Detecting, attributing, and projecting global marine ecosystem and fisheries change: FishMIP 2.0

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Key Points:

- Detecting, attributing, and projecting climate change risks on marine ecosystems and fisheries requires models with realistic dynamics.
- FishMIP 2.0 incorporates fishing and climate impact trajectories to assess models and more accurately detect past ecosystem changes.
- Our framework will be used to help support model improvement, building confidence in future projections to better underpin policy advice.

Abstract

There is an urgent need for models that can robustly detect past and project future ecosystem changes and risks to the services that they provide to people. The Fisheries and Marine Ecosystem Model Intercomparison Project (FishMIP) was established to develop model ensembles for projecting long-term impacts of climate change on fisheries and marine ecosystems while informing policy at spatio-temporal scales relevant to the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) framework. While contributing FishMIP models have improved over time, large uncertainties in projections remain, particularly in coastal and shelf seas where most of the world's fisheries occur. Furthermore, previous FishMIP climate impact projections have mostly ignored fishing activity due to a lack of standardized historical and scenario-based human activity forcing and uneven capabilities to dynamically model fisheries across the FishMIP community. This, in addition to underrepresentation of coastal processes, has limited the ability to evaluate the FishMIP ensemble's ability to adequately capture past states - a crucial step for building confidence in future projections. To address these issues, we have developed two parallel simulation experiments (FishMIP 2.0) on: 1) model evaluation and detection of past changes and 2) future scenarios and projections. Key advances include historical climate forcing, that captures oceanographic features not previously resolved, and standardized fishing forcing to systematically test fishing effects across models. FishMIP 2.0 is a key step towards a detection and attribution framework for marine ecosystem change at regional and global scales, and towards enhanced policy relevance through increased confidence in future ensemble projections.

Plain Language Summary

Historically, the largest human impact on the ocean has been overfishing. In the future, it may become climate change. To understand and predict how human activities will affect marine ecosystems in the future, we need models that can be used to accurately detect and attribute the effects of drivers and their impact on past ecosystem trajectories. By doing this, we build confidence in the ability of sets of these models ("ensembles") to capture future change. FishMIP 2.0 provides a way to construct and test these ensembles and provides scenarios of both changing climate and socio-economic conditions, and of how future fisheries will evolve and adapt over time.

1 Introduction

Marine ecosystems are changing in response to the effects of climate and other direct human stressors, leading to loss of biodiversity and declines in ecosystem functions and services (IPBES, 2022; IPCC, 2023). Threats from human activities on marine ecosystems such as climate change and overfishing are likely to increase with a growing human population, putting marine life and people at risk, particularly in developing nations (Blanchard et al., 2017). Effective actions to conserve marine biodiversity and secure human wellbeing require accurate detection of past changes in ecosystem states, combined with an understanding of the processes driving those changes. While we have strong empirical and modelling evidence of the ecological impacts of climate change on marine ecosystems (Cooley et al., 2023; Barrier et al., this issue), there are still large uncertainties in our understanding of the relative and cumulative effects of multiple anthropogenic pressures (overfishing and climate change in particular) on complex living systems, at regional to global scales. Resolving these uncertainties is crucial to build confidence in the use of model projections, to inform the development of pathways and policies that will most effectively mitigate negative human impacts and help human communities adapt to change.

The Fisheries and Marine Ecosystem Model Intercomparison Project (FishMIP) aims to improve understanding and projections of the long-term impacts of climate change and other stressors on marine fisheries and ecosystems. FishMIP provides an approach for quantifying climate impacts and their uncertainties, contributing to vulnerability assessments, and testing mitigation and adaptation scenarios. In its first stage, FishMIP 1.0 (Tittensor et al., 2018) comprised 6 global and 8 regional models that captured the processes behind biomass flow through ecosystems in markedly different ways. Since then, a growing diversity of models has helped us build a knowledge base of potential impacts of global marine ecosystem responses, with the likely directions and magnitudes of change divergent for many regions of the world (Tittensor et al., 2021). However, to fulfil their potential and maximize policy relevance, impact model intercomparison projects, such as FishMIP, should be able to integrate multiple stressors, work towards a detection and attribution framework, and undergo thorough calibration and testing to build a deep understanding of model performance when capturing observed historical changes (Frieler, 2023).

