (e.g. Petrik *et al.*, 2022) as suggested by Steenbeek *et al.* (2021).

Many of the improvements that Earth system models could make to reduce uncertainty in marine ecosystem models have been mentioned in previous sections. For example, coastal shelf circulation, coastal upwelling, basin-shelf exchanges, and eddies are relevant for upper trophic levels (Drenkard *et al.*, 2021; Stock *et al.*, 2011), necessitating higher-resolution models. Similarly, riverine and sediment exchanges at coastal land-ocean interfaces should also be represented (Liu *et al.*, 2019, 2021). Additionally, Petrik *et al.* (2022) advocate for resolving more zooplankton processes since they are ecologically important in the roles they play in carbon export, nutrient cycling, and as prey for higher trophic levels.

Critical to Earth system model and marine ecosystem model improvements are continued and expanded observations of the marine environment and their synthesis.

PART B. USING FISHMIP PROJECTIONS TO HELP SUPPORT REGIONAL-SCALE POLICY AND MANAGEMENT

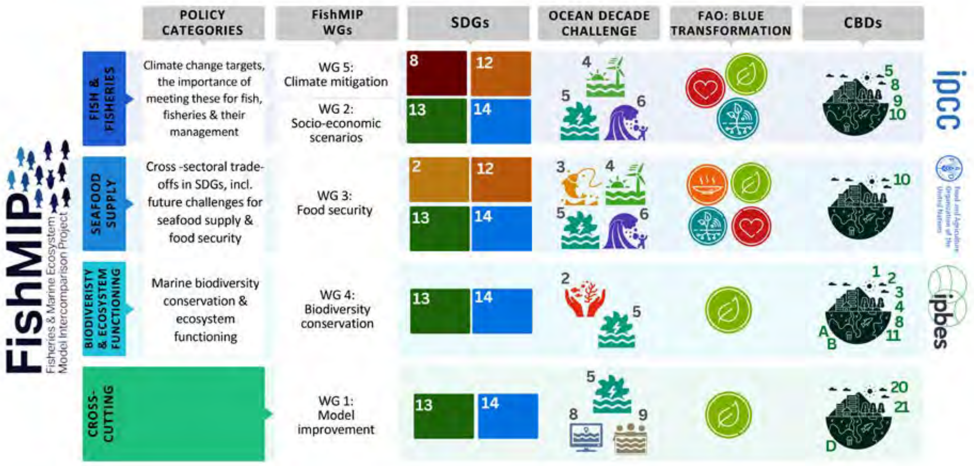
Chapter B.1. Using FishMIP projections to help support regional-scale policy and management

Authors: Andrea Bryndum-Buchholz, Camilla Novaglio, Joshua Cinner, Marta Coll, Elizabeth A. Fulton, Lauren Koerner, Catherine Longo, Heike K. Lotze, Julia Mason, Juliano Palacios-Abrantes, David J. Welch, Julia L. Blanchard

FishMIP's global ensemble model projections provide useful information for regions of the world where limited information exists on the potential impacts of climate change on ecosystems and fisheries, and/or to complement more detailed regional-scale model projections of future climate change impacts where they are available (Pethybridge *et al*., 2020). Provided the caveats, uncertainties and limitations are understood for specific applications, and in the absence of more detailed information, these outputs can be used to help support adaptation plans that require knowledge of potential climate change impacts on fisheries and the marine ecosystems underpinning them; develop alternative pathways for the sustainable use of the oceans; and ensure fisheries management is resilient to the impacts of climate change. For example, FishMIP outputs can be combined with additional sectoral information as either an index of exposure in climate vulnerability assessment frameworks (Li *et al*., 2019) or as a hazard in climate risk assessments (Papathoma-Köhle, Promper and Glade, 2016). This information can be used by decision-makers to support long-term strategic planning and adaptation within and across sectors; to support adaptation strategies such as flexible fisheries management measures and livelihood diversification; and to access distribution risks associated with trade (Boyce *et al*., 2020; Cinner *et al*., 2022; Fulton *et al*., 2017; Nash *et al*., 2022). In addition, because FishMIP global projections are also spatial, they can help support research on the climate resilience of spatial marine management measures such as marine protected areas (Bryndum-Buchholz *et al*., 2023; see Section B.1.1 on North Atlantic), and help identify regions where flexible fisheries management and policy changes are likely to be needed to ensure future stability and food security in different regions of the world (Bryndum-Buchholz *et al*., 2023; Pethybridge *et al*., 2020).

Novaglio *et al.* (2024) provide a review of policy applications and future directions for aligning FishMIP with what is needed to inform policy, including the SDGs and FAO's Strategic Framework and Blue Transformation (Figure 23). This section summarizes several illustrative case studies of how recent global FishMIP model ensemble projections have been and are being used alongside additional information to assess climate impacts, vulnerability, and risks to i) spatial marine management and conservation plans, ii) sustainable fisheries management, and iii) coastal food security and livelihoods.

Figure 23. FishMIP working groups and policy goals



Notes: Overview of FishMIP working groups (WGs) and their respective policy categories, and of how they address the Sustainable Development Goals (SDGs) https://www.un.org/sustainabledevelopment/sustainable-development-goals/, the Ocean Decade Challenges https://oceandecade.org/challenges/, the four betters (better production, nutrition, environment, life) of the FAO Strategic Framework 2022-31 https://www.fao.org/strategic-framework/en, supported by the Blue Transformation https://doi.org/10.4060/cc0459en, and the targets (numbers) and goals (letters) of the Convention on Biological Diversity (CBDs) https://www.cbd.int/gbf/targets.

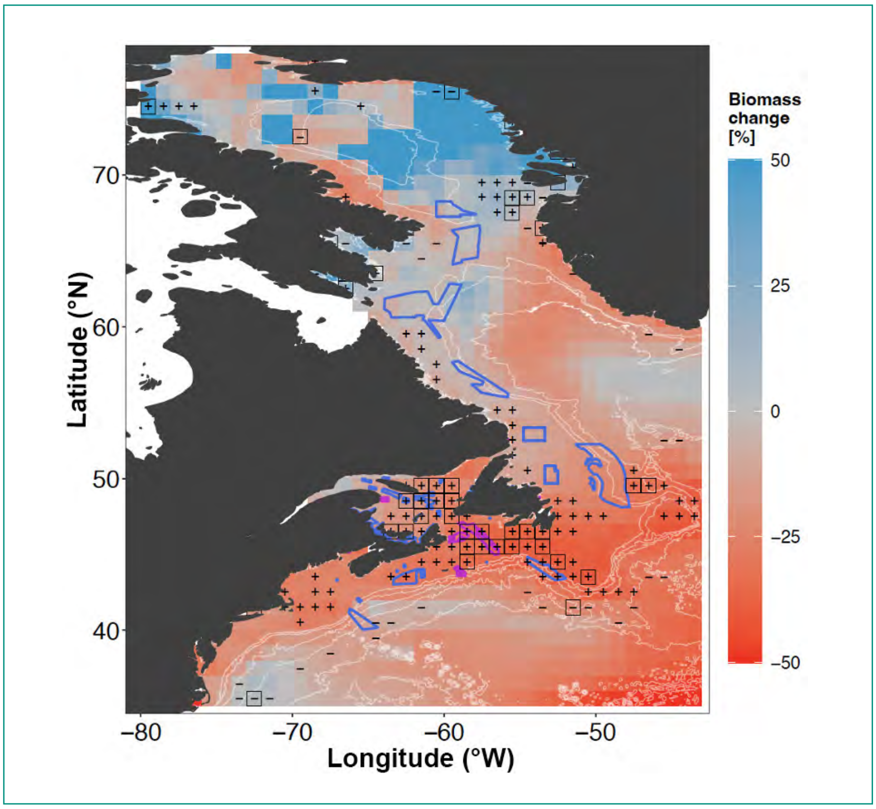
Source: Novaglio, C., Bryndum-Buchholz, A., Tittensor, D.P., Eddy, T.D., Lotze, H.K., Harrison, C.S., Heneghan, R.F. *et al*., 2024. *The Past and Future of the Fisheries and Marine Ecosystem Model Intercomparison Project*. ESS Open Archive. 16 January 2024. 10.22541/essoar.170542252.20348236/v1.

SECTION B.1.1. INFORMING CLIMATE-SMART FISHERIES MANAGEMENT AND MARINE CONSERVATION IN THE NORTH ATLANTIC

On a regional scale, FishMIP projections have informed fisheries management and marine conservation planning in the Northwest Atlantic Ocean. Focussing on the Northwest Atlantic Fisheries Organization (NAFO) Convention Area, Bryndum-Buchholz *et al.* (2020) summarized projected trends of total marine animal biomass under differing climate change scenarios. For projections under the high emissions scenario, end-of-century total marine animal biomass decreased by 5–40 percent relative to 1990–1999 in NAFO statistical divisions with historically high fisheries landings, while in Arctic and sub-Arctic statistical divisions with lower historical landings it increased by between 20–70 percent. These FishMIP projections highlight potential risks to marine ecosystems and the challenges to fisheries management in a rapidly changing ocean.

Using FishMIP projections, Bryndum-Buchholz *et al.* (2023) assessed future trajectories of climate change impacts on total marine animal biomass and six key environmental drivers to evaluate the consequences for marine protected areas (MPAs) and other effective area-based conservation measures (OECMs) in Atlantic Canada. Results were used to identify climate change hotspots (i.e. areas where environmental drivers are projected to change most) and refugia (i.e areas where environmental drivers are projected to remain close to their current state) (Figure 24). Under the high emissions scenario, no existing MPA or OECM in Atlantic Canada overlapped with any identified climate refugia, while 75 percent of MPAs and 39 percent of OECMs were within climate change hotspots (Figure 24). These projections provide important long-term context for adaptation and climate-smart spatial marine conservation planning in Canada and the Northwest Atlantic region. Additional applications of model-based projected results are being used to analyse the impact of conservation measures in the Mediterranean Sea, and to determine where to place MPAs to achieve the goal of protecting 30 percent of the region by 2030 (Gomei *et al*., 2021).

Figure 24. Cumulative environmental impacts indicating climate hotspots and refugia across the Northwest Atlantic ecosystem



Notes: Cumulative environmental impacts indicating climate hotspots and refugia across the Northwest Atlantic ecosystem under the high emissions scenario and current marine conservation areas in Canada's Exclusive Economic Zone. Biomass changes (percentage) indicate relative ensemble mean changes of total marine animal biomass in 2090–2099 relative to the historical reference period 1990–1999. '+' signs indicate identified climate change hotspots, and '-' signs indicate identified climate refugia. Square outlines around +/- indicate high biomass and environmental change. Blue shapes: OECMs. Pink shapes: MPAs. Shapefiles for marine conservation areas provided by the Canadian Protected and Conserved Area Database (https://bit.ly/2UHjdNd).

Source: Bryndum-Buchholz, A., Blanchard, J.L., Coll, M., Pontavice, H. Du, Everett, J.D., Guiet, J., Heneghan, R.F. *et al*., 2023. Applying ensemble ecosystem model projections to future-proof marine conservation planning in the Northwest Atlantic Ocean. Facets 8: 1–16.

SECTION B.1.2. CLIMATE RISKS TO SUSTAINABLE FISHERIES CERTIFICATION

FishMIP ensemble projections are being used in a project led by the Marine Stewardship Council (MSC), in collaboration with a number of partners including FAO, that aims to evaluate the challenges and opportunities that climate change creates for fisheries certification. This will be achieved through a global risk assessment that will inform the MSC's strategy on how to incentivize climate-smart fisheries management. The risk assessment focuses on fisheries currently certified to the MSC Fisheries Standard, fisheries working towards certification, and fisheries that have been suspended from the MSC programme: this is a total of more than 500 fisheries, that account for some 19 percent of the global wild catch (https://www.msc.org/what-we-are-doing/science-and-research/our-climate-change-research/assessing-climate-risks). The project uses FishMIP projections of exploitable fish biomass under different emissions scenarios as climate change exposure indicators that will require management adaptation.

The findings of this study will be used to identify hotspots where risks to efforts to meet the MSC standards are likely, and to help incentivize climate-resilient fisheries management through its inclusion within the certification process. The findings will also provide a valuable contribution to the wider fisheries science and policy community tackling fisheries management and climate change issues.

SECTION B.1.3. VULNERABILITY OF COASTAL FISHERIES IN PACIFIC ISLAND COUNTRIES AND TERRITORIES

FishMIP has contributed to an update of The Pacific Community's (SPC) climate change vulnerability assessment of fisheries and aquaculture for 22 Pacific Islands Countries and Territories (PICTs). As the previous climate vulnerability assessment for tropical coastal fisheries was based on expert elicitation (Bell *et al.*, 2021), the aim of the recent assessment was to use a less subjective approach that combines both direct (percentage change in fishable biomass) and indirect (key coastal habitat changes) impacts. To better reflect coastal fisheries, the exploitable fish biomass variable was used but with size classes restricted from 10 g to 10 kg. This was combined with a bias correction method that integrated coral reef structural complexity and fish biomass (Graham and Nash, 2013) that had been trialled in a previously well modelled region (the Great Barrier Reef, Australia). The projected relative changes in fish biomass and habitat change were used as multipliers for current fisheries yields to project changes in fisheries yields and assess changes in per capita fish supply across the 22 PICTs, revealing projected declines over much of the region (Welch *et al.*, forthcoming). Differential outcomes were identified, however, with some locations (e.g. Pitcairn Islands) potentially seeing only small changes in production, while other locations will potentially see quite large drops in potential catch (e.g. Solomon Islands, Papua New Guinea, Federated States of Micronesia, Palau, Samoa, Tokelau, Tuvalu; Welch *et al.*, forthcoming) (see also Part A).

