The Past and Future of the Fisheries and Marine Ecosystem Model Intercomparison Project

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Key Points:

- There is an urgent need for policy to develop strategies to adapt to the impacts of climate change on ecosystems and their services
- The Fisheries and Marine Ecosystem Model Intercomparison Project has contributed understanding of climate impacts on marine ecosystems
- The next 10 years will see the FishMIP improved ensemble model pushing the boundaries of the field and increasing outputs policy-relevance

Abstract

Climate-driven ecosystem changes are increasingly affecting the world's ocean ecosystems, necessitating urgent guidance on adaptation strategies to limit or prevent catastrophic impacts. The Fisheries and Marine Ecosystem Model Intercomparison Project (FishMIP) is a network and framework that provides standardised ensemble projections of the impacts of climate change and

fisheries on ocean life and the benefits that it provides to people through fisheries. Since its official launch in 2013 as a small, self-organised project within the larger Inter-Sectoral Impact Model Intercomparison Project, the FishMIP community has grown substantially and contributed to key international policy processes, such as the IPCC AR5 and AR6, and the IPBES Global Biodiversity Assessment. While not without challenges, particularly around comparing heterogeneous ecosystem models, integrating fisheries scenarios, and standardising regional-scale ecosystem models, FishMIP outputs are now being used across a variety of applications (e.g., climate change targets, fisheries management, marine conservation, Sustainable Development Goals). Over the next decade, FishMIP will focus on improving ecosystem model ensembles to provide more robust and policy-relevant projections for different regions of the world under multiple climate and societal change scenarios, and continue to be open to a broad spectrum of marine ecosystem models and modellers. FishMIP also intends to enhance leadership diversity and capacity-building to improve representation of early- and mid-career researchers from under-represented countries and ocean regions. As we look ahead, FishMIP aims to continue enhancing our understanding of how marine life and its contributions to people may change over the coming century at both global and regional scales.

1 Introduction

In 2013, the Fisheries and Marine Ecosystem Model Intercomparison Project (Fish-MIP - www.fishmip.org) was officially launched at the 1st Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) cross-sectoral workshop in Potsdam, Germany. This launch filled a crucial gap in ISIMIP's mission "*to improve global and regional risk management by advancing knowledge of the risks of climate change through integrating climate impacts across* *sectors and scales in a multi-impact model framework"* (ISIMIP, n.d.), which until then had only included terrestrial sectors and lacked contributions from the marine realm.

FishMIP tackled this gap through the development of an ensemble modelling framework to quantitatively assess uncertainties across marine ecosystem models and, further, to contribute to a multi-sectoral, multi-scale assessment of climate change impacts. This was and is a novel approach within the marine ecosystem modelling world, as most global studies of climate impacts on marine ecosystems were using single marine ecosystem model approaches of coupled-biophysical models (e.g., Cheung et al, 2011, Blanchard et al. 2012, Barange et al. 2014, Lefort et al. 2015). Using single marine ecosystem models, even if forced by multiple earth-system models (ESMs), limits our ability to quantify and understand the sources and range of uncertainty associated with the different ways ecosystems and fisheries have been conceptualised, mathematically formulated and computationally implemented in models, as there are very different interpretations of how best to integrate ecological processes into modelling frameworks (Tittensor et al. 2018, Lotze et al. 2019, Heneghan et al. 2021). Today, FishMIP comprises 100+ marine ecosystem and climate-impact modellers and contributors from around the world, aiming to collectively fulfil its (still unchanged) mission: "*to bring together diverse marine ecosystem models to help better understand and project long-term impacts of climate change on fisheries and marine ecosystems, and to use our findings to help inform policy"* (www.fishmip.org). Specifically, FishMIP aims to answer questions around the future of fish and fisheries, food security, marine biodiversity and marine ecosystem functioning.

FishMIP's ensemble modelling framework combines simulations from multiple marine ecosystem models, all forced by standardised inputs and scenarios, as defined by a specific project protocol (Tittensor et al. 2018). Such a standardised approach is necessary to make the results comparable and to be able to calculate an ensemble mean and the variation around it. To develop a simulation protocol that works for many different models, and doing so in a collaborative, open way, involves many painstaking steps, discussions, and coordination among climate and ecosystem modellers. The first steps towards the FishMIP 1.0 protocol were taken in 2014 and published in 2018 (Tittensor et al. 2018), followed by publishing the first ensemble results of six global marine ecosystem models in 2019 (Lotze et al. 2019).

The FishMIP 1.0 protocol established the foundational framework for FishMIP modelling efforts (Tittensor et al. 2018). It was specifically designed to support the Intergovernmental Panel on Climate Change (IPCC) and focussed on assessing climate change impacts on marine ecosystems by using heterogeneous marine ecosystem models forced by standardised outputs from two Earth System Models (ESMs), GFDL-ESM2M and IPSL-CM5A-LR, and four Representative Concentration Pathways (RCPs) provided by the Coupled Model Intercomparison Project Phase 5 and 6 (CMIP5 and CMIP6; https://esgf-node.llnl.gov/search/cmip5/; Bopp et al. 2013), and standardised to a common 1° resolution global grid defined by ISIMIP. This protocol will be further developed into the FishMIP 2.0 protocol, which focuses on both climate change and fishing impacts, and extended to consider topics, such as food security, of interest to other policy bodies, including the Food and Agriculture Organization (FAO). Currently, FishMIP has achieved several major milestones and developments along the way that have contributed to scientific understanding and policy applications (Figure 1).