Fishing activity is a longstanding driver of change affecting targeted fisheries stocks (biomass, age and size structure), bycatch species, biodiversity, and ecosystem structure and function.

These impacts in turn affect the long-term stability of ecosystems and the fisheries they support, along with all the benefits that they provide, including food security, nutrient provision, economic rents, and employment (Cheung et al., 2023; Garcia & Rosenberg, 2010; Scherrer et al., 2023). Understanding how these impacts exacerbate or cancel out climate change is essential for both fisheries management and adaptation (Cheung et al., 2022; Portner & and co-authors, 2021, Scherrer et al., 2020). However, the lack of consistency in FishMIP's historical fishing forcing has hampered our ability to tease apart the relative and combined effects of global climate change and fishing and to estimate the extent to which future fisheries are at risk (Tittensor et al., 2021). This has been due to a lack of standardized historical fishing effort data at the global scale, which has led to a wide variety of ways in which fishing has been included in previous FishMIP model outputs - ranging from no fishing (Tittensor et al. 2021), to fixed fishing rates assuming maximum sustainable yield (e.g. Cheung et al. 2022), to simplified bioeconomic fleet dynamics (e.g. Scherrer & Galbraith, 2020), to detailed regional fishing effort or mortality for multiple fleets (e.g. Coll et al. 2020). Furthermore, the lack of standardized future scenarios describing how unfolding socioeconomic and environmental conditions are likely to affect future fishing fleets, from artisanal to industrial scales, means that we have not yet been able to explore the potential future cumulative and interactive impacts of fishing and climate pressures on marine ecosystems (Maury et al., this issue). Previous ensemble projections have therefore focussed on investigating the effects of climate change 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).

In tandem, the ability of models to capture historical states and trends (i.e., model skill) is important for building confidence in the robustness and reducing the range of uncertainty in future projections. This is also the first step towards a detection and attribution framework, which is becoming prevalent in climate impact science (Mengel et al., 2021) and has been called for in ecological and biodiversity science (Gonzalez et al., 2023, Steenbeek et al. this issue, Mason et al. in this issue). However, our ability to test model skill in a systematic way has been limited by the availability of large-scale standardized calibration and evaluation data from fisheries-dependent and -independent sources, and by the ability to fully integrate an evaluation approach into the formal ensemble modelling protocol.

Here, we present "FishMIP 2.0", a new simulation framework, which aims to tackle a) a lack of standardized historical fishing data, b) a lack of future fisheries scenarios, and c) a comprehensive integration of a marine ecosystem model (MEM) assessment and evaluation into the simulation protocol. The framework is centred around two simulation modelling protocols that collectively contribute to the 3rd Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3) simulation round (Frieler, 2023). We describe the rationale and forcing data associated with these simulation protocols and how they can be used to accelerate our capacity to model past, present, and future states of marine ecosystems. We also identify additional challenges that need to be overcome to help develop more robust models of climate change impacts to support effective policy and management for different regions of the world.

2 Simulating the past and future of marine ecosystems and fisheries: an overview

The FishMIP 2.0 model ensemble currently consists of 9 global marine ecosystem models and potentially over 30 regional marine ecosystem models (Figure 1). All these models can be forced with both climate and fishing input variables, and do so in different ways, hence the ensemble captures MEM structural uncertainties (Supplementary Information). Our experimental framework has two “tracks" whereby our model ensembles are evaluated with observations under a realistic historical simulation (forced by an atmospheric reanalysis-driven ocean-biogeochemistry simulation), prior to carrying out past-to-future scenario projections with inputs that are solely based on coupled climate models. Detection of past change under “Track A” (ISIMIP3a) of our experimental framework aims to provide an opportunity to assess the degree to which temporal changes in climate, fishing, and/or dynamic river inputs contribute to capturing past changes in global catches and regional biomass trends, and to develop benchmarks that will help build confidence for our projections under future scenarios (Luo et al., 2012). “Track B” (equivalent to the Group III simulations of ISIMIP3b) of our simulation framework aims to assess and compare future pathways of ecosystems and fisheries, characterise potential risks for biodiversity and human societies, and identify adaptation pathways that avert and mitigate risks to help direct human development towards a more sustainable future.