The outcomes of this report are intended to assist South Pacific fisheries managers and decision-makers in assessing losses and damages to coastal fisheries and risks to aquatic food security in the region (Welch *et al.*, forthcoming).

SECTION B.1.4. COMBINED FISHERIES AND AGRICULTURE RISKS FOR COMMUNITIES IN THE INDO-PACIFIC

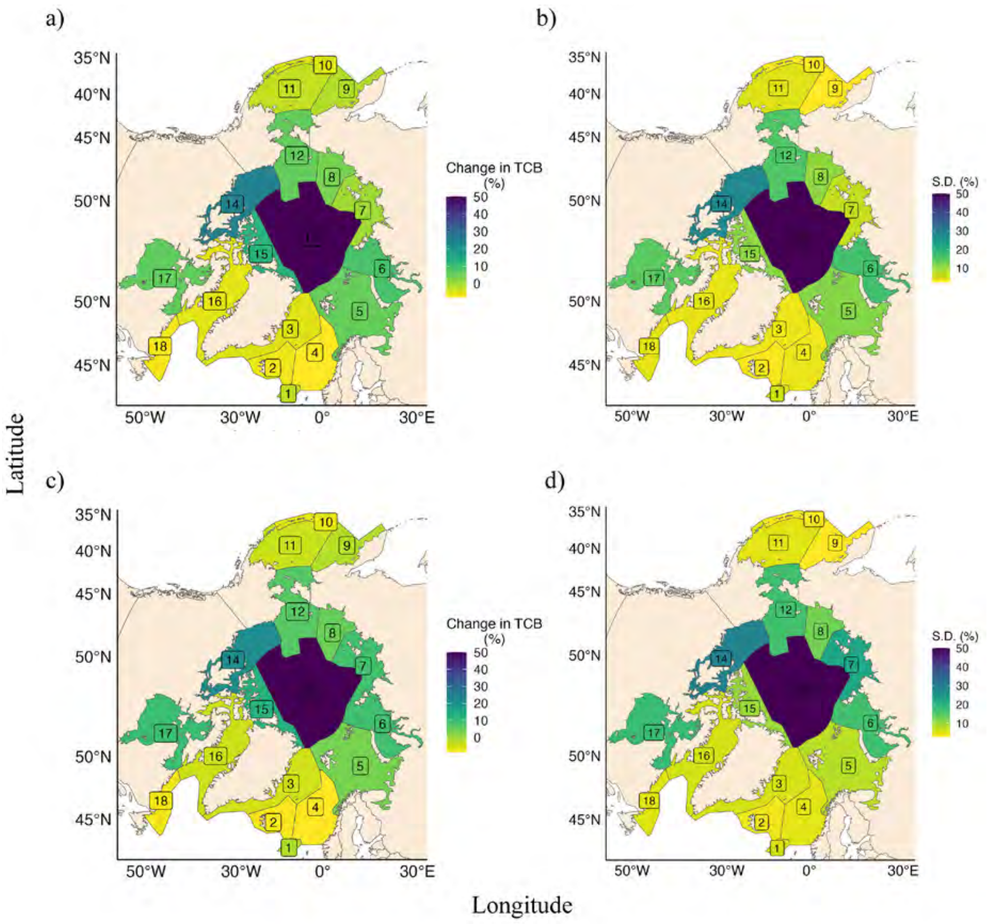
To assess fisheries and agriculture climate vulnerabilities in the Indo-Pacific, FishMIP outputs have been combined with agricultural crop projections (from the Agricultural Model Intercomparison and Improvement Project, AgMIP – https://agmip.org/) and socioeconomic household surveys in 72 coastal communities across five Indo-Pacific countries (Indonesia, Madagascar, Papua New Guinea, Philippines and Tanzania; Cinner *et al*., 2022). This study showed that fisheries are in more trouble than agricultural crops, and that poor people are in the most danger. The study revealed three key findings. First, while the projected potential losses to fisheries are higher than those associated with agricultural crops, there is substantial within-country variability. For example, under the high emissions scenario, Indonesia is projected to experience potential losses to fisheries close to the average among study sites across all countries (~16 percent), but with large variability across all sites in Indonesia. Likewise, there is also substantial within-country variation in how communities are likely to experience climate change impacts, based on their sensitivity.

The second key finding is that under the high emissions scenario, losses are projected for fisheries and crops alike in most regions. For example, by 2100 tropical areas could lose up to 200 suitable plant-growing days per year due to climate change, and ocean biomass could drop by up to 40 percent. Yet assessments of climate change impacts rarely consider changes to crops and fisheries simultaneously. Those that do are at a national scale, and thus do not capture how households and communities will be affected by climate change at a local scale. For instance, the coarse national scale does not capture whether people simultaneously engage with both sectors: this would determine whether people have the capacity to switch across sectors or are particularly susceptible to a combined decline. Lastly, strong mitigation could reduce the proportion of places facing a double burden by half, as one-third of places are expected to experience an increase in crop production with a loss in fisheries. However, the potential gains are unlikely to offset the losses because several communities are engaged in fisheries but not crop production. Worryingly, communities with lower socioeconomic status are particularly exposed to the impacts of climate change and have higher dependence on natural resources, meaning that they are expected to be hit harder.

SECTION B.1.5. ASSESSING KEY UNCERTAINTIES IN THE ARCTIC

The potential risks associated with increased fishing activity in the Arctic Ocean due to sea ice loss and poleward stock shifts pose significant challenges for transboundary management and governance. While FishMIP global ensemble results for the Arctic are highly uncertain, their potential use has been explored in the context of supporting fisheries policy and decision-making (Mason *et al*., 2024). In particular, characterizing the areas of highest uncertainty and risk was a key step in prioritizing research needs during a 16-year moratorium on industrial fishing in the Arctic High Seas. The FishMIP results generally project biomass increases in more northern Arctic ecosystems and decreases in southern Arctic ecosystems. However, wide inter-model variability exceeds projection means in most cases, indicating a high level of uncertainty (Figure 25; see also Section A.3.1). While this study deemed these projections unsuitable for informing specific policy actions, high uncertainties highlight the urgent need for investment in sustained, collaborative research to fill data gaps and improve modelling capacity, as well as for the development of risk frameworks that integrate uncertainty to support a precautionary approach.

Figure 25. Percentage change in total marine animal biomass for the Arctic



Key:

1	Faroe Plateau	2	Iceland	3	Greenland Sea	4	Norwegian Sea
5	Barents Sea	6	Kara Sea	7	Laptev Sea	8	East Siberian Sea
9	East Bering Sea	10	Aleutian Islands	11	West Bering Sea	12	Chukchi Sea
13	Central Arctic	14	Beaufort Sea	15	Northern Canadian Archipelago		
16	Baffin Bay	17	Hudson Bay	18	Labrador Sea		

Notes: Ensemble mean change (percentage) in total marine animal biomass (TBC) in 2030–2049 relative to the reference period of 1995–2014 and standard deviation (SD) under a) and b) the low (SSP1.26) and c) and d) high (SSP5.85) emissions scenarios, by Large Marine Ecosystems (LME) in the Arctic.

Source: Figure adapted from Mason J.G., Bryndum-Buchholz A., Palacios-Abrantes J., Badhe R., Morgante I., Bianchi D., Blanchard J.L. *et al*., 2024. Key Uncertainties and Modeling Needs for Managing Living Marine Resources in the Future Arctic. *ESS Open Archive*. 23 May 2024. DOI: 10.22541/essoar.171650300.09423291/v1.

Chapter B.2. Climate-enhanced regional marine ecosystem model ensembles

Authors: Tyler D. Eddy, Kelly Ortega-Cisneros, Ricardo Oliveros-Ramos, Elizabeth A. Fulton, Marta Coll, Kieran J. Murphy, Lynne Shannon, Denisse Fierro-Arcos, Julia L. Blanchard

Global marine ecosystem models are a more recent development than regional marine ecosystem models, the latter having been in use for more than 50 years (Andersen and Ursin, 1977; Bax and Eliassen, 1990; Polovina, 1984). The accuracy and reliability of global models has matured quite rapidly, but there are two main factors that make regional models important for helping us understand climate impacts and potential future states that relate to sources of uncertainty.

The first factor is the heterogeneous distribution of ocean production, which occurs more intensely in upwellings and along coastlines, areas that are not well represented in many of the global Earth system models that global marine ecosystem models sit upon. Downscaling approaches are a well-recognized way of taking large-scale trends from global Earth system models and recasting them on more relevant regional scales. This is done so that the downscaled products can be used to drive regional models that directly address scales most national fisheries managers are concerned with. The second factor is the reputation and familiarity of regional models, which already have a recognized role in informing some management processes (Howell *et al*., 2021; Pethybridge *et al*., 2020), contain taxa at a resolution not possible in most global models (due to the system specificity of such detail versus the generalizable forms needed in many global models), and are closely fitted to system-specific data, the equivalent of which is not available globally (Tittensor *et al*., 2018, 2021).

SECTION B.2.1. INTERCOMPARISON OF REGIONAL AND GLOBAL MARINE ECOSYSTEM MODEL PROJECTIONS

The FishMIP regional model community employed climate change projections to evaluate agreement in long-term trends among regional and global marine ecosystem models for ten regions (Eddy *et al*., 2024) across two IPCC assessment rounds (CMIP5 and CMIP6). The initial aim of comparing regional and global marine ecosystem model projections was to bolster confidence in the use of global models at regional scales, given that the majority of coastal zones do not have a corresponding regional model. However, for some regions there was poor agreement in direction of change among regional and global models (Pethybridge *et al*., 2020). Essentially, the reasons that were proposed for the potential disagreement all relate to the capacity for regional models to resolve processes not possible in the global models, leading to dynamics and feedback not expressed in global models as yet.

Examples of specific reasons for the differences between regional and global models include:

- Regional FishMIP models often have greater combined functional diversity (size/age/trophic level) and ecological or taxonomic resolution.

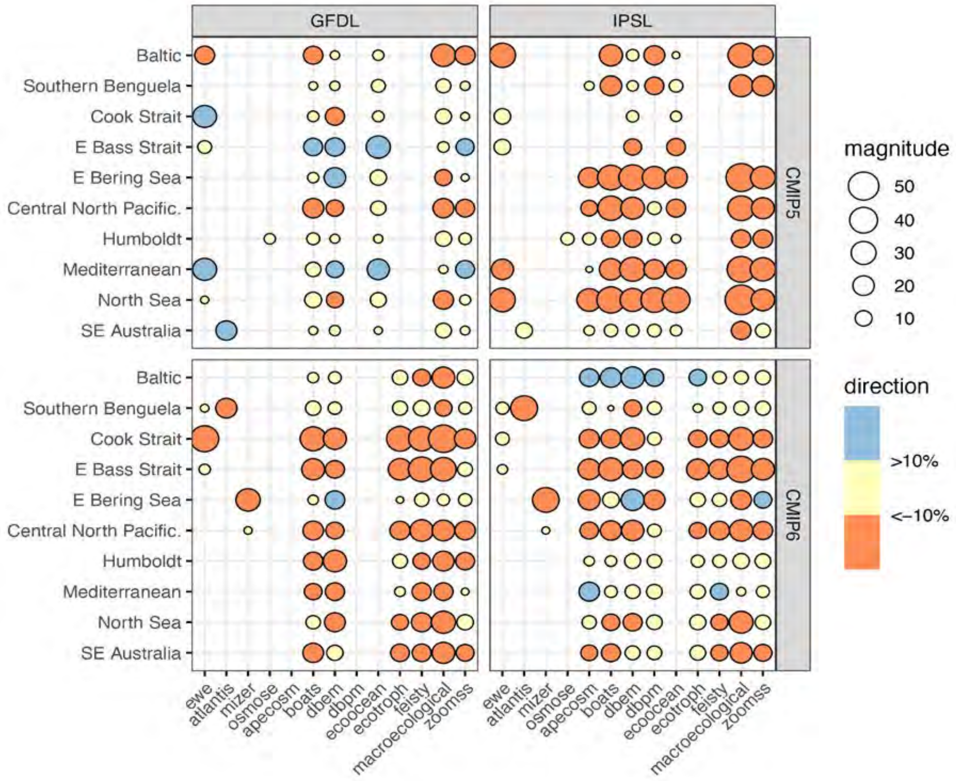
- Regional FishMIP models generally include more ecological processes and simulate predator-prey interactions more explicitly than global models, but they may not include all the climate drivers captured by global models.

- Coastal regions in global Earth system models and FishMIP models are of coarse spatial resolution, while regional FishMIP models are often developed at finer scales (in spatial regional models this also means they can resolve physical processes not possible in global models).