In this review, we chart the development, progress, and applications of FishMIP over the past decade, with the overarching aim of asking how far we have come in meeting the above mission and what future directions are needed to better deliver policy support at a time where rapid and robust answers are needed to guide strategies to reduce the impacts of climate-driven changes in marine life and the resources it provides. We synthesise how FishMIP results have helped address key policy questions both within the marine ecosystems and fisheries sector and in cross-sectoral studies, as well as tracking the research impact of selected key papers. Finally, we highlight the path ahead over the next decade of FishMIP 2.0 (Blanchard et al., *this issue).*

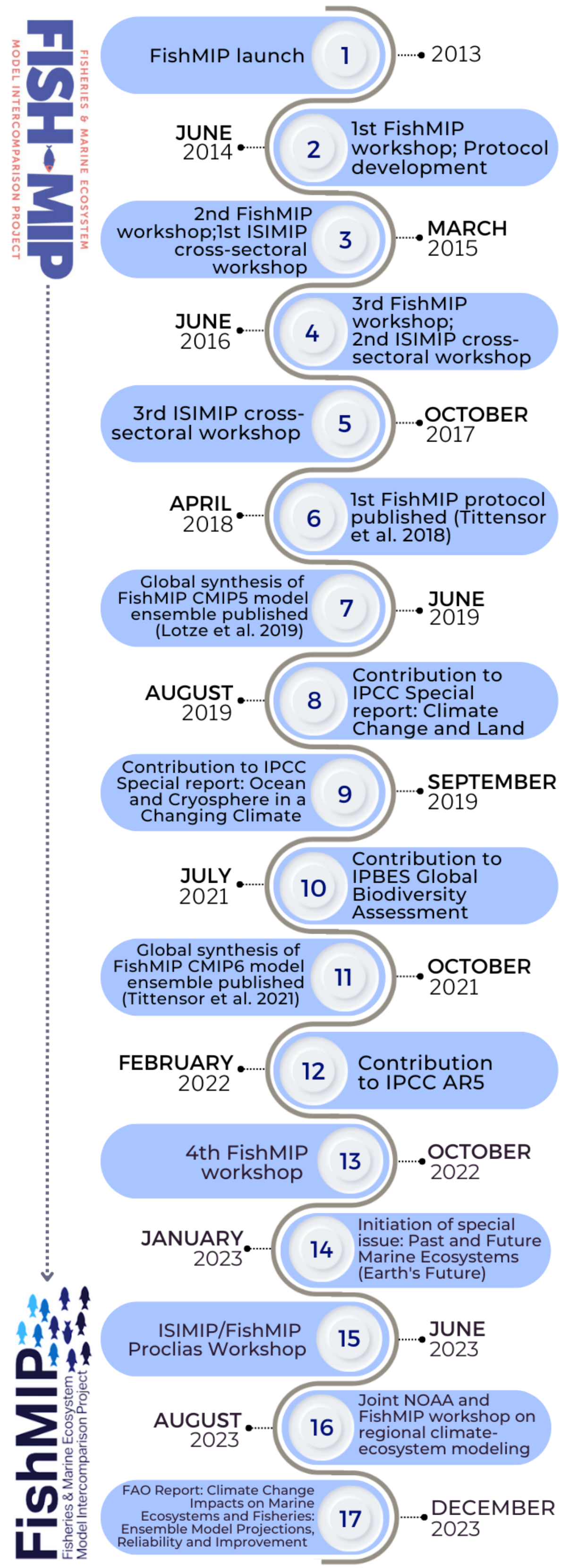

Figure 1. Timeline of FishMIP development and milestones since 2013.

2 Growing applications and impact

Several key FishMIP papers have shown a growing level of research impact through time, in terms of number of citations and policy uptake. They have helped answer questions about key topics in the FishMIP mission: fish and fisheries, seafood supply, marine biodiversity and marine ecosystem functioning, thus supporting policies related to these key areas. By analysing the number of citations since 2016, derived from the FishMIP Google Scholar (https://tinyurl.com/usw9e92p), we identified six key FishMIP papers with >100 cumulative citations each (Figure 2).

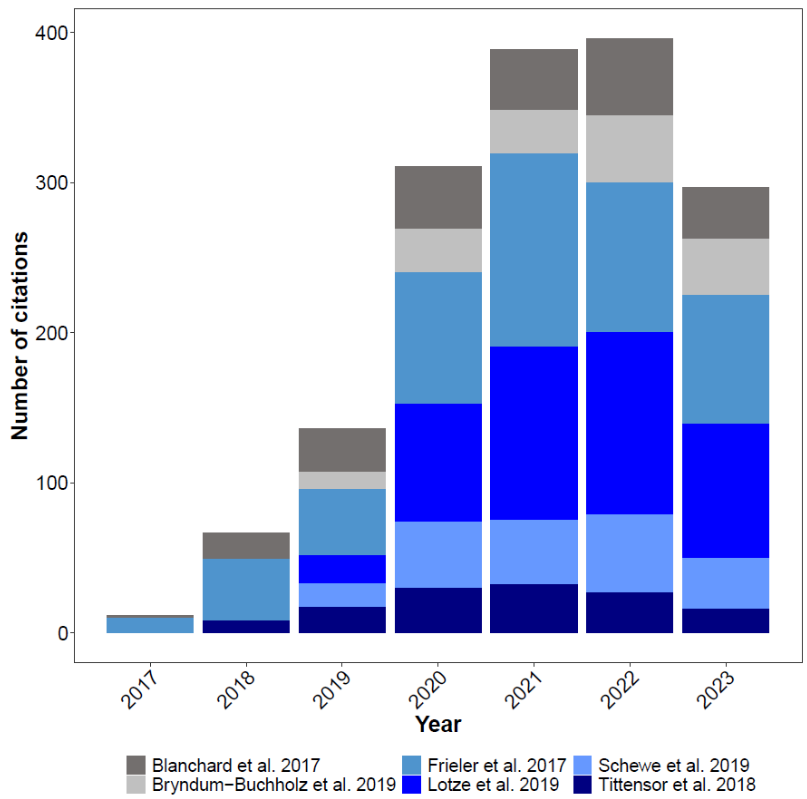

Figure 2. Number of citations per year since 2017 for six key FishMIP papers (cumulative citations >100), derived from the FishMIP Google Scholar https://tinyurl.com/usw9e92p**.**

Based on a cross-checked Altmetric analysis, we determined the policy uptake of FishMIP publications and which policy themes were addressed. Our cross-check removed duplicates in the Altmetric records and added missing reports that were not captured by Altmetric at the time of analysis (Table S1). Over time, FishMIP publications have addressed three main, often intersecting, policy categories: 1) climate change targets, and the importance of meeting these targets for fish, fisheries and their management; 2) cross sectoral trade-offs in Sustainable Development Goals (SDGs), including future challenges for seafood supply and food security; and 3) marine biodiversity conservation and ecosystem functioning (Figure 3). The category of "Other", included policy reports that did not fit into the main categories identified. FishMIP publications have led to the use and the uptake of FishMIP output into national and international policy documents, including reports by the IPCC, IPBES, FAO, World Bank and UN (Table S2).

