ADVANCING EARTH AND SPACE SCIENCES

Earth's Future

COMMENTARY
10.1029/2023EF004402

Special Collection:
Past and Future of Marine Ecosystems

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 detect past ecosystem changes more accurately
- Our framework will help support model improvement, building confidence in future projections to underpin policy advice

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

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. *Earth's Future*, *12*, e2023EF004402. https://doi.org/10.1029/2023EF004402

Received 10 JAN 2024
Accepted 31 OCT 2024

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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 been limited by a lack of global standardized historical fishing data, low resolution of coastal processes, and uneven capabilities across the FishMIP community to dynamically model fisheries. These features are needed to evaluate how reliably the FishMIP ensemble captures past ecosystem states - a crucial step for building confidence in future projections. To address these issues, we have developed FishMIP 2.0 comprising a two-track framework for: (a) Model evaluation and attribution of past changes and (b) future climate and socioeconomic scenario projections. Key advances include improved historical climate forcing, which captures oceanographic features not previously resolved, and standardized global fishing forcing to test fishing effects systematically across models. FishMIP 2.0 is a crucial step toward a detection and attribution framework for changing marine ecosystems and toward enhanced policy relevance through increased confidence in future ensemble projections. Our results will help elucidate pathways toward achieving sustainable development goals.

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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 will 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 scenarios of both changing climate and socio-economic conditions, to better assess how future fisheries could 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, 2019; 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 modeling evidence of the ecological impacts of climate change on marine ecosystems (Cooley et al., 2023; Barrier et al., 2024), 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 for building confidence in model projections, informing the development of pathways and policies that will most effectively mitigate detrimental human impacts, and helping 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.

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 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., 2024). 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 (Heneghan et al., 2021; Lotze et al., 2019; Tittensor et al., 2018, 2021).

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 toward 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; Mason et al., 2024; Steenbeek et al., 2024). Model skill assessment has been constrained by two factors: limited access to large-scale

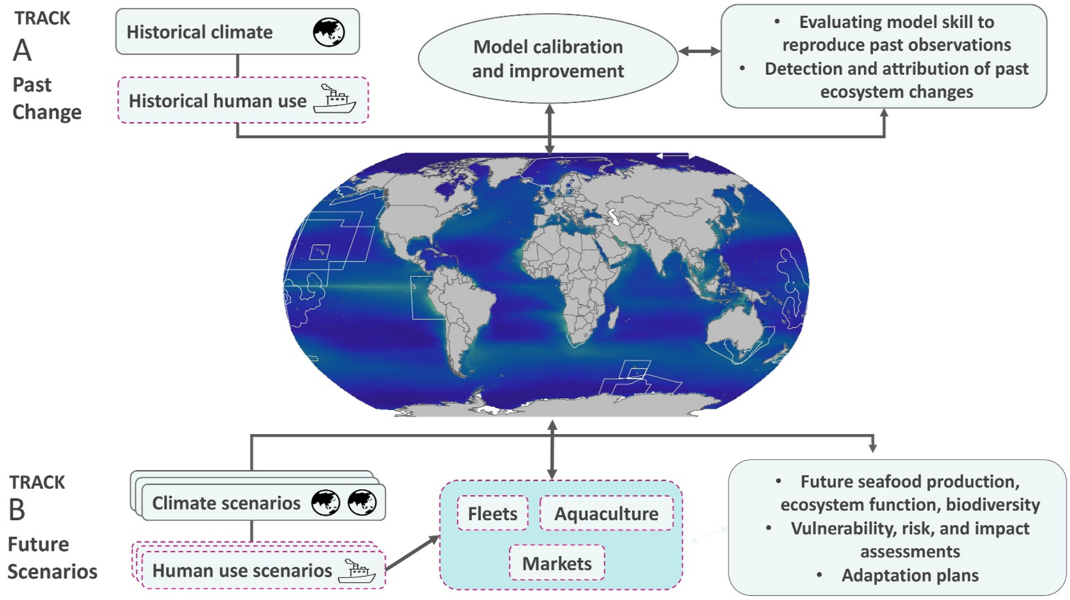

Figure 1. FishMIP 2.0 two-track model evaluation, detection, and projection. New components developed for FishMIP 2.0 are highlighted by the dashed red contours. Currently, we have 9 global marine ecosystem models and over 30 regional marine ecosystem models (areas outlined in white on the map depict spatial domains of regional models), contributing to model simulations (see Table S1 and Figure S2 in Supporting Information S1). 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 toward ISIMIP3a and Track B contributes to ISIMIP3b Group III. Further details are available at https://fishmip.org/protocols.html.

standardized observational data for calibration and evaluation, and challenges in incorporating evaluation methods into the ensemble modeling framework.