- Regional models include a mix of temporal and spatial-temporal, ecological and socioeconomic dynamics, depending on regional data availability, that are often simplified in global models.

Within a given region and model type, climate forcing from different Earth system models (GFDL vs IPSL) produced disagreement in the direction of change for some regions (Figure 26). The degree of model agreement in terms of magnitude and direction of change improved under the most recent CMIP6 model projections. There was also a slightly higher level of agreement in the direction of change between global and regional ecosystem models in CMIP6 compared to CMIP5. However, the same regional marine ecosystem models were not available to compare across CMIP5 and CMIP6, and usually there was only a single regional marine ecosystem model in each region. For one region in CMIP6 there was more than one regional ecosystem model (Atlantis and EwE in Benguela; Table A2), and the two regional models demonstrated some disagreement in the direction of change (Figure 26). The FishMIP regional model community is currently working to improve these multi-scale comparisons, including by facilitating the development of climate-enhanced, regional-scale marine ecosystem model ensembles (see Section B.2.2). Until the differences between regional and global models can be better understood, alongside observational evaluation of a comparable set of models for each region, interpretation of regional-scale projections should carefully consider inter-model uncertainty.

Figure 26. Percentage change in total marine animal biomass across regional and global FishMIP models



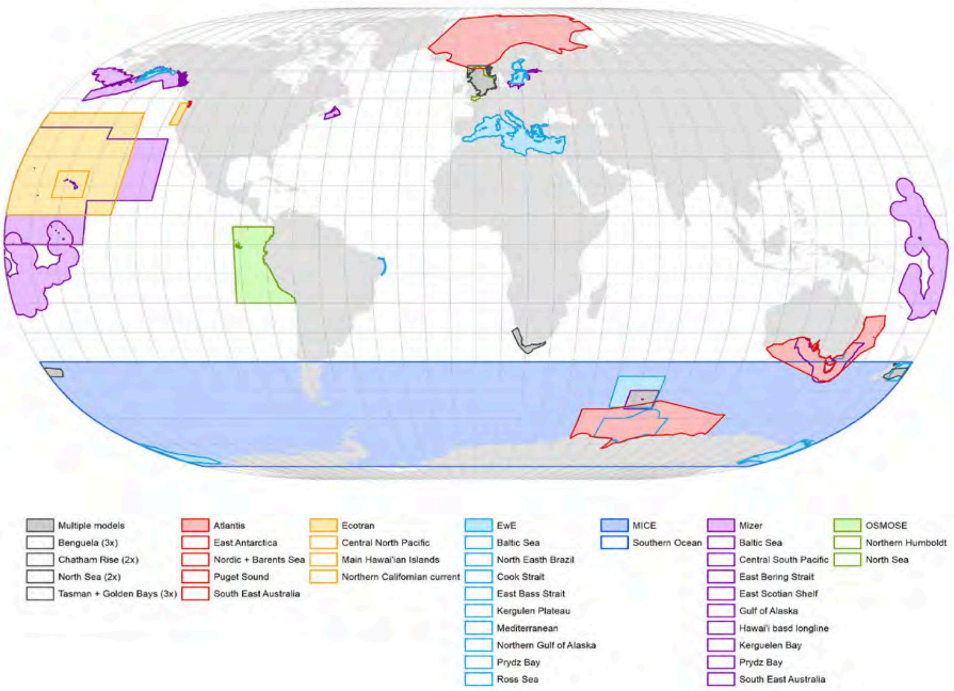
Notes: Comparison in the direction (orange = decrease, yellow = negligible change, blue = increase) and magnitude (circle size) of average percentage change across models in total marine animal biomass projected over 2045–2055 relative to 1990–1999 for all regions with both regional and global ecosystem models. Comparison shows different Earth system model climate forcing (GFDL, IPSL) and under earliest (CMIP5) and latest (CMIP6) IPCC rounds. Regional marine ecosystem models are leftmost on the x-axis: EwE, Atlantis, Mizer, and OSMOSE (Table A2). The rightmost nine models on the x-axis are global marine ecosystem models.

Source: Figure created from data in Eddy, T.D., Heneghan, R.F., Bryndum-Buchholz, A., Fulton, E.A., Harrison, C.S., Tittensor, D.P. *et al*., 2024. Global and regional marine ecosystem model climate change projections reveal key uncertainties. ESS Open Archive. 10 May 2024. 10.22541/essoar.171535471.19954011/v1.

SECTION B.2.2 BUILDING GLOBAL CAPACITY FOR REGIONAL MARINE ECOSYSTEM MODEL ENSEMBLES

To enhance capacity for undertaking regional-scale climate change risk assessments, ensembles of diverse yet comparable marine ecosystem models are needed within regions. As an open and international network FishMIP offers a shared approach for providing tools and data to implement climate change scenarios in a consistent way that is comparable within and across regions and with global ecosystem models. This is important to help modellers to undertake intercomparisons or to create ensemble estimates of change, and therefore to understand the ecological processes that are associated with higher uncertainty levels and to identify robust results. Currently, regional FishMIP model ensembles are available for two regions only: Southeast Australia (e.g. Novaglio *et al.*, 2022) and Southern Benguela (South Africa; Ortega-Cisneros *et al.*, 2018). However, this number is increasing, with the North Sea, Mediterranean Sea, Southern Ocean (e.g. Murphy *et al.*, 2024), and New Zealand being some of the regions with model ensembles that have recently joined FishMIP (Figure 27). Many more regional marine ecosystem modellers, particularly in the Americas, have expressed interest in joining FishMIP in the near future.

Figure 27. Regional marine ecosystem models planning to contribute to FishMIP

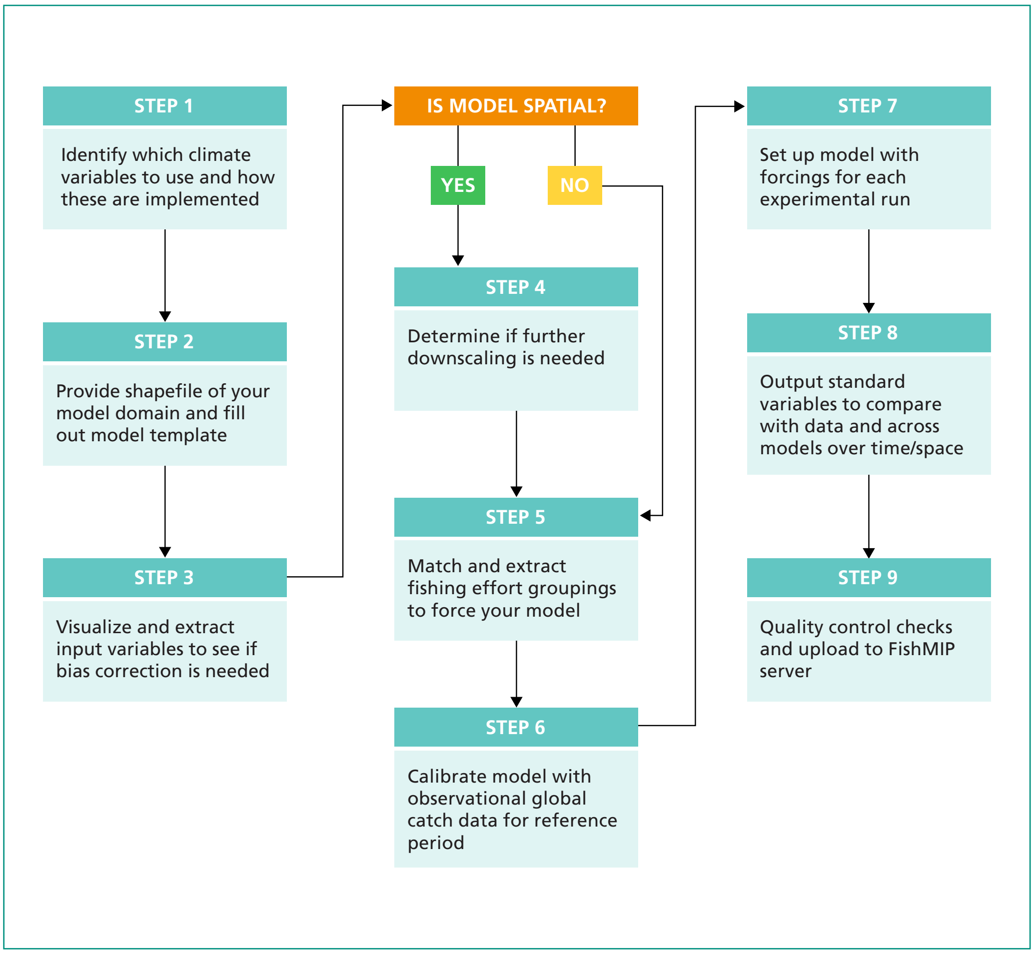


Notes: Map of regional marine ecosystem model spatial domains, including areas for which models already exist and those in development by FishMIP participants planning to contribute simulations in the current simulation round.

Source: Adapted from Ortega-Cisneros, K., Fierro-Arcos, L.D., Lindmark, M., Novaglio, C., Woodworth-Jefcoats, P., Eddy, T.D., Coll, M. *et al.*, 2024. An Integrated Global-to-Regional Scale Workflow for Simulating Climate Change Impacts on Marine Ecosystems. ESS Open Archive. 16 May 2024. DOI: 10.22541/essoar.171587234.44707846/v1.

FishMIP regional marine ecosystem models are available for different geographic regions and, in aggregate, also cover a range of model types (Appendices Table A2; Figure 28). To facilitate regional-scale implementation of the FishMIP simulation framework, a specific workflow and data tools have been developed (Figure 28; Ortega-Cisneros *et al.*, 2024). This workflow considers the numerous decision-making steps of integrating global and regional-scale FishMIP simulation processes. It is intended to help guide modellers from the selection of climate input data to the uploading and sharing of marine ecosystem model projection results.

Figure 28. Workflow for running climate change simulations to assess marine ecosystem and fisheries change using regional marine ecosystem models



Source: Figure from Ortega-Cisneros, K., Fierro-Arcos, L.D., Lindmark, M., Novaglio, C., Woodworth-Jefcoats, P., Eddy, T.D., Coll, M. *et al.*, 2024. An Integrated Global-to-Regional Scale Workflow for Simulating Climate Change Impacts on Marine Ecosystems. ESS Open Archive. 16 May 2024. DOI: 10.22541/essoar.171587234.44707846/v1.

An outstanding challenge for regional-scale marine ecosystem model climate change projections is to get access to accurate high-resolution inputs. For example, global Earth system model outputs have often been used directly as inputs for regional marine ecosystem models, but this is not ideal, primarily due to differences in spatial resolution. Regional marine ecosystem models are often developed with higher spatial resolution than global Earth system models, and for particularly productive regions where important processes are not well resolved in global models (e.g. coastal dynamics, upwelling, mesoscale features). Therefore, outputs from global Earth system models should be downscaled before being used as inputs for regional marine ecosystem models. Initial efforts within FishMIP have made use of different methodologies to deal with this issue, ranging from simple approaches (e.g. the 'anomaly' approach) to more complex methods (e.g. statistical downscaling and bias correction) (Oliveros-Ramos *et al*., 2023). Working towards community best practice in this area requires close collaboration with climate modellers and data providers. This issue is discussed further in Part C.

PART C. NEXT STEPS: INTRODUCING FISHMIP 2.0 AND BEYOND

Chapter C.1. Understanding and accurately predicting past and future changes

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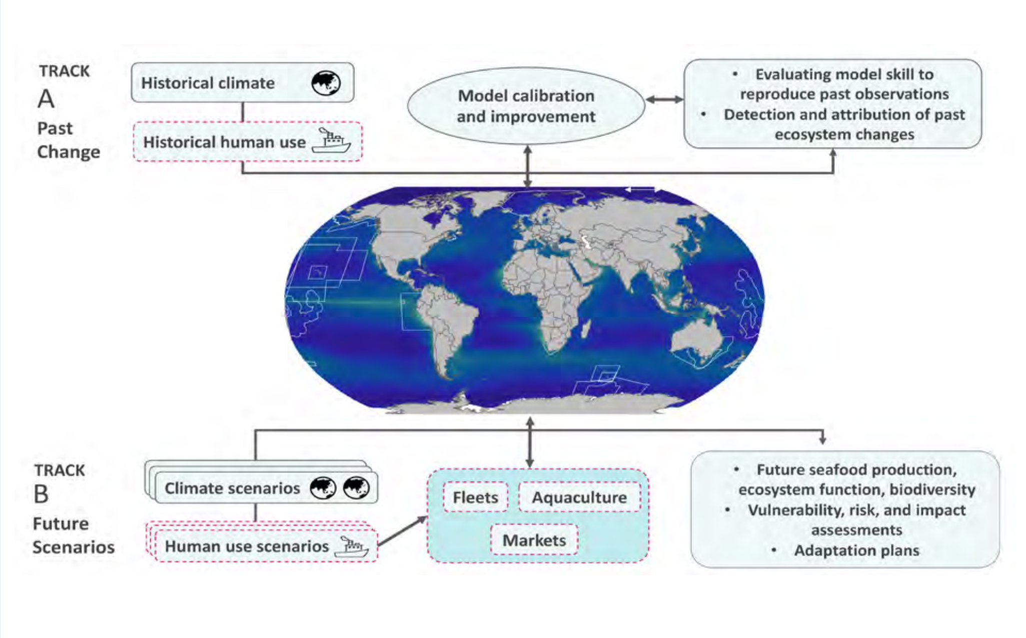
To understand and predict how human activities will affect marine ecosystems in the future, models need to be accurate in detecting and attributing the effects of specific drivers on past ecosystem changes. Previously FishMIP's primary focus has been on reporting climate change effects on marine fish biomass in the absence of other direct human influences (Lotze *et al*., 2019; Tittensor *et al*., 2021; Tittensor *et al*., 2018; Heneghan *et al*., 2021). This has been due to the lack of standardized historical fishing effort data at the global scale, meaning that fishing has been incorporated in only a small subset of the global models, in a variety of ways. To systematically tease apart the relative and combined effects of global climate change and fishing, and the extent to which future fisheries are at risk under different management scenarios (Tittensor *et al*., 2021; Scherrer *et al*., 2020), a consistent approach for incorporating fishing drivers is needed. This is especially important for the development of scenarios describing how evolving socioeconomic and environmental conditions are likely to affect future fishing fleets, from artisanal to industrial scales, and to provide knowledge on the potential cumulative and interactive impacts of fishing and climate pressures on marine ecosystems (see Chapter C.2).