FishMIP projections have been previously limited to future scenarios with either no fishing or future fishing held constant at contemporary levels (e.g. 2005 or 2015 levels; Lotze et al., 2019). We improve upon this by developing a set of future scenarios, the Ocean System Pathways (OSPs, Maury et al., this issue), which extends previous work (Maury et al., 2017) and is based on the IPCC Shared Socio-economic Pathways (SSPs, e.g. Riahi et al., 2016). The OSPs include detailed and contextualised storylines focused on the fisheries sector, as well as quantitative driver pathways (including economic, governance and management drivers), and a modelling framework that allows the incorporation of fleet and economic dynamics into the FishMIP MEMs to interactively (i.e. with two-way coupling) simulate fish prices, fishing effort, catches, and fisheries revenues, for different commodities, fishing fleet types and spatial scales, in a consistent and standardized manner across a range of ecosystem models.

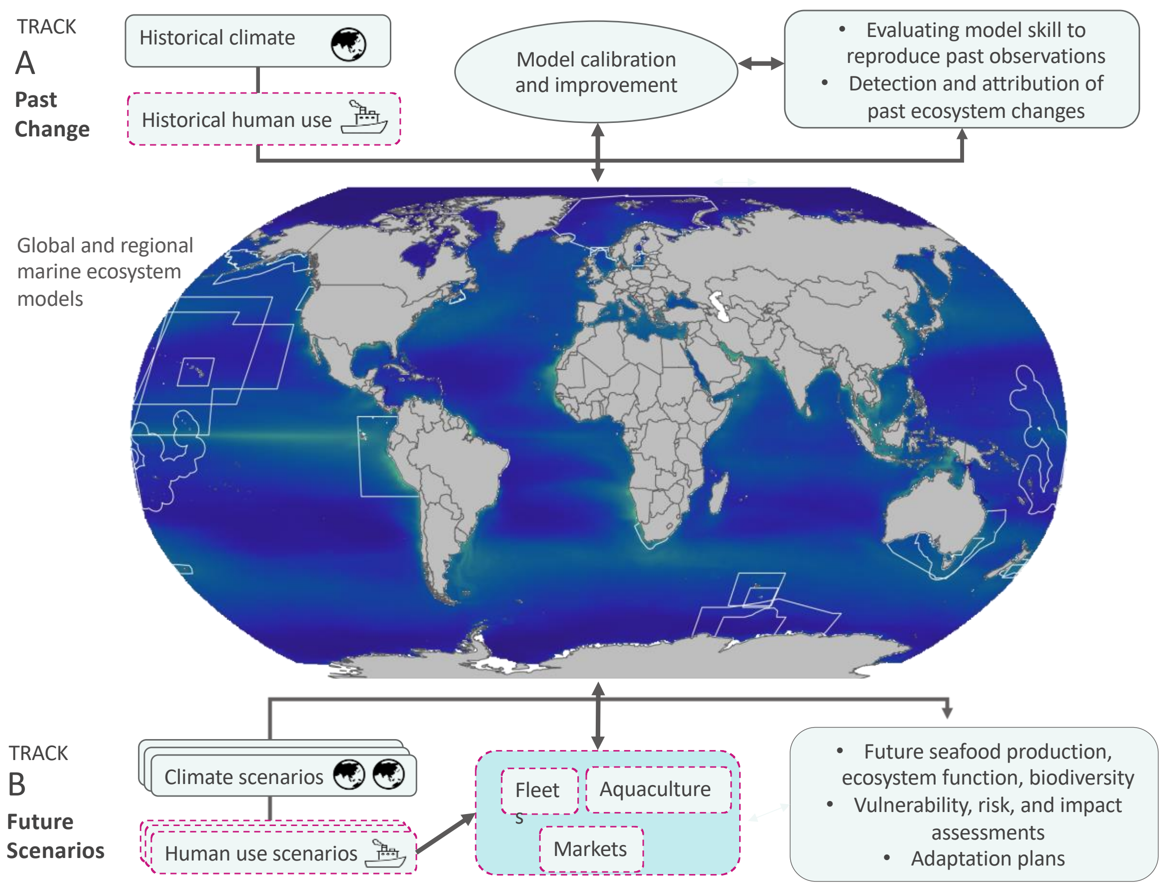

Figure 1. FishMIP 2.0 two-track model evaluation, detection, and projection. New components developed for FishMIP 2.0 are highlighted by the dashed red contours. Currently we have 9 global marine ecosystem models and over 20 regional marine ecosystem models (areas outlined in white on the map depict spatial domains of regional models), contributing to model simulations (see Table S1 and Fig. S2). Spatial grid cells show ¼ degree input for GFDL depth integrated primary production being used in Track A (see SI for all climate forcing variables).

Track A contributes towards ISIMIP3a and Track B contributes to ISIMIP3b Group III. More details on the protocols are available here for Track A: https://github.com/Fish-MIP/FishMIP2.0_TrackA_ISIMIP3a and Track B: https://github.com/Fish-MIP/FishMIP2.0_TrackB_ISIMIP3b.

3 Forcing data and scenarios

Both past and future ensembles require model inputs (e.g. climate and fishing forcings) that are standardized to be able to consistently carry out the simulation experiments across the FishMIP marine ecosystem models (MEMs) ensemble over space and time.

Track A - *Observed Drivers of Past Change*