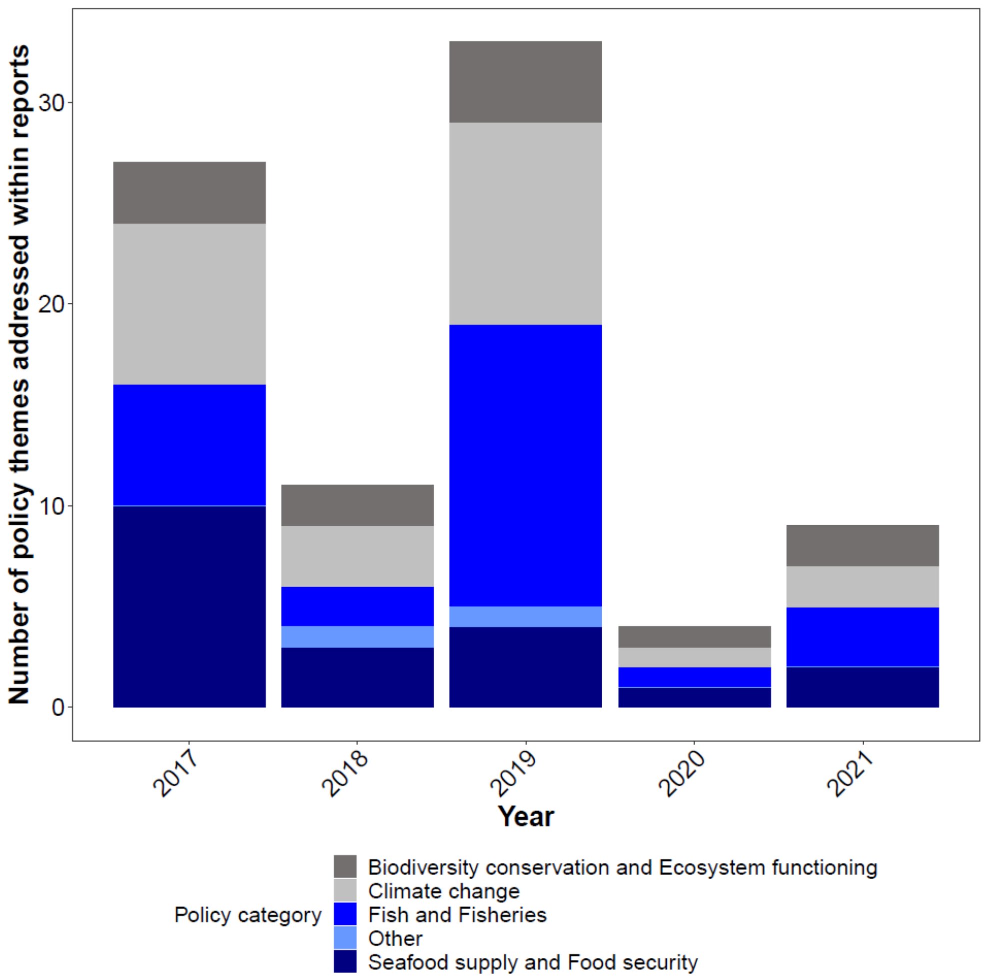

Figure 3. Number of policy categories addressed in policy reports that use FishMIP data or cite published FishMIP and ISIMIP publications between 2017-2021. Note that some policy reports address multiple themes. See the number and title of policy reports citing FishMIP and ISIMIP publications in the Supplemental Material, Table S1, S2.

2.1 Climate change targets

A primary objective has been, and continues to be, to provide future projections to the IPCC as evidence of the benefits of limiting climate change. This includes the first synthesis and inter-comparison of standardised climate-change driven marine ecosystem model outputs on global (Lotze et al. 2019) and regional scales (Bryndum-Buchholz et al. 2019), which were integrated into the IPCC Special Report for the Ocean and Cryosphere in a Changing Climate (IPCC 2019b). These works showed consistent and exacerbated future declines in ocean biomass under the high emissions scenario (RCP8.5) compared to the low emissions scenario (RCP2.6), with substantial geographical variation, and thus highlighted the benefits of climate mitigation actions.

Large uncertainties across the ensemble projections within the global FishMIP CMIP5 results (Lotze et al. 2019) and for key regions (Bryndum-Buchholz et al. 2019) led to a targeted simulation experiment in 2018-2019 to tease apart the effects of different climate drivers on individual marine ecosystem model projections of future fish biomass change (Heneghan et al. 2021). This analysis revealed that the nature of lower trophic level coupling in models was a key source of inter-model uncertainty. Despite CMIP6-forced projections revealing a narrower spread of ecosystem projections, with a more pessimistic outlook relative to CMIP5 (due to both higher climate sensitivity of FishMIP models and higher warming in CMIP6) that was integrated into the IPCC's 6th assessment report (Tittensor et al. 2021; IPCC 2022), All four FishMIP papers led to recommendations for improved understanding of uncertainty and a need for more robust regional-scale projections.