To address these issues, 'FishMIP 2.0' has been developed to provide consistent data and scenarios to tackle questions related to changing climate and socioeconomic conditions, and to how future fisheries will evolve and adapt over time (Blanchard *et al*., 2024) across global and regional scales. This framework is divided into two tracks: 'Past change' and 'Future scenarios' (Figure 29).

Figure 29. FishMIP 2.0 two-track model evaluation, detection and projection



Notes: New components developed for FishMIP 2.0 are highlighted by the dashed red contours. Currently there are nine global marine ecosystem models and more than 30 regional marine ecosystem models (areas outlined in white on the map depict spatial domains of regional models) contributing to model simulations.

Source: Blanchard, J.L., Novaglio, C., Maury, O., Harrison, C.S., Petrik, C.M., Fierro-Arcos, L.D. *et al*. 2024. Detecting, attributing, and projecting global marine ecosystem and fisheries change: FishMIP 2.0. ESS Open Archive. 22 January 2024. DOI: 10.22541/essoar.170594183.33534487/v1.

The next two sections (C.1.1 and C.1.2) describe key components required to implement Track A ‘Past change’ of FishMIP 2.0. These include the development of a formal model evaluation framework to assess how well FishMIP models capture past catches, and improved realism in climate and fishing input variables to reduce key limitations and uncertainties associated with previous projections. Section C.1.3. focusses on Track B ‘Future scenarios’ of FishMIP 2.0, including the development of fishing scenarios and their implementation in all FishMIP models.

SECTION C.1.1. MODEL EVALUATION FRAMEWORK

Despite major advances in marine ecosystem global modelling and uncertainty tackled by FishMIP, formal and objective assessment of model accuracy is currently lacking – yet it is critically needed to ensure projections are rigorous, reliable, and improved when necessary. While the main messages from climate models are usually well received, there is a need for effective communication on the uncertainty associated with model projections. Filling this gap is a crucial step for building credible models to meet the needs of industry, policy and society.

Inspired by recent advances in Earth system model evaluation (Eyring *et al*., 2019), FishMIP is designing an ensemble-wide standardized model evaluation framework to answer the following question: How well do climate and socioeconomic forced global and regional marine ecosystem models capture past states, trends and variability in marine animal biomass and catches at different scales?

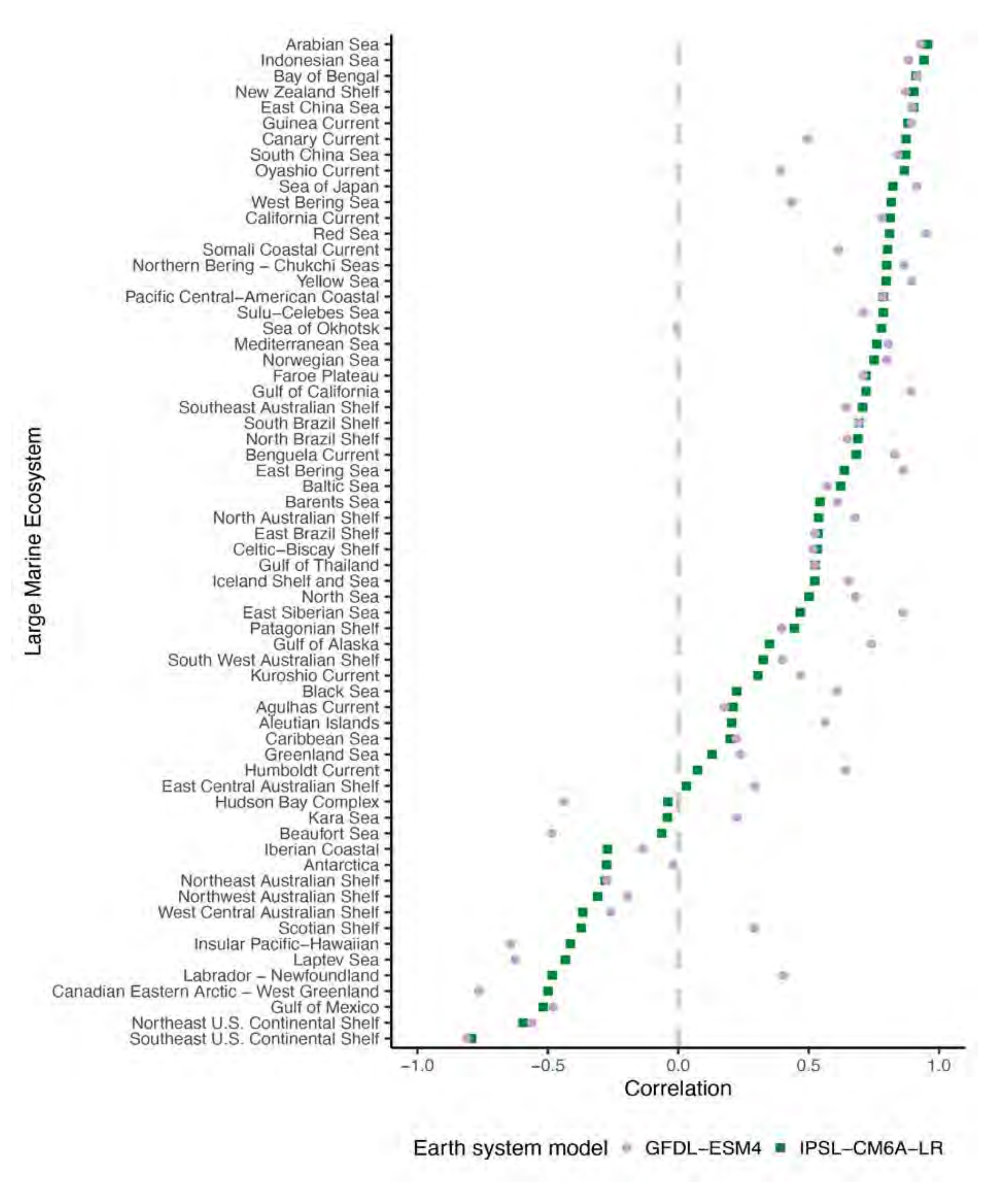
The specific aim of a model evaluation framework is to review each model's ability to replicate observed data, to determine if the model is fit for purpose – i.e. whether it can generate the required outputs at the necessary level of accuracy to answer the questions it is being used for (Geary *et al*., 2020; Kubicek *et al*., 2015; Rykiel Jr, 1996) – and to identify areas of model improvement.

Thus far, outputs of global marine ecosystem models contributing to FishMIP have been evaluated independently and using different methods (Blanchard *et al*., 2012; Carozza, Bianchi and Galbraith, 2017, 2016; Cheung *et al*., 2010; Christensen *et al*., 2015; Maury, 2010; Petrik *et al*., 2019). To build confidence in marine ecosystem model projections, FishMIP is working towards an ensemble-wide standardized model evaluation framework for cross-model validation and benchmarking, including a standardized set of metrics that guide model improvement to meet FishMIP standards (Rynne *et al*., 2024; Steenbeek *et al.*, 2024).

To explore the proposed framework, existing simulations for historical catches from two of the global ecosystem models (EcoOcean and BOATS, Table A1) could be compared with observed catches (Rynne *et al*., 2024). Agreement between modelled and observed fisheries catches is higher for the latest FishMIP simulations (CMIP6) compared to earlier simulations (CMIP5), suggesting there have been advances in the most recent versions of the FishMIP models and/or the Earth system model projections. At a global scale, the latest fishery catch projections are strongly correlated with the trend of observed catch over time, indicating that models can capture broad-scale fishing dynamics. However, discrepancies in the magnitude of simulated and observed fisheries catches nevertheless exist, and vary across large marine ecosystems, highlighting regional differences in model performance.

For some regions, model performance differs depending on the Earth system model providing input data (Figure 30). Patterns across large marine ecosystems pinpoint regions where model improvement is most needed, and show that climate variables from Earth system models are an important source of uncertainty for marine ecosystem model projections. For instance, the two ecosystem models use net primary production as a major driver of the biomass production underpinning fisheries catches (Chassot *et al*., 2010; Stock *et al*., 2017). These estimates are highly uncertain for some regions and differ strongly across Earth system models, and such uncertainty propagates through marine ecosystem models (Kwiatkowski *et al*., 2020; Tagliabue *et al*., 2021). In addition, a range of other factors – including a simplified representation of fishing dynamics, a lack of relevant processes, models' internal parameterizations, and quality of observations – may also drive the lower correlation scores for some regions (Guiet *et al*., 2024).

Figure 30. Correlation between observed and modelled time series of fisheries catches in large marine ecosystems for a marine ecosystem model driven by two Earth system models



Notes: Example of correlation in a global marine ecosystem model (BOATS) between observed and modelled fisheries annual catch time series for each large marine ecosystem forced using climate variables from the two Earth system models considered: IPSL-CM6A-LR and GFDL-ESM4. Correlation values (ranging between -1 and 1) are ranked from best to worst according to outputs from IPSL-CM6A-LR-forced BOATS. A high correlation indicates a common trend between modelled and observed time series. Central Arctic and Canadian High Arctic – North Greenland large marine ecosystems were excluded as data was available for GFDL-ESM4-forced BOATS only.

Source: Figure adapted from Rynne N., Novaglio C., Blanchard J., Bianchi, D., Christensen, V., Coll, M., Guiet, J., *et al*. 2024. A skill assessment framework for the Fisheries and Marine Ecosystem Model Intercomparison Project. *ESS Open Archive*. 15 May 2024. 10.22541/essoar.171580191.17895127/v1.

Evaluation of the ecological, fishery and economic components of models also needs to go beyond the comparison between modelled and empirical catch time series. This is because biases in catch observations can mislead the evaluation process, and catch time series alone give little information on how well models' ecological and economic components are performing. Future work will also evaluate how well modelled abundance and biomass time series compare with survey-derived estimates, for key regions across the globe (Maureaud *et al*., 2024), using both global and regional databases.

SECTION C.1.2. IMPROVING THE REALISM OF FISHING AND CLIMATE INPUTS

A further step forward in the development of an ensemble-wide standardized model evaluation framework for FishMIP is to improve the consistency and realism of historical model inputs. For this step to be achieved, a consistent global data set for fishing effort has been developed for systematic integration into FishMIP models, which has been derived from Rousseau *et al*. (2024). The resulting dataset spans almost two centuries and provides fishing effort estimates disaggregated into large marine ecosystems, countries and territories' waters under national jurisdiction, fishing countries, fishing sectors, fishing gears, and functional groups (Blanchard *et al*., 2024, Novaglio *et al*., 2024) for global and regional spatial model domains. These datasets are currently being used to drive FishMIP global and regional models to ensure a common experimental dataset. They are being used in other modelling experiments to estimate regional fishing exploitation levels (fishing mortality relative to fishing mortality at maximum sustainable yield) for different fish types, to simulate the ecological effects of such exploitation levels in all large marine ecosystems and the High Seas (van Denderen *et al*., 2024), and to validate historical changes in fishing effort from inclusion of fleet dynamics in models (Maury *et al*., 2024) .

The spatial resolution of global Earth system models' outputs (1 degree) that have been used thus far to directly force FishMIP marine ecosystem models for climate change projections is often cited as being too coarse to represent important coastal and oceanographic processes; a key source of uncertainty in projections. Such processes include upwelling, tidal mixing, eddies, and river inputs, all of which contribute to dynamics affecting primary production and transfer of energy through marine food webs to fisheries production (Barange *et al*., 2014; Holt *et al*., 2010; Watson *et al*., 2004). This is important to resolve because coastal and shelf ecosystems contribute a quarter of global primary production and the majority of global fish production. Additionally, fully coupled Earth system models are often not able to capture the exact timing of shorter-term climate oscillations known to influence fisheries catches (including El Niño cycles) – these are required for a more rigorous evaluation and detection of past climate-driven ecosystem changes. To directly tackle this, FishMIP 2.0 includes simulations that draw on higher resolutions and links that account for changing land-use (e.g. from agriculture systems) and river nutrient inputs through time (Liu *et al*., 2019, 2021). The use of higher-resolution inputs is helpful for capturing spatially explicit regional marine ecosystem models that are able to use 1-degree resolution inputs. It is anticipated that more accurate bias-adjusted climate-related forcings will soon become available for future projections.