The past century has seen an exponential global expansion of both industrial and artisanal fishing, in tandem with coastal impacts of land-based activities and long-term climate change. The historical climate forcing data that underpins our core model evaluation experiment (black lines in Figure 2A) are from the latest GFDL-MOM6 (Adcroft et al., 2019) and COBALTv2 (Stock et al., 2020) coupled physical and biogeochemical ocean models that are forced by an atmospheric reanalysis product (JRA-55; Tsujino et al., 2018) and run on a 0.25 degree tripolar grid. The GFDL-MOM6-COBALTv2 model also includes dynamic river freshwater and nitrogen inputs derived from long-term trends in land-use change (Liu et al., 2021). Because Earth System Models (ESMs) do not always include river dynamics from land use change, we have additionally included a sensitivity test that fixes land-used derived river inputs at average levels across 1950-1960 (Liu et al., 2021). To be able to attribute past ecosystem change to fishing versus climate drivers of change, we are also working towards a counterfactual (no-climate change) forcing, using these simulations.

To provide standardized data on past changes in fishing activity through time and space, we use the global gridded fishing effort data reconstruction by (Rousseau et al., 2022, 2024) for 1950-2010, and reconstructed historic effort backwards to 1861 using generalized additive models (see SI). We aggregated spatial fishing effort into large marine ecosystems, country-level exclusive economic zones, and United Nations FAO and/or specific regional MEM domains. Global and regional modellers can carry out their own finer-scale spatial allocation of fishing effort within these regions, to ensure fishing activity occurs in spatial grid cells that are consistent with modelled fish biomass. We provide descriptions for how each model in our ensemble, so far, uses these inputs (see links in SI, Table S2 and S3).

To be able to attribute past ecosystem change to fishing, our experimental setup compares "reconstructed fishing" and 'no fishing' simulation runs and could be extended to include 'low' fishing, based on average fishing effort across 1950-1960 (Figure 2). Further details of this experiment and data forcings are provided here: https://github.com/Fish-MIP/FishMIP2.0_TrackA_ISIMIP3a.