A further investigation revealed that large uncertainties and limited quantitative and standardised ensemble model validation hamper the robustness of modelling outputs and may have restricted the use of these outputs in management and policy contexts (Steenbeek et al. 2021). Among the clear gaps in improving confidence in and robustness of marine ecosystem model projections are: 1) the limited cross-ecosystem model validation against historical data (Heneghan et al. 2021, Rynne et al. *this issue*); and 2) the high computational cost of marine ecosystem model simulations, which makes it difficult to develop large ensemble simulations to conduct systematic sensitivity analysis and parameter estimation (Steenbeek et al. 2021). Solutions to these challenges are currently being developed by the FishMIP community, including the collaborative development of a model validation framework (Rynne et al. *this issue*), distributed computation to tackle the high computational cost of marine ecosystem model simulations (Steenbeek et al.2021), and collaboration with the Earth System Grid Federation (ESGF2) to better validate marine ecosystem drivers in CMIP6 (Fu et al. 2022).

2.2 Climate-resilient fisheries management

Global projections of ocean biomass have been used to assess fisheries management challenges in the Northwest Atlantic under different climate change scenarios (Bryndum-Buchholz et al. 2020a, Lotze et al. 2022). Here, the FishMIP ensemble revealed regionally disparate biomass changes, with high projected decreases overlapping with historical and current areas of high fisheries landings, while areas with lower historical landings, such as Arctic and sub-Arctic areas, showed large biomass increases, albeit with large uncertainties (Bryndum-Buchholz et al. 2020a). For Australia, more specifically, Pethybridge et al. (2020) explored contrasting futures for national, large-scale fisheries stocks, using an ensemble of regional and two of the global FishMIP models (DBEM, DBPM). Across Australia, demersal fisheries were projected to experience larger climate-related impacts than pelagic fisheries, notably Australia’s invertebrate fisheries. Using the ensemble approach, this study highlighted priorities for fisheries specific, proactive, and flexible management systems that effectively account for climate change impacts.

The call by Pethybridge et al. (2020) for proactive and flexible fisheries management adaptation in Australia was complemented by a comprehensive review of the implementation of climate change adaptation in fisheries management policy and legislation (Bryndum-Buchholz et al. 2021). Here, global FishMIP projections of ocean biomass changes within 11 Exclusive Economic Zones (EEZs) were used to illustrate the impact of climate change on marine ecosystems and fisheries, and highlighted the urgency of developing adaptation plans by the respective nations responsible for these EEZs (Bryndum-Buchholz et al. 2021). This was critical information, since across these EEZs, none of the reviewed fisheries management policies and legislation explicitly addressed climate change impacts or mandated the integration of those impacts into stock assessments or decision making. The findings of this study were highlighted in the IPCC 6th assessment report (IPCC 2022). Understanding climate change impacts on marine ecosystems and fisheries governance is imperative for ensuring that they remain productive and sustainable in a changing ocean.

While these FishMIP studies address questions around climate change impacts on marine ecosystems and fisheries management, projections of climate impacts did not account for impacts due to fishing. At the time of these analyses, a standardised, spatially and temporally explicit, representation of future fishing scenarios (i.e. future evolution of fishing effort, mortality or exploitation rate) was unavailable. Developing the Ocean System Pathways (OSPs), a set of standardised fishing scenarios and the associated modelling framework required to simulate them (Maury et al, *this issue*), has been one of FishMIP's key challenges and has led to the development of the FishMIP 2.0 protocol (Blanchard et al., *this issue*). This process commenced in 2021 following extensive community consultation on research and policy priorities. It involves defining an expanded set of simulations directly targeted at specific policy processes that includes dynamic fisheries and socioeconomic scenarios (Maury et al., *this issue*) using models that have gone through a validation and benchmarking stage (Blanchard et al., *this issue*).

2.3 Food security and cross sectoral trade-offs

A preliminary synthesis of CMIP5 projections from FishMIP and the Agriculture Model Intercomparison Project (AgMIP) provided the first cross-sectoral ensemble assessment of joint climate change impacts across land and sea (Blanchard et al. 2017), highlighting trade-offs for food security in the Special Report on Climate Change and Land (IPCC 2019a). This assessment showed that the ceiling of food production from both land and sea is expected to face declines in most countries (Blanchard et al. 2017). Other studies using projections to assess cross-sectoral impacts have followed and shown that, under a high emissions scenario, most countries are expected to face losses in both agriculture and fisheries production, while under a low emissions scenario they would experience gains in both sectors, thus advocating for prompt climate mitigation actions (Thiault et al. 2019).

Building on this work and using detailed household surveys enabled an assessment of future local impacts on agriculture and fisheries production for coastal communities of the Indo-Pacific (Cinner et al. 2022). This study showed that potential losses to fisheries are generally higher than those to agriculture, and that strong climate change mitigation could drastically reduce the risk of simultaneous losses in agriculture and fisheries production for most of the coastal communities considered. The socio-economic benefits of meeting climate mitigation targets were also highlighted in another study linking marine ecosystem model projections to a range of socio-economic indicators, at national to global scales (Boyce et al. 2020). These benefits include preventing the widening of existing climate-driven equity gaps, in particular for nations that are heavily dependent on decreasing food resources and face increasingly poor nutritional status, wealth and ocean health (Boyce et al. 2020). This work was integrated into the 6th IPCC assessment report, emphasising socio-economic consequences in the context of climate change impacts and adaptation (IPCC 2022).

Looking ahead, as extreme climate events increase, the frequency and intensity of sudden losses to food production on land and in the sea are expected to increase, with negative repercussions for food supply and security, livelihoods and human well-being (Cottrell et al. 2019). To prepare for such losses, we need marine ecosystem models that are capable of estimating the full extent of impacts of extreme climate events, and cross-sectoral assessments that make use of such modelling outputs to account for the complex linkages across food systems. A test of how well the current suite of models from multiple sectors can capture the impacts of an extreme climate event revealed that severe impacts on agriculture and ecosystem productivity are largely underestimated, and further highlighted the need to improve such models' ability and to work on cross-sectoral aspects (Schewe et al. 2019).

2.4 Marine biodiversity conservation and ecosystem functioning

The FishMIP-CMIP5 ensemble contributed to the 2019 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) global assessment of biodiversity and ecosystem services, by providing insights into future climate change impacts on marine biodiversity and ecosystem functioning, as well as the potential consequences for ecosystem services (Blanchard et al. 2017, Tittensor et al. 2018, Lotze et al. 2019, 2022, IPBES, 2019).