SECTION C.1.3. FUTURE SOCIOECONOMIC PATHWAYS

There is an urgent need to develop future policy-relevant scenarios that encapsulate the range of possible climatic and socioeconomic changes, to be able to assess their potential impacts on marine ecosystems and their services. These scenarios form a common basis for modelling studies that aim to inform policy on the threats and actions to mitigate undesirable ecological and socioeconomic outcomes while exploring sustainable futures (Kim *et al*., 2023; Maury *et al*., 2017; O'Neill *et al*., 2017).

Socioeconomic scenarios, specifically tailored to ocean systems, have been developed by the marine climate change research community. The simplest scenarios are based on changes in fishing pressure where greater pressure removes more fish, leading to different socioecological outcomes (Cheung *et al*., 2022; Nielsen *et al*., 2018). Future socioeconomic scenarios based on lower and upper production limits for aquaculture and fisheries have also been proposed by FAO to investigate actions for achieving food and nutrition security (FAO, 2022c). More complex scenarios contemplate simultaneous changes in multi-level socioeconomic drivers, including coupling supply, demand and fishing efficiency to changes in ecosystem states, and under alternative future societal pathways (Maury *et al*., 2017; Maury *et al*., 2024). These drivers include demand for per-capita consumption of aquatic food, fishing costs and fish price, fisheries management targets and compliance, technological improvements, and investments (Maury *et al*., 2017; Nielsen *et al*., 2018; van Putten *et al*., 2012, Scherrer *et al*., 2020).

The FishMIP Scenarios Working Group is currently using the Oceanic System Pathways (OSPs) that have been mapped to the Shared Socioeconomic Pathways (SSPs), and capture five different plausible socioeconomic fisheries trajectories (Maury *et al*., 2024, 2017). Advances focus on extending the Oceanic System Pathways to include aquaculture and a broader suite of fisheries, as well as translating the qualitative scenarios into quantitative inputs to force models (Maury *et al*., 2024). Current efforts by FishMIP and international partners are developing a framework that will enable modellers to implement the quantitative scenarios and to capture missing components of changing fishing fleet dynamics over time and space (Maury *et al*., 2024).

SECTION C.1.4. CLIMATE MITIGATION SCENARIOS

Thus far, FishMIP projections have focused on scenarios related to future global pathways in the context of coupled RCPs and SSPs, and soon they will extend to consider Ocean System Pathways. However, considering the ongoing discussions on climate change mitigation, including marine CO_2 removal and solar geoengineering (National Academies of Sciences, 2021), FishMIP is working on future protocols to tackle the potential impacts of such interventions on marine ecosystems and fisheries.

The responses of marine ecosystems and their associated fisheries to climate engineering solutions are unknown and are crucial to understand (Zarnetske *et al.* 2021). A long-term goal of FishMIP is to use output from geoengineering simulations as input for the global marine ecosystem models. These geoengineering simulations utilize the 'middle of the road' emissions scenario (SSP2–4.5) and keep the global mean surface air temperature near 1.5 °C above the pre-industrial level using two methods: marine cloud brightening and stratospheric aerosol injection (Richter *et al*., 2022).

Chapter C.2. Future directions and priorities

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To increase the policy uptake and relevance of FishMIP work and outputs, and to further meet the needs of national and international partners such as FAO and the IPCC, FishMIP envisions three main areas of future development. These are detailed in the following sections.

SECTION C.2.1 TOWARDS MORE ROBUST REGIONAL MARINE ECOSYSTEM AND FISHERIES PROJECTIONS TO SUPPORT ADAPTATION

Among the immediate steps required to advance FishMIP work and its impact is to highlight robust regional projections that can be used for vulnerability assessments and the development of adaptive and climate-resilient fisheries management and conservation policies and practices. This implies focusing more on spatiotemporal scales that are relevant for management, and thus providing ensemble projections at country and sub-national level and at seasonal and monthly scales, with consideration of relevant coastal dynamics and with the final aim of contributing to real-time assessments. The achievement of this paramount step will depend on a better coverage of robust, spatially explicit regional models that capture key climate drivers. This is particularly important for the Global South, which is currently under-represented, so that regional extractions from the more generalized global marine ecosystem models will no longer be the only way to fill in the information gap (Cinner *et al*., 2022). Successfully achieving such an outcome will also depend on using the FishMIP network to help build regional ecosystem modelling coordination and capacity; a better integration of outputs from global and regional models; the availability of regional multi-model ensembles for model intercomparison and for a more precise quantification of uncertainty at the regional scale; and improved model accuracy at annual to decadal timescales.

SECTION C.2.2 ACCESSIBLE DATA TOOLS FOR POLICY

The second direction of growth for FishMIP is the development of tools that make it easier to communicate and use FishMIP results, for a wider uptake including by scientists, management and policy bodies. To increase consideration of FishMIP outputs by the scientific community, FishMIP data and analyses must not only be available and reproducible (e.g. https://data.isimip.org/), but also easily accessible through, for example, a FishMIP data analysis package (e.g. written in R and Python programming languages). A FishMIP-dedicated website (www.fishmip.org) has been developed, where summarized results can be downloaded and explored. In future this could be further developed in the style of the IPCC interactive climate atlas (https://interactive-atlas.ipcc.ch/). These developments are intended to help meet the needs scientists, management and policy bodies as well as the wider public.

Available products would include global ecosystem model ensembles that are down-scalable to coastal regions and regional model ensembles, with both objectively benchmarked for their predictive skill to ensure quality, transparency, accuracy and relevance for the world's coastal ecosystems. They would also include readily accessible spatiotemporal outputs of Earth system models and methods for integrating outputs of climate impact models within and across food sectors (e.g. marine biomass and catches from the Marine Ecosystem Models, and outputs on crops from the Agricultural Model Intercomparison Project); visualization and data inputs for transparent country-level vulnerability and adaptation assessments; and a virtual online lab for exploring and comparing outputs of climate model impacts under different future scenarios.

SECTION C.2.3. TACKLING THE NEXUS OF BIODIVERSITY, WATER, FOOD AND HEALTH TO SUPPORT THE BLUE TRANSFORMATION

The most challenging direction of proposed future developments is the improved representation of ecological and industrial processes, both those developing as marine industries grow, and those spanning the land-to-sea divide. This includes the representation of the interconnected food systems of fisheries, aquaculture and agriculture, and their respective impacts on and vulnerabilities to changes in biodiversity and ecosystem functions and services. While we have already begun comparison across sectors (e.g. marine fisheries and agriculture on land; Blanchard *et al.*, 2017), greater efforts to understand the consequences across system linkages in the context of climate change is needed to ensure the SDGs are achieved (Cottrell *et al.*, 2018; Singh *et al.*, 2021). This involves three main areas of work, which are described in the following paragraphs.

Better analysis of trade-offs across multiple objectives for marine ecosystems

FishMIP's projected changes to marine ecosystem properties (e.g. marine animal biomass, exploitable fish biomass) under climate change can be extended to further contribute to the Nexus assessment initiated by the IPBES. Nexus aims to assess the interlinkages among the SDGs related to food and water security, health for all, protection of biodiversity on land and in the oceans, and the mitigation of and adaptation to climate change (IPBES, 2021). For example, regional and global models could test and identify the most effective management configuration for food and biodiversity under different climate scenarios (Arneth *et al.*, 2023).

Greater dynamic representation of the anthropogenic aspects of marine systems is another potential future advance. Beyond embedding the social and market drivers of fisheries or connecting marine ecosystem models to trade and supply/value networks, integration with many more sectors – such as aquaculture, shipping, mining, marine renewable energy, tourism and cultural uses, coastal hardening or development, land use, infrastructure development, restorative actions etc. – could be achieved through integrated systems models. This may remain relevant for a subset of marine ecosystem models which will be created to consider regional planning and cumulative effects, and also what a more marine-oriented human future might look like. Experience to date in Australia (Fulton *et al.*, 2017), Patagonia (Steven *et al.*, 2019) and elsewhere is that this is a non-trivial exercise with (i) many outstanding gaps in understanding around relevant processes, direct and indirect connections; and (ii) challenges around handling the wide range of relevant scales and computation demands.

Aquatic foods: inclusion of aquaculture and inland fisheries

Aquatic foods are increasingly recognized as offering an environmentally efficient form of animal protein with critical benefits for human health (Crona *et al*., 2023). Currently 51 percent of global fish production comes from aquaculture (37 percent marine and 63 percent inland) (FAO, 2024). To date, FishMIP ecosystem ensembles have not explicitly been used to examine risks to and from aquaculture production under future scenarios, but this is a crucial part of future work. The impacts of climate change on aquaculture have been examined using different approaches (e.g. habitat suitability, individual growth, and bioenergetic models) (Froehlich, Gentry and Halpern, 2018; Fuentes-Santos *et al*., 2021; Klinger, Levin and Watson, 2017; Barange *et al*., 2018). Similar to FishMIP models, these approaches require outputs from Earth system models to be translated to spatial and temporal scales that are relevant for coastal mariculture and inland aquaculture (Falconer *et al*., 2020). However, for a comprehensive picture of climate risk, improved knowledge on where current aquaculture activities take place, and accounting for the interconnected reliance on resource use among fisheries, agriculture, aquaculture via feed ingredients, water, and land/sea use is required. Inland fisheries remain a challenge due to their data-limited nature and the difficulties of capturing inland systems using Earth system models (Paukert *et al*., 2017).

Integrated assessments of terrestrial, freshwater and marine food systems

While cross-sectoral work through ISIMIP enables consistent comparison across sectors, further work is needed on addressing the interconnections among sectors and the terrestrial, freshwater and marine ecosystems they are embedded in. Integrated assessment models are beginning to recognize the need to include marine and freshwater fisheries components; this would enable questions of resource competition, driven by socioeconomic and climate scenarios, to be addressed across these sectors. While challenging, capturing these linkages will help to ensure a more complete consideration of the trade-offs associated with changes in human diets on planetary health and biodiversity, particularly in the context of the Blue Transformation (Bennett *et al*., 2021; Cottrell *et al*., 2018, 2019; Farmery *et al*., 2021).

Data and code availability

Code to produce summary data used for the creation of this report and associated code is available here: DOI 10.5281/zenodo.12528168

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Appendices

TABLES

TABLE A1.

FishMIP global marine ecosystem models and their characteristics

Marine ecosystem model	Model type	Key forcing variables	Taxonomic groups included	Key references
APECOSM	Composite (size- and trait-based; functional group structure)	Carbon concentrations (small phytoplankton, large phytoplankton, small zooplankton, large zooplankton), particulate organic matter (small and large), zonal and meridional currents, turbulent mixing, temperature, water density, dissolved oxygen concentration, light irradiance. All fields 3D and monthly.	Epipelagic fish, migratory mesopelagic fish, resident mesopelagic fish	Maury, 2010
BOATS	Size-based	Mean temperature 0–75 m, NPP	All commercially fished species, both finfish and invertebrates	Carozza, Bianchi and Galbraith, 2017, 2016
DBEM	Species distribution model	Surface and bottom O_2, pH, salinity and temperature. Ice cover, current velocity, NPP, NPP picoplankton[5] and NPP diatoms. All variables on a yearly basis.	956 species of exploited fishes and invertebrates	Cheung *et al*., 2010
DBPM	Composite (size- and trait-based)	Surface and bottom temperature, phytoplankton carbon groups	All benthic and pelagic marine animals weighing between 1 mg and 1 tonne	Blanchard *et al*., 2012
EcoOcean	Composite (tropho-dynamic and species distribution model)	SST, seafloor temperature, column average temperature, phytoplankton carbon groups	Includes 51 functional groups representing the whole spectrum of marine organisms from bacteria to whales, and integrates explicit information for 3 400 species of vertebrates, invertebrates and primary producers	Christensen *et al*., 2015
EcoTroph	Trophic-level-based	NPP, SST, integrated mesozooplankton[4] carbon	Implicitly all groups, including pelagic and demersal fishes and invertebrates	Gascuel, Guénette and Pauly, 2011
FEISTY	Composite (size- and trait-based)	Seafloor temperature, seafloor detritus flux, mean temperature 0–100 m, integrated mesozooplankton carbon 0–100 m	Small pelagic fish, large pelagic fish, demersal fish, benthic invertebrates	Petrik *et al*., 2019
Macro-ecological	Size-based	NPP, SST	Implicitly all marine organisms from 1gram to 1 tonne	Jennings and Collingridge, 2015
ZoomSS	Composite (size- and trait-based; functional group structure)	Chlorophyll-a, SST	Flagellates, cilliates, omnivorous copepods, carnivorous copepods, larvaceans, salps, chaetognaths, euphausiids, jellyfish, fish	Heneghan *et al*., 2020

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[4] Mesozooplankton: planktonic (aquatic organisms unable to propel against currents) animals in the size range of 0.2–20 mm

[5] Picoplankton: planktonic organisms in the size range of 0.2 to 2 µm

TABLE A2.