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 modeling protocols that collectively contribute to the third Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3) simulation round and simulation modeling protocols 3a and 3b (Frieler, 2023; https://www.isimip.org/protocol/3/). ISIMIP3a is designed for model evaluation and attribution of impacts across sectors (e.g., fisheries, water, agriculture) using observation-based inputs. ISIMIP3b is designed for quantification of long-term impacts of climate change, based on climate models and comparison of future conditions relative to historical or pre-industrial control scenarios (Frieler et al., 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. In doing so, we highlight several other key studies that have made FishMIP 2.0 possible, including but not limited to those in the "Past and Future of Marine Ecosystems" Earth's Future Special Collection. 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 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 (in Supporting Information S1). 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 based on coupled climate models. Detection of past change under "Track A" (ISIMIP3a) of our experimental

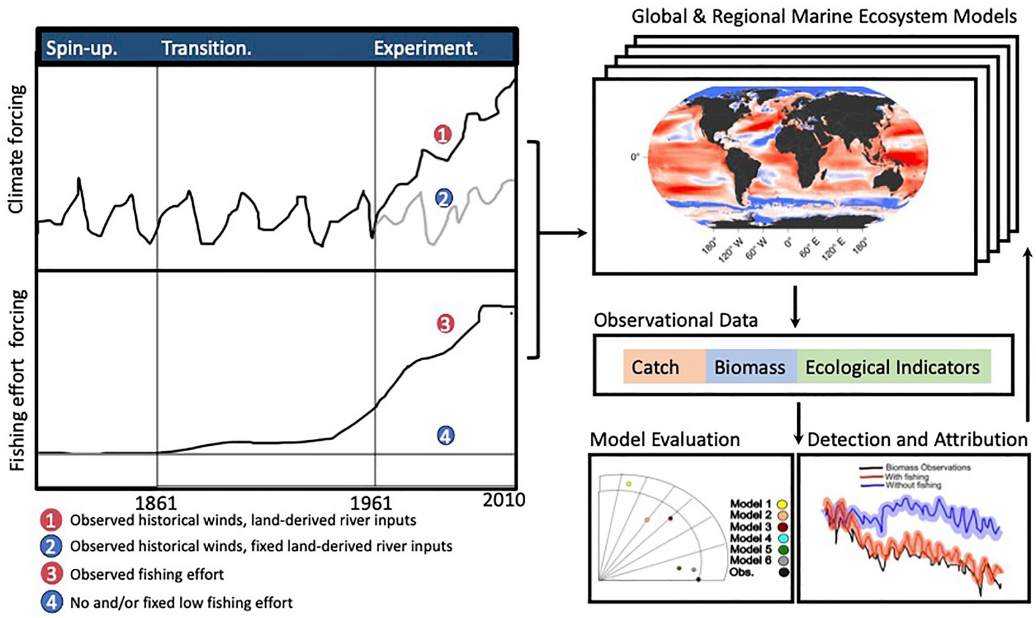

Figure 2. Conceptual representation of simulation experiment forcing being used to carry out historical model evaluation, detection and attribution experiments of past ecosystem and fisheries changes (Track A, contributing to Inter-Sectoral Impact Model Intercomparison Project 3a). Forcings are illustrative only, the full list of climate variables is provided in SI and https://fishmip.org/protocols.html.

framework aims to provide an opportunity to assess the degree to which temporal changes in climate, fishing, and/or dynamic coastal riverine 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 (Eyring et al., 2019; Luo et al., 2012. "Track B" of our simulation framework (equivalent to the Group III simulations of ISIMIP3b) aims to assess and compare future pathways of ecosystems and fisheries, characterize potential risks for biodiversity and human societies, and identify adaptation pathways that avert and mitigate risks to help direct human development toward 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., 2024), 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 contextualized storylines focused on the fisheries sector, as well as quantitative driver pathways (including economic, governance, and management drivers), and a modeling 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. The approach captures different commodities, fishing fleet types, and spatial scales, in a consistent and standardized manner across a range of ecosystem models.

3. Forcing Data and Scenarios

Both past and future tracks require 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) 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° 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 toward 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 back to 1861 using generalized additive models (see SI, Novaglio, Rousseau, et al., 2024). We aggregated spatial fishing effort into large marine ecosystems, country-level exclusive economic zones, major fishing regions of the Food and Agriculture Organization of the United Nations (FAO) and/or specific regional MEM domains. Global and regional modelers 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 modeled fish biomass. We provide descriptions for how each model in our ensemble, so far, uses these inputs (see links, Tables S2 and S3 in Supporting Information S1).