The enhanced FishMIP-CMIP6 model ensemble was applied to regional marine conservation questions (Bryndum-Buchholz et al. 2023a), ultimately generating knowledge for the United Nations Sustainable Development Goals (SDGs), particularly SDG 13 (climate action) and SDGs 14 (life below water). Here, projections of ocean biomass and key physical variables for Atlantic Canada were combined to identify climate refugia and hotspots and to evaluate the future ability of marine conservation areas to protect biodiversity. Results provide important long-term context for adaptation and for building climate-resilience into spatial marine conservation planning in the region.

The effects of climate change on ecosystem structure were recently assessed using the enhanced global FishMIP-CMIP6 ensemble (Guibourd de Luzinais et al. 2023). By analysing changes within marine food webs in the model ensemble, the study quantified the extent of trophic amplification (the larger decline in the biomass of higher trophic level organisms relative to the decrease in primary producer biomass) and highlighted a more complex response within food webs than anticipated due to disparate parameterization and structure of the individual FishMIP models. Rather than a consistent amplification, results showed how temperature changes can attenuate or even offset trophic amplification across marine ecosystems (Guibourd de Luzinais et al. 2023).

3 Looking ahead with FishMIP 2.0

With the Paris agreement climate change target, the associated Global Stocktake revision to come after the UNFCCC COP28 (https://www.cop28.com/en/) and the 2030 agenda for sustainable development (SDGs) imminent, delivering policy-relevant climate impact and adaptation science is of paramount importance across sectors and disciplines. For the ocean and its living marine resources, FishMIP model ensemble projections are used to support vulnerability and climate risk studies and adaptation plans for different countries and regions of the world. To date, FishMIP has informed climate, biodiversity, fisheries, food security, and marine conservation sectors. FishMIP results can increasingly be used to inform current and future progress towards United Nations Sustainable Development Goals (https://sdgs.un.org/goals), specially: Climate Action (SDG 13), Life Below Water (SDG 14), Zero Hunger (SDG 2), Decent Work and Economic Growth (SDG 8), and Responsible Consumption & Production (SDG 12), and a range of Ocean Decade Challenges (https://oceandecade.org/challenges/) (Figure 4, Table S3). However, to successfully guide potential actions for informing progress towards the above goals, we highlight several focal areas for FishMIP 2.0 to focus on over the next decade.

We have developed five key areas for focal working groups (WGs), described below, that are designed to contribute to a range of SDGs and to provide scientific information needed to strengthen resilience and adaptive capacity to climate-related hazards, integrate climate change measures into policies and planning, and sustainably manage marine resources (Figure 4, Table S3). Each working group also addresses specific Ocean Decade Challenges, FAO Blue Transformation goals, as well as targets and goals of the Convention of Biological Diversity (CBD). Together, they will create research capacity to:

3.1 WG1: Marine ecosystem model improvement to enhance policy relevance

Previous studies have highlighted that projections of climate change impacts on marine ecosystems and fisheries have large uncertainties, particularly in regions where rapid changes are occurring, e.g., polar waters (Lotze et al. 2019; Tittensor et al. 2021). However, robust model ensembles of climate impact projections and their associated inter-model variability, on which reliable future sustainable pathways can be based, are needed to inform decision making. To be reliable, these projections must be accompanied by appropriate estimates of uncertainty, where lower uncertainty means higher confidence in the direction, magnitude, and geographical pattern of change (Payne et al. 2016).

Improving model ensemble skills through appropriate calibration and validation of individual marine ecosystem models is one of the primary goals of current and future FishMIP efforts. This requires a stronger assessment of the ability of individual marine ecosystem models to capture past ecosystem states and environmental- and exploitation-driven changes, including the development of standardised datasets against which to evaluate historical model simulations (Blanchard et al. *this issue*) and standardised methodological frameworks for model skill evaluation (Rynne et al., *this issue*). The FishMIP Model Improvement Working Group (WG 1; Figure. 4) is developing tools to assess the reliability of marine ecosystem model ensembles through advanced skill assessment techniques (Novaglio et al., *this issue*; Rynne et al., *this issue*) using global and regional observational datasets, ranging from fisheries catches and effort to fish abundance and biomass surveys, including novel data streams (e.g., satellite data, eDNA). This working group will also develop tools to help build regional marine ecosystem model ensembles spanning a gradient of data-rich to data-poor regions.

In addition, confronting marine ecosystem models with observations helps to identify the processes that affect simulation outputs and the parameterisation that needs to be refined, ultimately leading to the improvement of marine ecosystem models (Heneghan et al. 2021). FishMIP 2.0 will assess the ability of the FishMIP ensemble to detect past ecosystem and fishery changes, including the attribution of changes to specific stressors. As the majority of fisheries catches are made in coastal waters, this is likely to require improved representation of coastal physical and biogeochemical processes in ESMs and increased reliability of projections for coastal regions. This will in particular involve the use of higher-resolution ESM input data that better represent coastal enrichment processes such as upwelling and nutrient runoff from land-based human activities, sediment dynamics (Liu et al. 2021; Frieler et al. 2023), as well as regional downscaling of global ESMs (Drenkard et al. 2021, Jacox et al. 2020, Holt et al. 2017), and the use of standardised fishing effort for global and regional models (Rousseau et al., in press).

An improved FishMIP model ensemble, forced by improved ESMs, will contribute knowledge to major science-policy efforts (e.g. IPCC, IPBES), policy processes (e.g. FAO Committee on Fisheries, and Convention on Biological Diversity) and international targets, such as SDG 13 (Climate Action) and 14 (Life Below Water), as well as SDG targets focussing on increasing scientific knowledge and capacity to improve ocean health and effective climate change-related planning and managing (e.g., 13.3, 14.B, 14.A; https://sdgs.un.org/goals/goal13#targets_and_indicators, https://sdgs.un.org/goals/goal14#targets_and_indicators). Likewise, improved marine ecosystem models and ESMs will help address Ocean Decade Challenges 8 (Create a digital representation of the Ocean), and 9 (Skill, knowledge and technologies for all; Table S3).