Types of regional marine ecosystem models contributing to FishMIP, their main characteristics, the climate inputs needed to force these models and example areas where they have been applied.

Ecosystem model	Input forcings	Climate and socio-economic inputs	Comments	Example areas
Atlantis	End-to-end ecosystem model considering the biophysical, economic and social dimensions.	Sea water potential temperature, sea water salinity, sea water X velocity, sea water Y velocity, fishing effort or mortality Optional: Dissolved oxygen concentration, pH, mole concentration of diatoms, diazotrophs, picophytoplankton	Fully three-dimensional data is input into the model as raw values averaged over the different Atlantis model boxes and depth layers	California Current, Chatham Rise, East Antartica, Nordic and Barents Sea, Puget Sound, southern Benguela, southeast Australia, Tasman and Golden Bays
Ecopath with Ecosim (EwE)	Trophic-based model including three components: Ecopath – a static, mass-balanced snapshot of the system; Ecosim – a time dynamic simulation module for policy exploration; and Ecospace – a spatial and temporal dynamic module primarily designed for exploring impact and placement of protected areas	Sea water potential temperature, primary organic carbon production by all types of phytoplankton, fishing effort or mortality Optional: Sea water salinity, dissolved oxygen concentration	Temperature is input as raw values, averaged over the whole model area for Ecosim and the model grid for Ecospace	Baltic Sea, Bering Sea, California Cur-rent, Chatham Rise, Cook Strait, Gulf of Alaska, Kerguelen Plateau, Mediterrane-an Sea, North Sea, northeastern Brazil, southern Benguela, southeast Australia, Tasman and Golden Bays
Mizer	Dynamic multispecies size-spectrum models of fish communities	Sea water potential temperature, mole concentration of diatoms, diazotrophs, picophytoplankton, mesozooplankton and microzooplankton, fishing effort or mortality	Temperature is input as raw values, averaged over various depth ranges (based on species' vertical behaviour) and over the model area	Baltic Sea, Chatham Rise, Bering Sea, Eastern Scotian Shelf, Gulf of Alaska, Hawai'i-based longline fishery, Kerguelen Plateau, North Sea, Prydz Bay, southeast Australia, Tasman and Golden Bays
OSMOSE	Multispecies and individual-based model (IBM) which focuses on fish species	Sea water potential temperature, primary organic carbon production by all types of phytoplankton, mole concentration of diatoms, diazotrophs, picophytoplankton, mesozooplankton and microzooplankton, dissolved oxygen concentration, fishing effort or mortality Optional: Sea water salinity	Inputs need to be spatially explicit and interpolated to the OSMOSE grid	Northern Humboldt, North Sea

TABLE A3.

FishMIP ensemble model outputs in relation to ecosystem indicators and relevance to Sustainable Development Goals (SDGs). The last column shows the number and list of models producing the output.

Model output	Ecosystem Indicators	Relevance to SDGs	Number and list of models
Total consumer (marine animal) biomass	Marine animal biomass	13, 14	9 APECOSM BOATS DBPM DBEM EcoOcean EcoTroph FEISTY MACRO-ECOLOGICAL ZooMSS
Total Biomass in log10 size categories	Exploitable fish biomass (10 g to 100 kg), size spectrum slope, proportion of fish > 100 g	13, 14, 2, 8, 12	6 APECOSM BOATS DBPM EcoTroph MACRO-ECOLOGICAL ZooMSS
Total demersal biomass in life history categories	Demersal biomass Benthic:pelagic ratio	13, 14	3 DBPM EcoOcean FEISTY
Total pelagic biomass in life history categories	Pelagic biomass Benthic:pelagic ratio	13, 14	4 DBPM EcoOcean FEISTY ZooMSS
Total catches	Catch production	13, 14, 2, 8, 12	2 BOATS EcoOcean
Total catches in log10 size bins	Catch size spectrum, Large fish catch, Forage fish catch, Proportion of large/ small fish in catch	13, 14, 2, 8, 12	1 BOATS
Total demersal catches in life history categories		13, 14, 2, 8, 12	1 EcoOcean
Total pelagic catches in life history categories		13, 14, 2, 8, 12	1 EcoOcean

TABLE A4.

Ensemble mean percentage change in exploitable fish biomass and standard deviation (sd), as well as model agreement (agr) in the direction of change by mid-century (2041–2050) and end of century (2091–2100) compared to the reference decade (2005–2014), under the low and high emissions scenarios, by country, area and territory. Values in bold indicate significant difference in the two scenarios' projections in terms of end-of-century changes (2091–2100) relative to the reference period (2005–2014) ($p < 0.05$, Wilcox statistical test).

Continent	Country and Territory	Mid century SSP1-2.6			Mid century SSP5-8.5			End century SSP1-2.6			End century SSP5-8.5		
		mean	sd	agr	mean	sd	agr	mean	sd	agr	mean	sd	agr
Africa	Algeria	-4.5	7.4	80	-0.7	8.6	70	-9.7	5.5	90	**-15.7**	17.5	80
Africa	Angola	-13.8	8.5	100	**-24.6**	10	100	-4.7	15.4	70	**-38.6**	14.3	100
Africa	Ascension	-7.8	3.4	100	**-13.3**	8	100	-4.6	5.8	90	**-20.8**	11.9	100
Africa	Bassas da India	-7.5	10	80	-9.5	16	90	-2.3	8.1	50	**-11.7**	26.2	60
Africa	Benin	-7.6	3.6	100	**-13.3**	8.2	100	-1.4	5.1	60	**-21.9**	9.3	100
Africa	Bouvet Island	-1	4.4	70	-0.8	3.9	70	-4.5	5.3	80	**-9.5**	11.4	80
Africa	Cabo Verde	-6.3	11.9	60	-7.4	8.6	90	-6.3	13	50	**-23.3**	12.9	90
Africa	Cameroon	-4.4	5.8	75	**-9.3**	8.6	88	-0.8	6.3	62	**-19.2**	6.3	100
Africa	Comoros	-2	11.2	50	-4.5	15.7	60	0.9	8.9	50	**-9.3**	23.4	70
Africa	Congo	-7.3	5.5	90	**-14.2**	8.6	100	-3.1	6.1	50	**-26.1**	9.8	100
Africa	Côte d'Ivoire	-10.7	4.3	100	**-15.9**	7.8	100	-5.7	2.5	100	**-30.1**	10.6	100
Africa	Democratic Republic of the Congo	-9.4	4.9	100	**-15.4**	7.8	100	-4.6	6.3	60	**-29.9**	9.2	100
Africa	Djibouti	-4.7	4.1	75	-6.2	7.5	75	-2.9	4.8	75	**-24.4**	7.8	100
Africa	Egypt	16.5	11.1	100	**0**	5.9	60	18.2	16.7	90	**-17.4**	22.4	70
Africa	Equatorial Guinea	-9.8	5.6	100	**-17.4**	9	100	-4.3	7.6	60	**-28.6**	9.8	100
Africa	Eritrea	-10	9.6	90	-12.1	10.9	100	-7.8	13.5	80	**-21.3**	16	90
Africa	Gabon	-8.9	4.3	100	**-15.2**	8.1	100	-5	5.9	70	**-26.2**	6.7	100
Africa	Gambia	-14.2	7	100	-19.2	6.2	100	-7.2	6.3	100	**-36.3**	11.8	100
Africa	Ghana	-11.2	4.1	100	**-17.3**	5.8	100	-3.3	4.4	70	**-28.5**	7.6	100
Africa	Guinea	-8.1	4.2	100	**-11.9**	7	90	-4.1	4.7	90	**-23.4**	12.2	90
Africa	Guinea-Bissau	-11.1	7	90	-14.7	7.7	90	-5.5	7.8	90	**-29.3**	12.8	100
Africa	Juan de Nova Island	-5	9.2	60	-6.3	15.6	60	-1.2	7.8	50	-5.6	29.1	60
Africa	Kenya	-4	8.1	80	-3.2	7.1	70	0.3	5	60	**-20.9**	9.9	100
Africa	Kerguelen Islands	-4.6	4.6	90	-6	5.6	90	-7.3	5.3	90	**-16.9**	13.9	90
Africa	Liberia	-13.2	5.3	100	**-17**	5	100	-9.7	4	100	**-30.1**	11.2	100
Africa	Libya	5.3	12.4	50	**-0.3**	13.6	60	7	21.8	60	**-24.6**	8.5	100
Africa	Madagascar	-4.1	5.7	70	-4.5	13.2	50	0.8	9.3	50	**-10**	23.1	60
Africa	Mauritania	-10.7	6.2	90	-13.2	5.6	100	-8.7	6.4	90	**-28.7**	12.6	100

Africa	Mauritius	-3.5	9.1	50	-2.7	12.3	60	-5.1	11.2	50	-7.9	21.4	60
Africa	Morocco	2.8	11.1	60	**15.9**	14.4	90	-9.4	10.5	80	**17.7**	47.7	60
Africa	Mozambique	-5.2	5.2	90	-6	8.4	80	-0.4	6.7	50	**-9.8**	23.6	60
Africa	Namibia	-12.2	12.4	100	**-18.8**	14.6	100	-9.2	15.4	60	**-32.7**	20.4	100
Africa	Nigeria	-7.2	3.1	100	**-11.3**	9.3	90	-2.4	5.1	70	**-21.3**	5.6	100
Africa	Prince Edward Islands	-2.8	3.6	80	**-4.8**	5.5	80	-7.6	4.9	100	**-15.9**	15.2	70
Africa	Réunion	-3.9	10.2	50	-0.9	19.8	60	-1.2	13.1	50	1.5	36.4	60
Africa	Saint Helena	-8.7	4.5	100	**-13.1**	7.1	100	0.6	13.5	70	**-23.8**	10.4	100
Africa	Sao Tome and Principe	-8.6	5.4	100	**-14.5**	8.7	100	-3.9	6.2	70	**-22.8**	10.1	100
Africa	Senegal	-16	7.4	100	-20.4	6.7	100	-8.7	7.8	90	**-38.5**	12.8	100
Africa	Seychelles	-4.4	8.9	70	-6.8	9.9	90	-3.6	7.6	50	**-20**	12	100
Africa	Sierra Leone	-10.1	6.7	100	-12.2	5.8	100	-7.2	6.3	100	**-26.1**	12.3	100
Africa	Somalia	-6.2	4.5	90	**-8.3**	3.9	90	-4.4	5.2	70	**-27.3**	8.8	100
Africa	South Africa	-6.5	8.4	70	-8	8.3	90	-3.2	11.7	50	**-14.4**	13	90
Africa	Sudan	-15.1	6.2	100	**-17.8**	6.4	100	-12.2	5.4	100	**-41**	6.8	100
Africa	Togo	-11.4	5.5	100	**-16.5**	7.7	100	-1	6.7	60	**-24.7**	9.6	100
Africa	Tristan da Cunha	0.4	7.9	50	**-4.4**	6.4	80	5.1	12.2	60	**-15.8**	7.9	100
Africa	Tunisia	0.9	12.3	50	**-4**	12.4	60	-0.3	11.6	50	**-22.5**	17.3	90
Africa	United Republic of Tanzania	-3.5	11.1	50	-4.3	11.7	70	0.7	8.7	50	**-17.7**	16.3	100
Americas	Anguilla	-0.1	3.9	60	0.8	10	60	3.7	5.6	70	**1.8**	19.6	50
Americas	Antigua and Barbuda	-3.5	3.9	90	-2.2	7.2	60	0.9	5.2	60	**-5.8**	13	60
Americas	Argentina	-5.2	4.4	90	**-6.5**	5.8	80	-6.8	5.8	90	**-17.8**	15.2	90
Americas	Aruba	-8.1	12.4	70	-8.4	8.5	70	-5.8	10.9	60	**-13.4**	18.7	70
Americas	Bahamas	2.4	8.3	50	**-6.2**	9.1	70	3.6	7.3	70	**-6.2**	12.3	80
Americas	Barbados	-9.6	5.2	100	-11.4	6.4	90	-6.8	4	90	**-11.1**	13.3	90
Americas	Belize	-4.1	9.6	60	-6.5	9.6	70	-1.8	9.3	50	-5.4	21.2	60
Americas	Bermuda	-3.1	12.6	60	**-11.1**	13.6	80	2.9	15.8	50	**-25.3**	20.4	100
Americas	Bonaire	-9.9	12.2	70	-11.9	7.3	100	-10.9	11.6	70	**-20.3**	14.9	90
Americas	Brazil	-5.8	1.5	100	-7.3	2.4	100	-2.7	3.1	70	**-17.2**	7.9	100
Americas	Brazil (Trindade)	-9	6.2	90	**-2.2**	5.4	70	2.4	4.2	80	4.8	15.2	50
Americas	British Virgin Islands	4.4	5.2	70	4	12.7	50	7.8	6.1	80	8.3	23	50
Americas	Canada	-5.5	2	100	-5	3	100	-4.1	6.6	70	**-16.9**	11	90
Americas	Cayman Islands	-9.3	7.1	90	-8.9	5.4	90	-6.8	5.1	90	-13	16.1	70
Americas	Chile	-6.4	3.2	100	-6.1	3.7	100	-9.3	5.3	100	**-20.2**	12.6	100
Americas	Chile (Easter Island)	0	7.9	60	2	10.3	50	-0.5	7.3	50	**-9.8**	26.4	70