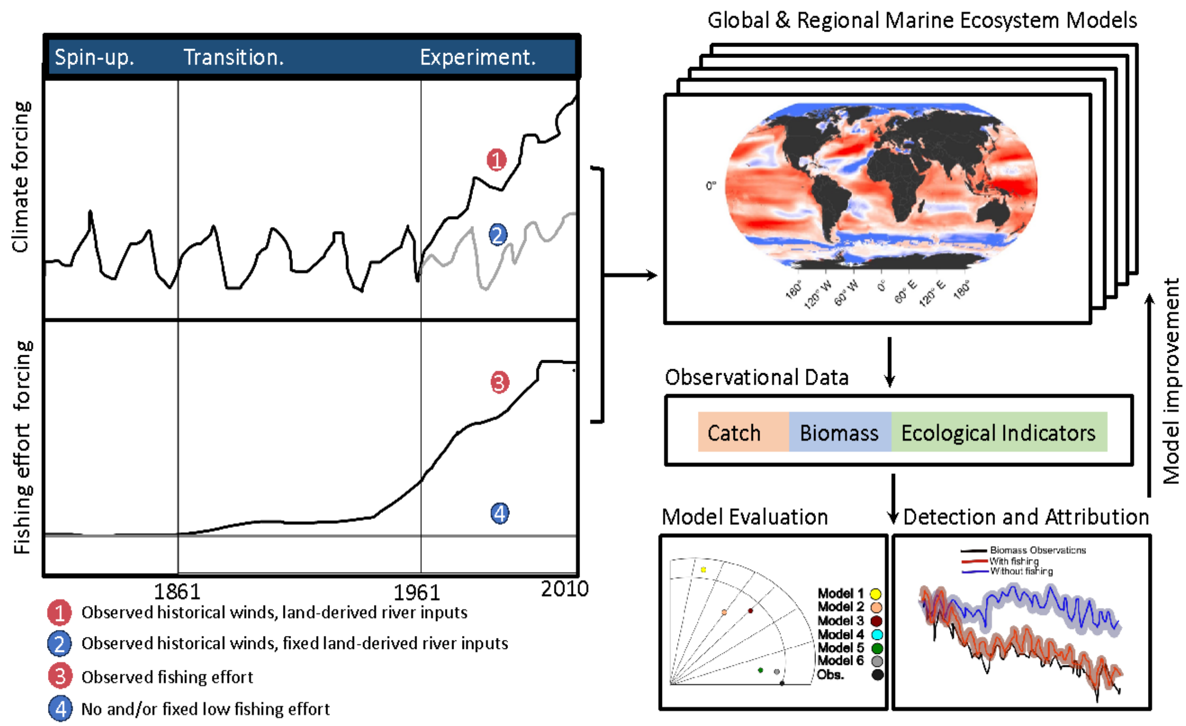

Figure 2. Conceptual representation of simulation experiment forcing being used to carry out historical model evaluation, detection and attribution experiments of past ecosystem and fisheries changes (Track A, contributing to ISIMIP 3a). Forcings are illustrative only, full list of climate variables provided in SI and here: https://github.com/Fish-MIP/FishMIP2.0_TrackA_ISIMIP3a .

Track B - *Future Scenarios and Drivers*

Our climate forcing for future scenario projections uses a variety of ocean physical and biogeochemical variables (SI, Table S1) from selected ESMs from the 6th round of the Coupled Model Intercomparison Project (CMIP6, Eyring et al., 2016; Tebaldi et al., 2021) prepared for the Intergovernmental Panel for Climate Change (IPCC). The CMIP6 simulations used include pre-industrial (PI) control runs, historical simulations, as well as SSP projections. The SSP (developed via in the Scenario MIP framework, O'Neill et al., 2016) are driven by different socioeconomic assumptions, which control greenhouse gas (GHG) emissions. SSPs capture harmonized, spatially explicit emissions and land use scenarios. In FishMIP 1.0, we used forcings from the GFDL and IPSL ESMs because they bracketed the uncertainty of climate change projections for ocean warming for CMIP5, being the coolest and warmest models, respectively, in addition to their divergent productivity trends (Bopp et al. 2013; Lotze et al. 2019; Fig. S1). Our new protocol also draws on the ISIMIP-adopted GFDL and IPSL CMIP6 simulations that contain the minimum set of variables needed for FishMIP 2.0 for SSP1-RCP2.6, SSP2-RCP4.5, SSP3-RCP7.0, SSP5-RCP8.5, historical, and pre-industrial control simulations (Figure 3); these two ESMs again have divergent climate sensitivities and productivity trends in CMIP6 (Tittensor et al. 2021; Petrik et al. 2022). In contrast to ISIMIP modelling efforts on land, detailed data required for bias correction of essential marine ecosystem drivers, such as plankton biomass, are not available due to sparse observations in the oceans. Instead, we are proposing to use simulations of future ocean climate that bias-correct atmospheric forcing using the JRA55 reanalysis product and hence enable a smooth transition between the historical (Track A) and future (Track B) scenarios, with better representation of ocean physical properties like coastal upwelling that are critical for marine ecosystem projections (Lengaigne et al., this issue) .