3.2 WG2: Socio-economic scenarios to foster sustainable fisheries

Billions of people depend on living marine resources and sustainable fisheries that are at risk due to climate change. The Socio-economic Scenarios Working Group (Fig. 4) will lead the development, implementation in models, testing and simulation of the OSPs, a set of SSP-consistent scenarios of the future of fisheries, including a modelling framework for embedding market and fleet dynamics into ecosystem models (Maury et al. *this issue*), that will, amongst other objectives, help to address where adaptive fisheries management measures are most needed, and which measures can successfully lead to climate resilient fisheries.

Policymakers across multiple sectors need projections of marine biomass, fisheries catches and seafood availability under scenarios of climate and socio-economic changes that take into account human behaviour and choices in order to inform management decisions on scales ranging from national to global. In addition, these projections are needed to test new conservation and adaptation strategies that will be developed during the next decade of climate-impact research and implementation. With better-validated models that can simultaneously capture human impacts and impacts on humans, FishMIP will be in a position to explore spatially and temporally explicit socio-economic fisheries scenarios that are consistent with and extend the climate scenarios considered thus far (Maury et al., *this issue*). This requires the implementation of dynamic fishing, which simultaneously depends on economic, governance and management drivers as well as changing climatic conditions, into all FishMIP models, the translation of qualitative OSP storylines into quantitative driver pathways, and the design of modelling experiments aimed at exploring the potential range of climate and socio-economic impacts on the marine realm along with adaptation and mitigation options (Maury et al. *this issue*).

Following extensive community consultation, the Socio-economic Scenarios Working Group has already made progress on the implementation of the features described above, with work on informing climate resilient fisheries planned to continue over the next decade, with the goal of contributing to the knowledge base required for major, international sustainability goals (Figure 4, Table S3).

3.3 WG3: Promote climate-resilient food-security

Climate change and resource use have affected and will continue to affect the substantial contributions that aquatic food already makes to the diet and livelihoods of many nations (FAO. 2020), highlighting the urgent need to strengthen the climate-resilience of aquatic food. To increase resilience and to meet the ever increasing demand for food (van Dijk et al. 2021, Costello et al. 2020), we need a better understanding of how marine ecosystems respond to perturbations, now and in the future, and of the linkages between land and sea food production systems. The Food Security Working Group (Figure. 4) will work on such topics. For instance, through well established cross-sectoral links with agriculture modellers (AgMIP), FishMIP will carry out the first ensemble model projection for aquaculture and combine agriculture, aquaculture, and fisheries projections to evaluate land-sea interactions and food security-biodiversity trade-offs. A larger set of indicators will be developed to simplify the integration of FishMIP results with those from other sectors, including AgMIP and the Food Model Intercomparison Project (FoodNut). Such integration would allow for answering questions on the sustainability of interconnected food systems of fisheries, aquaculture, and agriculture and their respective impacts on and vulnerabilities to changes in biodiversity and ecosystem functions and services, from regional to global scales.

A second core objective of this working group is to develop tools for improving the representation of coastal fisheries in key regions of the world and developing countries. Indeed, a clear policy and decision-making request to FishMIP is to strengthen the focus on regional and local scales, where projections are lacking (e.g. Tittensor et al. 2021). This means increasing the currently patchy coverage of regional ecosystem models, with the global south particularly underrepresented; focusing on the development of regional marine ecosystem model ensembles that are often difficult to assemble for regional institutions; promoting the development of dynamically downscaled climate projections, as well as less labour-intensive statistically downscaled projections; and increasing efforts on the analysis of global model outputs by Exclusive Economic Zones (plus the High Seas). To increase the coverage of regional models and the diversity of ecosystem modellers, resources such as the Global South Climate Database that lists climate experts and their skills will be explored (https://www.carbonbrief.org/global-south-climate-database/) and a higher number of postgraduate students and postdoctoral fellows from underrepresented regions will be engaged. Focusing on improving spatial and temporal resolutions of regional modelling outputs is an ongoing exercise, which will gather momentum throughout the coming decade of FishMIP, actively addressing multiple SDGs, Ocean Decade Challenges, and Blue Transformation goals, such as SDG 2 (Zero Hunger), Ocean Challenge 3 (Sustainably feed the global population), and Better Nutrition, Programme Priority Areas 1 to 4 (Figure 4, Table S3).

3.4 WG4: Protect ecosystems and biodiversity

Climate-adaptive marine ecosystem management has the potential to mitigate long-term effects of climate change and reduce biodiversity loss by restricting fisheries exploitation by space, time, species, and size. The Biodiversity Conservation Working Group (Figure. 4) will work to evaluate the extent to which Marine Protected Areas (MPAs) and other spatial conservation measures such as Other Effective Area-Based Conservation Measures (OECMs) can and will be able to contribute to marine ecosystem protection and restoration, in addition to exploring the impact of fisheries management decisions on marine biodiversity and ecosystem health. In particular, these modelling experiments will explore the role of MPAs and other area-based fisheries management strategies in enhancing biodiversity, and strengthening ecosystems' recreational value.

To quantify the benefits of good management and trade-offs between climate mitigation and adaptation pathways that emphasise different ecological and socio-economic values of marine ecosystems, the range of biodiversity metrics that can be captured with FishMIP models will be extended. Because most global FishMIP models do not include species but rather focus on size classes or functional groups, and hence cannot easily provide species-specific biodiversity indicators, a possible way forward is the use of traits or functional diversity or empirical relationships to convert modelled biomass to species richness and thus to indirectly translate modelling outputs to biodiversity. An additional aspect of the work will be aligning biodiversity-focussed scenarios with those used by IPBES, in particular the Nature Futures Framework (Pereira et al. 2020; Maury et al. *this issue*). Outputs of the biodiversity-focussed scenarios can also be used to inform the newly adopted Biodiversity Beyond National Jurisdiction (BBNJ; Tiller & Mendenhall, 2023) treaty by exploring changing biodiversity on the high seas.