Americas	Chile (San Felix and San Ambrosio islands)	-1.6	7.9	50	**1.9**	4.6	60	-2.8	8.6	50	-0.7	11.1	70
Americas	Colombia	-7.2	13.1	70	-6.7	8	80	-8.5	9.5	70	**-20.1**	19.6	90
Americas	Colombia (Serrana)	-4.8	13.3	50	-5.7	10	60	-3.7	12.8	50	**-12.4**	20.8	60
Americas	Costa Rica	-13.2	16.4	80	-9.8	14.5	80	-13.6	12.8	100	**-31.4**	26.9	90
Americas	Cuba	-4.8	4.5	100	**-7.3**	3.2	100	-4.8	5	90	-5.8	15.7	70
Americas	Curaçao	-8.3	12.2	60	-10.6	6.3	100	-7.9	12.2	60	**-19.1**	17.6	90
Americas	Dominica	-10.1	8.3	90	-8.8	7.9	90	-3.5	4.4	70	**-10.5**	12.6	70
Americas	Dominican Republic	2.3	7.7	50	2.1	9.3	50	4.1	5.6	70	**0.9**	18.6	50
Americas	Ecuador	-6.6	9.7	70	**-11.9**	10.1	100	-10.9	8.5	100	**-41.8**	21.2	100
Americas	Ecuador (Galapagos)	-7.9	5.7	90	-8.9	6.4	90	-9.4	6	100	**-38.1**	18.5	100
Americas	El Salvador	-14.3	16.2	90	-14.6	12.5	100	-12.6	8.6	100	**-34.7**	22.2	100
Americas	French Guiana	-4.6	10.9	60	-6.7	10.6	90	-0.9	15.8	60	**-3**	42.4	70
Americas	Greenland	-5.3	4.1	90	**-2.1**	6.8	70	-4.4	7.8	80	**-19.2**	10	100
Americas	Grenada	-5.1	9.8	80	-7.9	6.5	90	1.1	16.9	60	**-9.5**	22.8	90
Americas	Guadeloupe	-7.8	5.8	90	-7.4	7.6	90	-2.6	3.7	70	**-9.7**	11.7	90
Americas	Guatemala	-13.3	13.3	90	-15	10.8	100	-13	6.4	100	**-34.8**	18.5	100
Americas	Guyana	-7.2	7.2	90	**-9.7**	10.1	90	-4.2	9.3	90	**-7.8**	32.6	90
Americas	Haiti	-3.1	6.6	60	-3.4	5.2	80	-1.1	4.5	50	-2.3	18	50
Americas	Honduras	-5.5	10.3	70	-6.2	9.2	60	-3.3	9.4	60	**-9.4**	21.4	60
Americas	Jamaica	-5.7	8.6	70	-5.3	6.3	70	-2.7	4.2	60	-7.8	16.6	50
Americas	Martinique	-9.7	5.6	100	-10.1	6.1	90	-3.7	4	70	**-10.2**	11.5	90
Americas	Mexico	-7.1	3.8	100	-8.7	4.1	100	-9.1	4	100	**-16.6**	7.8	100
Americas	Montserrat	-7.6	7.2	90	-5.3	8.9	90	-2.1	6.2	60	**-7**	14.4	60
Americas	Nicaragua	-11.9	16.6	70	-12.2	12.9	90	-10.8	11.5	80	**-28.6**	22.1	100
Americas	Panama	-9	13.3	70	-8.3	10.9	70	-10.6	10.1	90	**-22.3**	20.6	80
Americas	Peru	-6	5.7	80	**-10**	7.1	90	-8.3	6.5	100	**-37.3**	20.4	100
Americas	Puerto Rico	-1.5	8.1	60	-1.4	9.6	60	1.5	6.5	50	**-1.3**	18.9	50
Americas	Saba	-4.8	5.6	70	-3.4	7.6	70	-0.1	4.7	70	**-3.8**	15.7	50
Americas	Saint Kitts and Nevis	-5.6	5.2	90	-3.8	7.7	80	-0.3	5.3	60	**-5.2**	14.6	60
Americas	Saint Lucia	-9.7	5.5	100	-11.2	5.8	100	-4.3	6.7	80	**-11**	14.5	90
Americas	Saint Pierre and Miquelon	-7.1	4.4	100	**-14.3**	6.6	100	-9.7	4.4	100	**-36.5**	15.9	100
Americas	Saint Vincent and the Grenadines	-7.9	6.6	90	-9.1	5.7	100	-2.2	11.1	80	**-9.2**	18.2	90
Americas	Suriname	-5.4	10.2	70	-7.7	11	90	-1.6	15.3	60	**-3.6**	43.7	90

Americas	Trinidad and Tobago	-8.7	9.9	90	-9.2	12.9	90	-7.3	12.8	90	**-9.4**	39.6	90
Americas	Turks and Caicos Islands	10.3	8.6	80	**6.5**	6.9	80	17	27.8	80	**12.1**	25.8	60
Americas	United States of America	-6.1	4.5	90	-7.3	6.1	90	-5.7	6.6	90	**-19.2**	13.6	90
Americas	United States of America (Alaska)	-9.3	4.5	100	**-12.9**	8	100	-11.6	4.4	100	**-33.5**	16.7	100
Americas	United States of America (Hawai'i)	-12.1	5.5	100	-16	9.3	100	-11.2	4.7	100	**-26.6**	17.6	100
Americas	United States Virgin Islands	-5.5	9.4	70	-4.1	9	70	-1.3	7.8	70	-4.5	18.1	50
Americas	Uruguay	-5.5	4.6	90	**-9**	7.9	90	-9	8.1	80	**-34**	18.9	100
Americas	Bolivarian Republic of Venezuela	-7.3	12.8	60	-8.8	7.7	90	-5.9	11.4	60	**-13**	19.6	70
Asia	Andaman and Nicobar Islands	-1.4	2.9	70	**-3.9**	4.3	80	-5.3	4	90	**-14.5**	6.5	100
Asia	Azerbaijan	-0.4	2.1	75	**-5.9**	3.7	100	-3.3	5.4	75	**-24.1**	13.7	100
Asia	Bahrain	-15.8	2.9	100	**-19.4**	2.3	100	-15.3	4.9	100	**-34.7**	7.4	100
Asia	Bangladesh	-4.4	3.7	90	-3.3	3.7	80	-1.7	2.7	80	**-11.6**	8.5	90
Asia	Brunei Darussalam	-7.8	3	100	**-10.3**	4.7	90	-8.6	2.3	100	**-25.6**	6.4	100
Asia	Cambodia	-3.9	5.3	90	-6.5	7.2	100	-5.3	6.6	90	**-16.5**	5.7	100
Asia	Chagos Archipelago	-9.4	6.3	90	**-14**	10.2	100	-13.7	4.8	100	**-32.5**	11.1	100
Asia	China	-11.1	3.6	100	-10.7	4.9	100	-8.7	4.3	100	**-30.7**	13.5	100
Asia	Cyprus	18.4	12.3	90	**2.8**	8	60	20.5	27.3	60	**-18.6**	24.1	90
Asia	Democratic People's Republic of Korea	-5.3	9.1	70	**-10.4**	10.4	80	-13.5	7.8	100	**-32.3**	26.1	90
Asia	India	-7.2	3.5	100	**-8.7**	2.5	100	-9.3	3.8	100	**-19.6**	8.1	90
Asia	Indonesia	-8.7	6.6	90	**-12.4**	6.3	100	-9.1	5.7	100	**-24.9**	12.3	100
Asia	Islamic Republic of Iran	-15	21.4	100	**-18.8**	19.5	100	-17.1	20.9	100	**-34.9**	14.1	100
Asia	Iraq	-8.4	4	100	**-15.4**	6.9	100	-14.7	4.4	100	**-63**	7.5	100
Asia	Israel	14.5	14.5	90	**4.9**	9.6	70	19.8	32.6	70	**2.1**	38.2	50
Asia	Japan	-7.8	4.9	100	-9.8	5.5	90	-7	5.1	100	**-32.4**	14.7	100
Asia	Jordan	-5.7	4	100	-9.8	3.1	100	-6.7	2.6	100	**-24.7**	6.9	100
Asia	Kazakhstan	-0.6	0.7	75	-3.4	4.4	75	-4.2	5.2	75	**-19.6**	16.6	75
Asia	Kuwait	-14.1	4.5	100	**-25.6**	4.9	100	-24.6	6.4	100	**-69**	4.1	100
Asia	Lebanon	15.3	14.7	80	**7.8**	11.5	80	19	30	60	**7.4**	42.3	50
Asia	Malaysia	-8.5	3.7	100	-9.5	3.5	100	-8	3.3	100	**-23.7**	4.9	100
Asia	Maldives	-7.9	3.6	100	-9.5	5.9	90	-11.5	5.3	100	**-19.4**	9.8	90

Asia	Myanmar	-3.3	3.7	80	-2.9	3.5	70	-3.2	4.3	80	**-11.7**	7.9	90
Asia	Oman	-11.1	7.7	90	-13.9	6.7	100	-10.4	8.3	90	**-33**	13.7	100
Asia	Pakistan	-8.1	6.6	90	**-11.1**	5.6	90	-10	6.3	100	**-20.8**	11.8	90
Asia	Philippines	-6.6	4.7	90	-8.1	8.1	90	-6.7	4.8	90	**-23.1**	12.6	100
Asia	Qatar	-14.8	25.8	90	**-16.6**	25	100	-14.8	25.2	100	**-32.2**	22.3	100
Asia	Republic of Korea	-8.7	6.2	90	**-11.7**	8.4	90	-7.7	3.9	100	**-30.7**	19.8	90
Asia	Saudi Arabia	-4	7.3	50	**-8**	6.3	100	-5.3	6	70	-13.2	23.9	60
Asia	Sri Lanka	-10.6	5.9	100	**-13.3**	6	100	-14.5	6.8	100	**-26.2**	9.4	100
Asia	Syrian Arab Republic	11.5	14.7	90	**-0.4**	12.8	60	10.4	22	70	**1.1**	44.3	50
Asia	Taiwan Province of China	-15.2	7.8	100	-14.4	5.7	100	-11.2	4.1	100	**-32.6**	10.9	100
Asia	Thailand	-2.5	4.7	70	-2.3	4.8	80	-4.7	5.4	80	**-14.4**	11.3	90
Asia	Timor-Leste	-5	6.3	70	-7.8	5.9	90	-5.8	5.4	90	**-13.3**	12.4	80
Asia	Türkiye	-4.8	4.6	90	-3.9	5.9	80	78.5	261.6	60	**47.4**	154.1	80
Asia	Turkmenistan	-0.2	3.1	75	**-4.9**	3.3	100	-2.4	5	75	**-26.4**	10.6	100
Asia	United Arab Emirates	-18.7	24	100	**-22.2**	23	100	-19.9	23.6	100	**-38.7**	19.2	100
Asia	Viet Nam	-10.1	4.1	100	-11.6	4.2	100	-8.4	5	100	**-22.7**	9	100
Asia	Yemen	-7	7.2	90	**-9.5**	4.5	100	-6	7.4	70	**-26.8**	10.8	100
Europe	Albania	10.3	6.6	100	**4.7**	9	67	11.3	6.8	100	**-33.7**	8.8	100
Europe	Belgium	-3.9	6.1	88	**-9.5**	8.7	88	-9.3	11.8	62	**-20.6**	16.2	100
Europe	Bulgaria	-5.9	5.7	80	-5.5	4.9	80	10.5	57.6	70	**2.9**	50.4	80
Europe	Canary Islands	3.5	13.1	50	**10.2**	16	70	-1.8	11.4	60	**20.1**	39.4	60
Europe	Croatia	-7	9.3	70	-7.3	9.8	80	-13.6	18.2	60	**-24.6**	15.5	100
Europe	Denmark	-7.6	6.3	100	-6.4	7.7	80	-8.6	8.4	100	**-21.4**	12.5	90
Europe	Estonia	-4.9	10.9	60	**-1.1**	7.4	60	-3.2	11.1	60	-7.2	18.6	50
Europe	Faroe Islands	-5.6	6.3	80	**0.9**	13.9	50	-2.2	13.2	60	**-23.3**	14.3	90
Europe	Finland	2.4	10.9	50	**5.9**	9	70	3.1	13	50	3.6	21.8	60
Europe	France	-8.6	8.3	100	**-3.7**	3.1	90	-7.4	6.7	90	**-28.2**	11.1	100
Europe	Georgia	-6.4	13.1	70	**3.1**	14.1	60	16.8	64.1	70	**61.1**	216.5	70
Europe	Germany	-2.4	2.5	80	**-4.6**	4.7	80	-3.2	3.8	80	**-16.9**	13.3	100
Europe	Greece	12.8	6.9	90	**-0.2**	6.7	60	10.7	11.4	80	**-21.8**	11.3	100
Europe	Guernsey	-12.4	6.1	100	-10.2	5.1	100	-18	4.9	100	**-30.6**	15	90
Europe	Iceland	-5.3	5.5	90	**-1.2**	10.8	60	-5	8.5	70	**-25.1**	9.2	100
Europe	Ireland	-12.1	7.1	100	**3.4**	11.4	60	-9.1	5.1	100	**-33.6**	6.1	100
Europe	Italy	10.7	9.9	80	**-1.4**	13.6	60	12.4	12.4	80	**-17.8**	14.7	90
Europe	Jan Mayen Island	-12	7.2	100	-12.8	10.7	90	-14.5	9.9	90	**-35.8**	10.8	100
Europe	Latvia	-3.6	8.1	60	-2	5.8	60	-3.3	6.3	70	**-10.9**	16.7	70