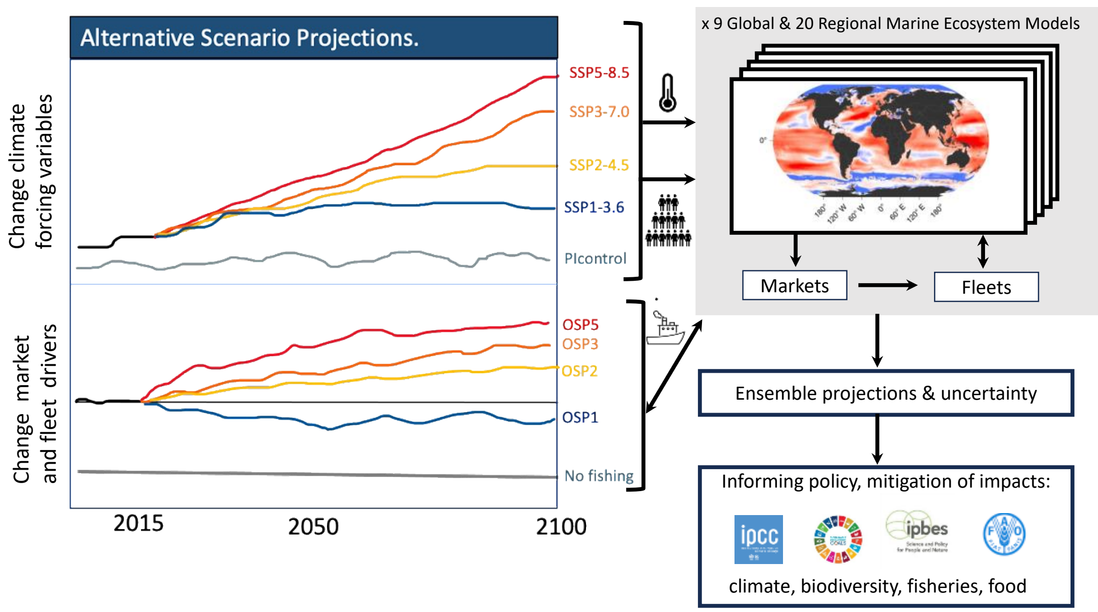

Figure 3. Conceptual representation of simulation experiment forcings over time being used to project future long-term changes under combined and relative effects of coupled climate and human development scenarios and example policy links (Track B). This experimental set-up also will contribute to the ISIMIP 3b Group 3 simulation protocol.

Combined with future climate change, our growing human population and demand for resources (Naylor et al., 2021) will place marine ecosystems under further pressure. To evaluate trade-offs and unintended consequences, future scenarios need to be compared to ensure any proposed solutions are sustainable, and ultimately need to be assessed in a cross-sectoral manner (Blanchard et al., 2017). The FishMIP Scenario working group has developed future qualitative scenario narratives and quantitative driver pathways that capture the dynamics of fisheries. dubbed the Ocean System Pathways (OSPs) (Maury et al., this issue).

Our future scenarios extend previous work (Maury et al., 2017) by providing driver pathways for national to global fishing fleets, from artisanal to industrial, in a dynamic and spatially explicit manner at the global scale and comprising aspects directly relevant to marine fisheries and aquaculture such as technological development in fishing fleets, changes in demand and price that respond to changing economies and ecosystems, governance, and management regulations (Maury et al., this issue). Notably, these scenarios are implemented in FishMIP 2.0 via a hierarchical framework that couples mini-fleet and mini-market models for MEMs that do not yet make these components explicit, while allowing those that do to retain their own representation (Cheung et al., 2021; Fulton et al., 2023; Scherrer & Galbraith, 2020). This results in a full two-way coupling in all MEMs, i.e. changes in marine ecosystems are reflected in changes in catch, which then are reflected in prices and changes in fishing effort which propagate down to changed ecosystem impacts. In this manner, climate-driven impacts on marine ecosystems are explicitly and directly coupled to the dynamics of fishing effort and its spatial distribution, fully linking the socio-economic and the ecological sides of fisheries.