The Biodiversity Protection Working Group aims at contributing to the knowledge base of SDGs 13 and 14, in particular to targets for sustainable management and protection of marine and coastal ecosystems and the conservation of coastal and marine areas, consistent with national and international law (SDG 14.2, SDG 14.5; Figure 4, Tabel S3). This work is also consistent with Ocean Decade Challenge 2 (Protect and restore ecosystems and biodiversity) and 5 (Unlock ocean-based solutions to climate change; Figure 4, Table S3).

3.5 WG 5: Assess intervention scenarios for climate change remediation

Reducing emissions and limiting global warming to 1.5 degrees Celsius has been repeatedly shown to improve prospects for future global fisheries and ecosystems (e.g., Boyce et al. 2020).

Additionally, as climate targets are slow to be reached, a wide range of climate intervention approaches are being debated to modify the Earth's radiation budget and remove greenhouse gases from the atmosphere (National Academies of Sciences, Engineering, and Medicine 2021, 2022). The many consequences of these interventions on fisheries and marine ecosystems are largely unknown, potentially detrimental, and therefore crucial to understand given their importance to the global food supply. The Climate Change Mitigation Working Group (Figure 4) will explore the potential impacts of climate interventions on marine ecosystems, in an effort to add to the knowledge base around geoengineering impacts and hence inform decision- and policymaking with due consideration of potential impacts on ecosystem services, biodiversity, and food security in future climate scenarios. While FishMIP is already contributing to climate risk and vulnerability assessments (Cinner et al. 2022), this focused set of policy-relevant and management-driven analyses will allow a more in-depth consideration of climate intervention strategies, and increase scientific knowledge, develop research capacity and transfer marine technology to improve ocean health (SDG target 14.A) and increase community resilience to ocean hazards (Ocean Decade Challenge 6; Figure 4, Table S3).

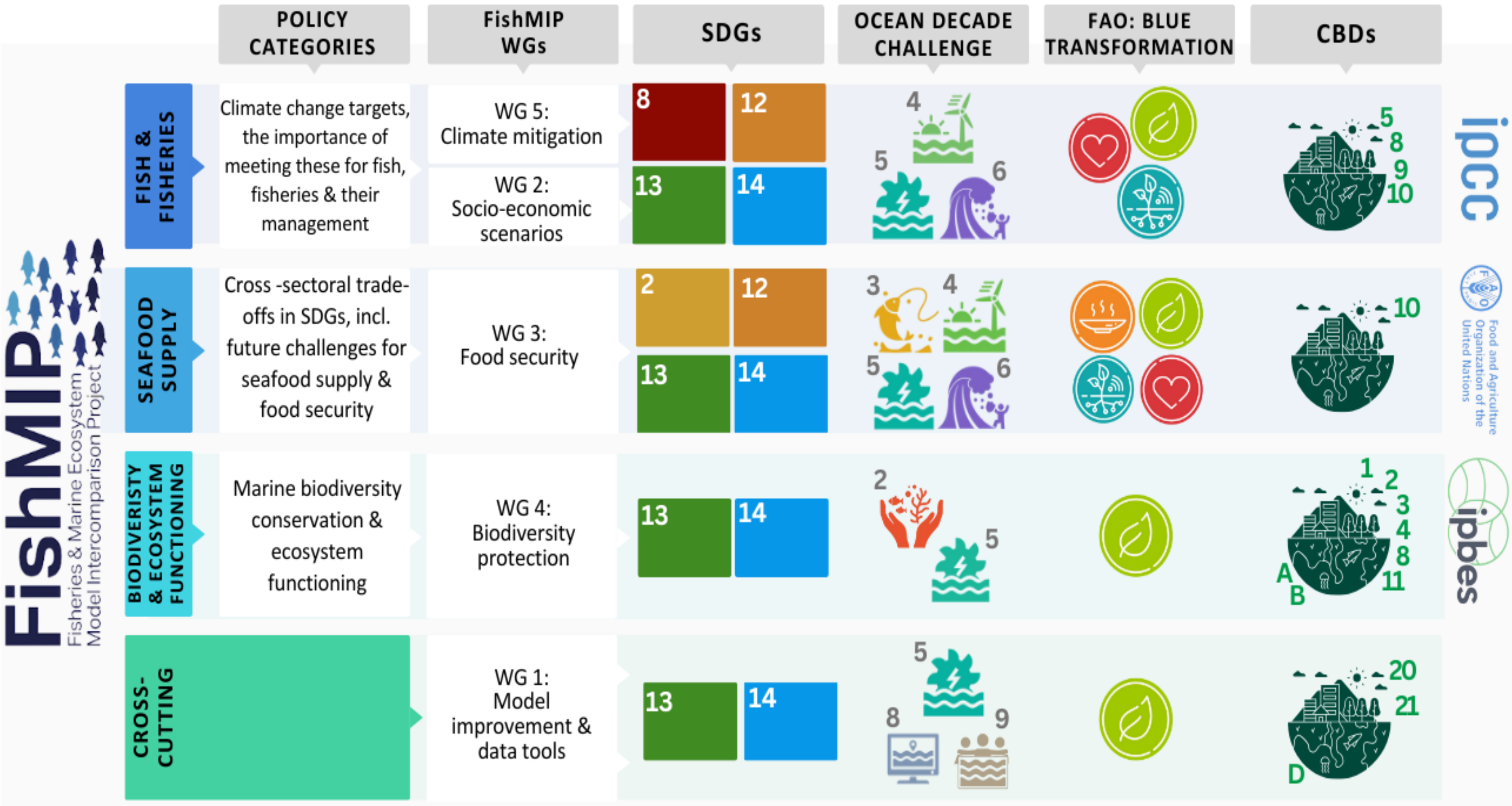

Figure 4. Overview of FishMIP goals and their respective policy categories, the objectives of current and future FishMIP working groups (WGs), and how both address targets and goals of the Sustainable Development Goals (SDGs), the Ocean Decade Challenges, the Food and Agriculture Organization (FAO) Strategic Framework for Blue Transformation, and the targets (numbers) and goals (letters) of the Convention of Biological Diversity (CBDs). Please note that SDGs, Ocean Decade Challenge, FAO and CBDs goals for WG5 and WG2 are grouped as both WGs fall within the broader Fish & Fisheries topic. Specific explanation of each target and goal are in Table S3.