Europe	Lithuania	-2.5	4.4	80	-3.9	5.4	80	-2.3	3.3	70	**-13.9**	16.2	80
Europe	Madeira Islands	-12.5	11.4	90	-12.2	14.8	90	-26.6	19.1	100	**-19.2**	44.1	80
Europe	Malta	3.8	15.6	50	0.5	17.5	60	8.9	31.4	50	**-21.8**	12.5	90
Europe	Montenegro	4.4	4.8	90	**-1.6**	5.7	60	-2.6	7.4	60	**-18.3**	21.7	80
Europe	Kingdom of the Netherlands	-3.3	5.1	70	**-6.9**	4.7	90	-7.4	8	80	**-23.8**	14.9	100
Europe	Norway	-8.4	2.3	100	**-4.2**	7.3	80	-9.2	7.2	90	**-27.8**	10.3	100
Europe	Poland	-2.9	4.9	70	-3.3	5.9	70	-3.2	5.5	60	**-14.3**	17.7	80
Europe	Portugal	-11.1	5.6	100	**-4.4**	7.4	70	-23.4	7.1	100	-26	29.4	90
Europe	Portugal (Azores Islands)	-25	14.1	100	**-29.4**	11.1	100	-28.6	4.4	100	**-60.4**	12	100
Europe	Romania	-2	2.4	70	-3.8	5.4	80	-0.5	6	60	**-4**	34.5	70
Europe	Russian Federation	-2	2.9	70	**-4.1**	4.1	80	-5.1	4.6	90	**-19.7**	11.9	100
Europe	Spain	-15.6	14.9	100	**-2.5**	4.9	60	-15.3	8.7	100	**-35.6**	10.5	100
Europe	Svalbard Islands	-5.2	7.2	80	-3.8	10.2	60	-6.8	13.4	50	**-22.2**	13.5	90
Europe	Sweden	-1.7	6.4	50	**1.4**	5.9	60	-1.1	9	60	-2.3	16.3	50
Europe	United Kingdom of Great Britain and Northern Ireland	-8.2	4.5	100	**0.1**	7.6	60	-5.9	6.2	90	**-23.8**	10	100
Oceania	American Samoa	-10.2	8.2	100	**-14.4**	11	100	-7.7	7.2	90	**-28**	25.7	90
Oceania	Australia	-4.2	3.9	90	**-9.8**	3.3	100	-5.2	3.4	100	**-23.6**	10.8	100
Oceania	Australia (Macquarie Island)	-8.6	5.9	100	-7.9	6.1	90	-12.9	8	90	**-18.4**	12.9	80
Oceania	Christmas Island	-6.5	7	80	-9.5	6.9	100	-6.2	7.1	80	**-18.7**	18.1	70
Oceania	Clipperton Island	-4.3	11.4	50	-6.1	9.5	70	-3.3	9.9	70	**-28.3**	17	100
Oceania	Cocos (Keeling) Islands	-7.4	5.5	90	-9.5	6.1	100	-9.1	8	100	**-19.9**	16.4	100
Oceania	Cook Islands	-4.7	6.1	80	**-9.1**	6.3	100	-2.7	4.4	70	**-26.7**	21.9	100
Oceania	Fiji	0.7	11.8	50	**-5.5**	16.6	50	-2.7	13.8	50	**-19.6**	29.1	60
Oceania	French Polynesia	-6.2	4.6	100	**-10.4**	7.5	100	-3.5	2.8	80	**-28.3**	18.9	100
Oceania	Guam	-0.9	17.3	50	-2.3	18.4	60	-6.3	10.2	70	2.6	53.1	50
Oceania	Heard Island and McDonald Islands	-3.7	2.9	80	-4	3.3	80	-6.8	3.9	100	**-15.1**	10.9	90
Oceania	Howland Island	-5.3	3.3	100	-3.2	6.1	70	-3.1	4.7	80	**-31.3**	17.4	90

Oceania	Jarvis Island	-7.6	3.3	100	-6	6.1	90	-5.4	4.9	90	**-27**	20.9	90
Oceania	Johnston Atoll	-7.7	16.8	60	-7.3	13.5	50	-8.6	12.4	70	-13	38.1	60
Oceania	Kiribati (Gilbert Islands)	-6.5	3.2	100	-4.2	5.2	80	-2.4	5.8	70	**-39.5**	15.7	100
Oceania	Kiribati (Line Islands)	-3.3	2.2	100	-4.9	6.1	80	-2.3	3.4	70	**-26.6**	20.1	90
Oceania	Kiribati (Phoenix Islands)	-6.1	2.9	100	-5.7	6.3	90	-3.9	3.5	90	**-38.2**	15.3	100
Oceania	Marshall Islands	-6.1	11	50	**-10.5**	7.7	90	-8	6	100	**-29.7**	24.8	80
Oceania	Federated States of Micronesia	-10.9	10.9	90	**-15.6**	7.5	100	-9.3	9	90	**-40.7**	23.9	100
Oceania	Nauru	-8	3.2	100	-6.9	4.5	100	-4.7	6.6	70	**-46.4**	18	100
Oceania	New Caledonia	-2.8	6.9	50	**-11.4**	12.3	90	-6.3	11.5	50	**-29**	22.3	100
Oceania	New Zealand	-5.7	3.2	90	**-9.6**	2.8	100	-7.7	4.6	90	**-26.2**	8	100
Oceania	Niue	-2	8.5	50	-5.8	12.6	60	-4.1	9	50	**-17.9**	27.8	80
Oceania	Norfolk Island	-3.1	5.7	90	**-17.6**	11.7	100	-4.5	5.7	90	**-38.6**	19.9	100
Oceania	Northern Mariana Islands	0.2	9.6	50	-2.1	16.4	50	-0.8	7.2	60	-0.9	47.2	50
Oceania	Palau	-12.8	16.4	80	**-20.1**	12.1	100	-13.1	12.9	90	**-41.6**	23.7	100
Oceania	Palmyra Atoll	-4.3	4.1	90	-5.3	10.8	60	-4.7	4.4	80	**-31.8**	9.6	100
Oceania	Papua New Guinea	-12.5	8.8	100	**-16.5**	9.4	100	-11.3	13.3	90	**-50.5**	19.3	100
Oceania	Pitcairn Islands	-7.8	6.9	90	-7.9	13.7	70	-4.8	2.8	100	-12.9	26.9	60
Oceania	Samoa	-10.9	8.2	100	**-15.5**	12.4	100	-9.6	8.2	100	**-28.7**	26.6	90
Oceania	Solomon Islands	-13.2	6.3	100	-16.3	12.9	100	-12.9	11.5	100	**-43.5**	25.1	100
Oceania	Tokelau	-11.8	5.8	100	-14	8.5	100	-11.8	5.4	100	**-39.7**	21	100
Oceania	Tonga	3.2	14.6	50	**-5.3**	15.7	50	-2.7	12.9	50	**-26**	21.7	100
Oceania	Tuvalu	-15	6.7	100	-15	6.5	100	-12.1	6.3	100	**-46.5**	21.3	100
Oceania	Vanuatu	-4.9	7.5	90	-8.2	16.5	60	-6.3	13.1	60	**-22.1**	28.7	80
Oceania	Wake Island	-3.5	11.5	50	-4.4	16.6	60	-3.9	11.3	70	-8.9	36.9	50
Oceania	Wallis and Futuna Islands	-12.3	7.1	100	-15.2	12.4	90	-12.1	7.7	100	**-30**	26.2	90

TABLE A5.

List of global marine ecosystem models and modelling groups (names of modellers and their institutions) that provided ISIMIP3b model simulations used in the creation of the FishMIP multi-model ensemble results presented in this report and described in Table A1. Further details can be found here: https://www.isimip.org/impactmodels/. Bold denotes models used to estimate size-based ensemble results shown in Part A.

Marine ecosystem model	Modeller names, contact details, and institution
APECOSM	Olivier Maury: L'Institut de recherche pour le developpement (France) Jonathan Rault: Institut de Recherche pour le Developement (IRD) (France) Laurent Bopp: Laboratoire des Sciences du Climat et de l'Environment (LSCE) (France)
BOATS	Daniele Bianchi: University of California Los Angeles (USA) Eric Galbraith: McGill University (Canada) Jerome Guiet: University of California Los Angeles (USA)
DBEM	William Cheung: Institute for the Oceans and Fisheries, University of British Columbia (Canada) Juliano Palacios-Abrantes: Institute for the Oceans and Fisheries, University of British Columbia (Canada)
DBPM	Julia Blanchard: University of Tasmania (Australia) Camilla Novaglio: Institute for Marine and Antarctic Studies (Australia) Ryan F. Heneghan: Griffith University (Australia)
EcoOcean	Villy Christensen: University of British Columbia (Canada) Marta Coll: Institute of Marine Science (ICM-CSIC) (Spain) Jeroen Steenbeek: Ecopath International Initiative Research Association, Barcelona (Spain)
EcoTroph	Didier Gascuel: AGROCAMPUS OUEST (France) Vianney Guibourd de Luzinais: AGROCAMPUS OUEST (France) Hubert du Pontavice: Institut Français de Recherche pour l'Exploitation de la Mer (France)
FEISTY	Colleen M. Petrik: University of California San Diego (USA)
Macroecological	Ryan F. Heneghan: Griffith University (Australia) Simon Jennings: Centre for Environment, Fisheries and Aquaculture Science, Lowestoft (UK)
ZoomSS	Jason Everett: University of Queensland (Australia) Anthony Richardson: University of Queensland (Australia)

TABLE A6.

List of core cited papers that form part of FishMIP 'Past and Future of Marine ecosystems' Special Issue in *Earth's Future*.

Reference
Blanchard J.L., Novaglio C., Maury O., Harrison C.S., Petrik C.M., Fierro-Arcos L.D., Ortega-Cisneros, K. *et al.* 2024. Detecting, attributing, and projecting global marine ecosystem and fisheries change: FishMIP 2.0. *ESS Open Archive. January 22,* 2024. 10.22541/essoar.170594183.33534487/v1.
Eddy, T.D., Heneghan, R.F., Bryndum-Buchholz, A., Fulton, E.A., Harrison, C.S., Tit-tensor, D.P., Lotze, H.K. *et al.* 2024. Global and regional marine ecosystem model climate change projections reveal key uncertainties. *ESS Open Archive.* 10 May 2024. 10.22541/essoar.171535471.19954011/v1.
Guiet, J., Bianchi D., Scherrer, K.J.N., Heneghan, R.F. & Galbraith, E. 2024. Small fish biomass limits the catch potential in the High Seas. *Authorea*. 5 March 2024. DOI: 10.22541/au.170967563.32290483/v1.
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Novaglio C., Bryndum-Buchholz A., Tittensor D.P., Eddy T.D., Lotze H.K., Harrison C.S., Heneghan R.F. *et al.* 2024. The Past and Future of the Fisheries and Marine Ecosystem Model Intercomparison Project. *ESS Open Archive.* 16 January 2024. 10.22541/essoar.170542252.20348236/v1.
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van Denderen P.D., Jacobsen N., Andersen K.H., Blanchard, J.L., Novaglio C., Stock, C.A., Petrik, C.M. Estimating fishing exploitation rates to simulate global catches of pelagic and demersal fish. *Authorea.* 15 March 2024. DOI: 10.22541/au.171052479.98620369/v1.

Climate change impacts on marine fisheries resources are changing the distribution and productivity of marine organisms around the globe. Knowledge and model projections to estimate fish biomass gains and losses are crucial for informing climate-resilient fisheries management and adaptation planning. This report was developed in collaboration with the Fisheries and Marine Ecosystem Model Intercomparison Project (FishMIP); it presents projections to 2100 of exploitable fish biomass under different climate scenarios, for all countries and territories. The results are based on state-of-the art modelling approaches produced by a global network of marine ecosystem modelers. Investigating the medium- and long-term effects of climate change on global marine ecosystems and fisheries, modellers collaborated to compare existing models worldwide and to produce an ensemble of projections, along with their associated uncertainties, under low and high-emission future scenarios. The report's elements are expected to support countries' efforts in updating their Nationally Determined Contributions to achieve the Paris Agreement goals.

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