The experimental protocol and scenario forcing to implement these future ensemble model runs are described here: https://github.com/Fish-MIP/FishMIP2.0_TrackB_ISIMIP3b. Our simulated future projections will provide knowledge on and uncertainty estimates around the evolution of fisheries under combined socio-economic and climate change scenarios and will provide a tool for developing and testing management and adaptation policies towards a sustainable future.

4 Evaluation data

Testing how skilfully MEM ensembles capture past changes in global ocean and coastal ecosystems and services is essential for building confidence in projections. Ideally, independent direct observations of ecosystem and fisheries state variables would be available to calibrate MEMs and evaluate their outputs. Yet, for many regions of the world, detailed standardized monitoring data on both socioeconomic and biological variables are lacking. The primary observational data in our framework are from global catch reconstructions (as in Rynne et al., this issue) and, for a subset of regions, fisheries-independent biomass bottom trawl survey data (van Denderen et al., 2023; Maureaud et al., 2021).

We hypothesize that forcing FishMIP models with more realistic fishing and environmental drivers of change will improve models' skill in reproducing both the inter-annual to decadal variability and the long-term trends in catches and biomass (Capotondi, et al. 2019; Jacox et al. 2020). First, because the environmental variability at the inter-annual to decadal temporal scales is better captured by the observationally based climate forcing (Liu et al., 2019) and, second, because the variability and trend of fishing effort are major drivers of biomass and catch changes (Agnetta et al., 2022). The simulation experiment framework (Fig. 2) will enable us to separate out - and potentially attribute - different drivers to ecosystem and fisheries change. Conversely, persistent regional misfit in both ocean and marine ecosystem models can help identify missing key processes and directions for model improvement (Kuhn & Fennel, 2019).

Comparing well-established metrics for quantifying model skill in time and space (Hipsey et al., 2020; Rynne et al. this issue) across models will enable us to develop model benchmarks and tools (Fu et al. 2022 such as those used for the International Land Model benchmarking, https://www.ilamb.org/ and) that we expect will ultimately lead to improved ecosystem models. As new data streams (e.g., eDNA), advanced statistical ensembles (Spence et al., 2023) and artificial intelligence approaches become increasingly accessible (Han et al., 2023), we envision scope for more rapid iterative ecosystem model development and improvement. Together, these should help reduce sources of uncertainty arising from models' structures or parameterizations. This will also include looking beyond biomass and catches towards more detailed and multifaceted aspects of biodiversity and ecosystem change. For example, we are testing theoretical predictions of how the relative effects of fishing and climate have altered biomass of functional groups and size classes (Novaglio et al, this issue) using an emergent constraints framework (Eyring et al., 2019).

While our current "Track A" evaluation focuses on fishing effort-forced MEMs, we plan to extend this to include a second evaluation experiment which aims to evaluate OSP methodology. The latter will also correspond to the historical component of our "Track B" OSP-driven model runs and will be cross-validated against price, fishing effort and catch data to ensure benchmarking of fully coupled fishing-MEMs prior to carrying out future scenarios. Ultimately, more robust past predictions will provide greater confidence in our future scenario projections and enable enhanced policy contributions.

5 Informing policy

Outcomes of simulations from our future scenario projections will enable us to examine differences in ecosystem indicators, fisheries yields, fishing effort, fish prices and fisheries profits, across and within regions. Relative comparison of future pathways will make it possible to assess climate change risks to future fisheries and seafood production for many regions of the world, in relation to human livelihoods, health and nutrition, and across other sectors. Advances made in FishMIP 2.0 are thus crucial to enable the development and comparison with integrated assessment models in other sectors to gain better understanding of human development on food security and biodiversity and to better inform integrative policies and decision making (Leclère et al., 2020).