4 Key challenges and solutions

Since its inception in 2013, FishMIP has faced and addressed important challenges. Discussion around these challenges and proposed solutions have been opportunities for learning and the lessons gained have often informed other modelling projects and teams, thus advancing marine ecosystem modelling more broadly. Most of these challenges are long-standing and require continuous work, while others have appeared only recently. Here is an overview of the main challenges:

Relevant climate models that simulate and save all the necessary data for the marine ecosystem models: Through the collaboration of FishMIP and CMIP (Ruane et al. 2016) we received improved representation of biochemical parameters in CMIP6 compared to CMIP5 which helped advance FishMIP projections (Tittensor et al. 2021). However, the number of ESMs that simulate, save and can provide all the physical and biogeochemical variables that are required to drive marine ecosystem models is still limited. Thus, this collaborative process between climate and marine modellers needs to continue and deepen.

Empirical data for model calibration and validation: the ever-increasing expansion of global, observational datasets will provide more opportunities to better calibrate, constrain and validate both climate and marine ecosystem models.

Improved ecosystem models: Each marine ecosystem model has its own idiosyncrasies and biases, and is necessarily an incomplete representation of the complexity of marine ecosystems. Thus, incorporating into the ensemble and comparing the predictions of more marine ecosystem models that are based on different paradigms or reflect different ecosystem structures and processes is highly informative (Tittensor et al. 2018) and can help identify gaps in individual models and make progress in addressing them. There are plenty of ways to improve, for instance, including marine ecosystem models that incorporate the potential for species acclimatisation and adaptation into the FishMIP ensemble would enable assessment of how this would affect projected future changes in distribution and abundance of marine animal biomass.

Compare global with regional projections: Regional ecosystem models may more accurately capture processes at management-relevant scales, both due to better resolution of physical and biogeochemical processes with finer regional ocean model resolution and use of regionally-tuned plankton models, and due to better representation of local ecosystem processes in regional marine ecosystem models. To address whether or why regional marine ecosystem models are more accurate and/or different from global models, systematic comparisons between global and regional model ensembles are needed, along with continued effort at regional downscaling of climate projections sensitive to the needs of ecosystem managers.

Optimal level of complexity: As FishMIP models evolve and new processes are being integrated to answer more complex questions, the ability to understand the effect of a change in a driver becomes more difficult. In the future, this difficulty will further increase when dynamic fishing is integrated in all FishMIP models. Increased validation of regional and global models and the implementation of detection and attribution analyses are expected to help in this regard.

Work-flow preceding modelling experiments: Efforts around the preparation of climate and fishing inputs have increased at every protocol iteration. This is due to the need to meet the requirements of an increasing set of models and to accommodate the different requests of global and regional models, with the latter often being forced, calibrated, and validated using high-resolution ocean model and fishing inputs that come from alternative sources and that are likely more appropriate for regional modelling than the standardised, global-scale FishMIP inputs. Solutions to this growing challenge include agreement on a downscaling method that takes global-scale inputs and provides more meaningful regional products. To reduce bottlenecks, the FishMIP team is developing a series of tools that ease access, downloading and formatting of climate model input data and to support global and regional modelling (www.fishmip.org; https://github.com/Fish-MIP).

Computational needs and quality: Computational needs have become a limiting factor for some modelling teams as inputs increase in resolution, hence in volume, and experiments expand to answer multiple questions. Model improvement is not only related to model structure and the choice of parameters but also to its computational quality - i.e., how efficient the code is. Improving the model computational quality depends on the economic, personnel and computational resources available to each modelling team (Steenbeek et al. 2021, Steenbeek et al. *this issue*).

Voluntary commitment: Currently FishMIP relies on voluntary commitments from modellers and scientists. Ensuring the long-term longevity of this ever growing project requires setting up mechanisms that guarantee consistent funding similar to those supporting other relevant projects in this field, e.g., CMIP. As a first step to increase its visibility to potential funders, FishMIP applied to become a UN Decade Action, making FishMIP a UN-endorsed project directly contributing to the Ocean Decade vision of '*the science we need for the ocean we want'* (https://oceandecade.org/decade-actions/)

Dissemination of outputs: FishMIP outputs are becoming harder to analyse and make widely available as they grow in complexity and number. To ensure a continuous and increasing use of these outputs, it is paramount that interactive tools where outputs can be stored, summarised and downloaded continue to be developed and innovative solutions to be explored and adopted.

5 Conclusion

Over the past decade, FishMIP has brought together and engaged an international community of marine climate, fisheries and ecosystem scientists and modellers, who have contributed substantially to the field of climate-impact science in the marine realm, and informed key international climate and biodiversity science-policy efforts. Along the way, FishMIP has faced important challenges, most of them requiring continuous work, such as improving the robustness of future projections through standardised marine ecosystem model evaluation, the development of fishery scenarios accounting for the socio-economic factors that drive the evolution of fishing effort and markets in interaction with ecosystems, and providing regional and local model-based projections to inform policy-making. By addressing these challenges over the next decade, FishMIP can play an important role in the development of marine ecosystem models at all scales, and accelerate their progress. It can also be useful in providing the information that fisheries management and marine conservation need to address the issue of resilience to climate change and develop effective adaptation strategies. Likewise, it can contribute to the knowledge base to achieve the UN Sustainable Development Goals, particularly those addressing hunger and life below water. Over the next decade, FishMIP will address long-standing scientific and policy challenges through the remarkable efforts of a large, diverse, collaborative, and growing scientific community around the world.

Data Availability Statement

No new data was produced as part of this manuscript. All data analysed is publicly available and cited in the manuscript.

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