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 simulation experiment are provided in the SI.

Track B—Future Scenarios and Drivers.

Our climate forcing for future scenario projections uses a variety of ocean physical and biogeochemical variables (Table S1 in Supporting Information S1) from selected ESMs from the 6th round of the Coupled Model Intercomparison Project (CMIP6, Eyring et al., 2016; Tebaldi et al., 2021) prepared IPCC. The CMIP6 simulations used include pre-industrial (PI) control runs, historical simulations, as well as SSP projections. The SSPs (developed via the Scenario MIP framework, O'Neill et al., 2016) are driven by different socioeconomic assumptions, which control greenhouse gas (GHG) emissions. Shared Socio-economic Pathways 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; Figure S1 in Supporting Information 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 (Petrik et al., 2022; Tittensor et al., 2021). In contrast to ISIMIP modeling 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., 2024).

Combined with future climate change, our growing human population and demand for resources (Naylor et al., 2021) will put marine ecosystems under further pressure. To evaluate trade-offs and avoid unintended consequences, a range of future climate-socioeconomic scenarios are needed to ensure any proposed solutions are sustainable, both within and across sectors, and in the face of uncertainties (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, called the OSPs (Maury et al., 2024).

Each OSP corresponds to an SSP and is paired with the corresponding IPCC reference climate change scenario identified in the ScenarioMIP (O'Neill et al., 2016): OSP1-SSP1-2.6, OSP2-SSP2-4.5, OSP3-SSP3-7.0, OSP4-SSP4-6.0, and OSP5-SSP5-8.5 (Maury et al., 2024). To illustrate how each of these scenarios can inform the intersection of climate, fisheries and biodiversity policy, we have mapped some of the key features in terms of levels of emissions, warming, degree of biodiversity protection and effectiveness of fisheries management for

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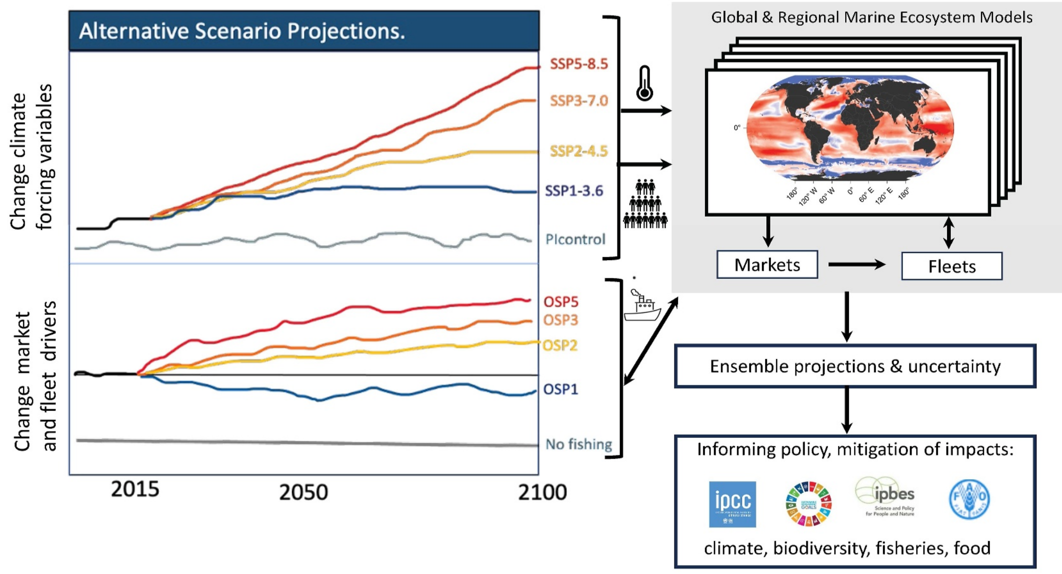

Figure 3. Conceptual representation of selected simulation experiment forcings over time being used to project future long-term changes under combined and relative effects of coupled climate and human development scenarios and example policy links (Track B). This experimental setup also will contribute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

four of the core scenarios (OSP1-SSP1-2.6, OSP2-SSP2-4.5, OSP3-SSP3-7.0, and OSP5-SP5-8.5) in Table 1. Further details are provided in Maury et al. (2024). In addition to qualitative storylines, the OSPs incorporate quantitative driver pathways, economic and fleet dynamics models that allow the simulation of fish prices, fishing effort dynamics and catches, and fisheries revenues, for different commodities and fishing fleet types interactively (i.e., with two-way coupling for a range of ecosystem models). Notably, this approach will build FishMIP community capacity to undertake fisheries scenarios by providing methods for MEMs that do not yet include socio-economic drivers, while allowing those that do to retain their own representation (Cheung et al., 2021; Fulton et al., 2023; Scherrer & Galbraith, 2020). The OSPs are the subject of a simulation protocol designed to inform the synthesis work of the IPCC and IPBES, as well as the political processes underway at the FAO with regard to fisheries management and food security (Maury et al., 2024).