Ultimately, in the face of multiple threats, we urgently need to understand how best to achieve healthy, resilient, and diverse ocean and coastal ecosystems that will continue to provide seafood and resources for generations to come. FishMIP 2.0 will provide improved modelling tools and data to test the scope for adaptation in the face of these combined threats for regions around the world. We hope that providing transparent assessments of model ensemble reliability will be a step-change in the confidence associated with FishMIP model projections; currently ranked as "low" to "medium" confidence according to the IPCC (Cooley et al., 2023). The combination of drivers that capture past and plausible future changes in fishing in the global ocean and more realistic coastal processes from climate model outputs will deliver projections that are more relevant for global and regional fisheries management.

Opportunities also exist for extensions of our core simulation experiments and their outputs, as a scaffolding to help inform the 2030 Agenda for Sustainable Development, at both global and regional scales. These could include simulations centred around interdependencies of UN Sustainable Development Goals (Nash et al., 2020) for meeting a sustainable blue future and the Post-2020 Global Biodiversity Framework, for example:

1. Wider range of future scenarios relevant for regional fisheries management adaptation plans to ensure food security under all SSPs (SDG14 Life below Water, SDG2 Zero Hunger, SDG1 No Poverty,..)
2. Climate-resilient Marine Protected Areas to protect and restore marine ecosystems (SDG14 Life below Water and SDG13 Climate Action)
3. Tests of climate intervention scenarios (e.g., geoengineering) to determine their potential impacts on ecosystem and fisheries and avoid unintended and irreversible consequences (SDG13 Climate Action, SDG14 Life below Water, SDG2 Zero Hunger)
4. Assess the future changes among biodiversity, water, food and health interdependencies (nexus assessment), which examines the interlinkages among the sustainable development goals related to food and water security, health for all, protecting (biodiversity on land and in the oceans and combating climate change (https://www.ipbes.net/nexus).

It is also notable that the Post-2020 Global Biodiversity Framework and in particular the United Nations Convention on Biological Diversity's 2050 global biodiversity goals requires cross-cutting and integrated actions (Leadley et al., 2010) across multiple targets (e.g., Target 1 on spatial planning, Targets 15/16 on sustainable consumption and production) that FishMIP 2.0's simulations are well-positioned to inform. By integrating climate impacts and a resolved and dynamic set of socioeconomic and fishing dynamics (Maury et al., this issue), trade-offs and synergistic benefits across multiple targets can be evaluated.

6 Conclusions

FishMIP 2.0 represents a substantial step forward from FishMIP 1.0, addressing some of the shortcomings and drawing from a larger pool of models and a more refined set of historical forcings and future scenarios, particularly around a more dynamic set of fisheries scenarios. Establishing an evaluation framework will help to quantify uncertainties, leading to improved models and greater confidence in projections. As a contributing sector to ISIMIP3, the opportunity for cross-sectoral evaluations of detection and projection of climate impacts will be enhanced (Frieler, 2023), as will the ability to explore and interrogate more comprehensive model outputs, all of which will be freely and publicly available (following ISIMIP terms of use, isimip.org). While the full integration of fishing provides a more tangible contribution to policy and management there is still a pressing need for publicly accessible fisheries and biological data needed to underpin skill assessments.

The integrated ensemble modelling of marine ecosystems has advanced rapidly over the past decade (Novaglio et al., this issue). FishMIP 2.0 will continue this trend, and as a community-led project, aims to continue its record of contributing to our understanding of how life in the oceans, and the benefits that it provides, will respond to accelerating global change.

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Open Research

All forcing data for FishMIP 2.0 protocols can be accessed at www.data.isimip.org. Climate forcings variables for Track A can be accessed here: https://data.isimip.org/10.48364/ISIMIP.920945 and fishing activity data can be accessed here: https://data.isimip.org/search/tree/ISIMIP3a/InputData/socioeconomic/fishing/histsoc/ . Additional tools, including Shiny apps for marine ecosystem modellers and end-users, can be found here: https://fishmip.org/tools.html. A repository for the archived FishMIP 2.0 Protocols available as living documents on GitHub (see list of links in Table S3 in SI) can be found here: 10.6084/m9.figshare.24972837 (upon publication).

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