The experimental protocol for implementing these future ensemble model runs can be found here: https://fishmip.org/protocols.html. 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 toward a sustainable future.

4. Detection and Evaluation of Data

Detection and attribution of past ecosystem change requires a combination of high-quality observational data and models realistic enough to capture the observed changes. 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 (Maureaud et al., 2021; D. van Denderen et al., 2023).

We hypothesize that forcing FishMIP models with more realistic fishing and environmental drivers of change will improve model accuracy 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

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Table 1

Mapping Key Features of a Selection of Linked OSP-SSP-RCP Future Scenarios in Terms of Emissions, Warming, Level of Biodiversity Protection and Fisheries Economy, Governance and Management

SSP	Emissions and warming scenario features	OSP	Marine fisheries economy, governance and management scenario features (see Maury et al. (2024))
SSP1-2.6	low GHG emissions: CO_2 emissions cut to net zero around 2075 Estimated averaged warming 1.8°C	OSP 1	"Sustainability first" -Demand for seafood increases but is met through increases in locally-sourced sustainable options-Sustainability and biodiversity conservation are guiding principles for fisheries policy. -Fisheries management is based on precautionary and adaptive reference points including but not limited to the use of Marine Protected Areas -Development of low-impact well-managed aquaculture
SSP2-4.5	intermediate GHG emissions: CO_2 emissions around current levels until 2050, then falling but not reaching net zero by 2100 Estimated averaged warming 2.7°C	OSP2	"Conventional Trends" -Demand for seafood continues to grow in globalized but unevenly distributed fish markets. -Fisheries management is unevenly effective and fisheries governance continues to disproportionately benefit high-income countries and firms. -Mariculture's growth slows due to the detrimental effects of global warming and other environmental impacts
SSP3-7.0	high GHG emissions: CO_2 emissions double by 2100 Estimated averaged warming 3.6°C	OSP3	"Dislocation" -Demand remains high because fish is a primary source of protein and other essential nutrients, but unequal distribution and access. -Widespread ineffective fisheries management and high levels of non-compliance, including unregulated high-seas
SSP5-8.5	very high GHG emissions: CO_2 emissions triple by 2075 Estimated averaged warming 4.4°C	OSP5	"High technology and market" -Growing global demand but decoupled from wild capture fisheries due to increasingly limited natural resources. -Technological advances enhance enforcement but market-forces hinder effective fisheries management by prioritizing consumers' immediate interest in low-cost products at the expense of biodiversity conservation

Note. The four SSP-RCP scenarios correspond to the Tier 1 scenarios in O'Neil et al., 2016. Estimated average warming is based on change in global surface temperature in 2081–2100 relative to 1850–1900 (ºC) (IPCC, 2021).

changes (Agnetta et al., 2022). The simulation experiment framework (Figure 2) will enable us to separate out - and potentially attribute - different drivers to ecosystem and fisheries change. Conversely, persistent regional misfits 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/) 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 different model structures or parameterizations. Evaluation will also look beyond biomasses and catch toward more detailed and multifaceted aspects of biodiversity and ecosystem change. For example, we will be able to assess the relative effects of fishing and climate change on ecosystem function and structure in more detail by examining biomasses of functional groups and size classes globally.

While our current "Track A" evaluation focuses on fishing effort-forced MEMs, we plan to extend this to include a second evaluation experiment that aims to evaluate OSP methodology (see Maury et al., 2024). The latter will also contribute 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 before simulating 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 improve understanding of human development on food security and biodiversity and to 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 modeling 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 centered around interdependencies of UN Sustainable Development Goals (Nash et al., 2020; Novaglio et al., 2024) for meeting a sustainable blue future and the Post-2020 Global Biodiversity Framework, for example:

1. Assess a wider range of future scenarios relevant for regional fisheries management adaptation plans to ensure food security under all SSPs (SDGs 1 No Poverty, 2 Zero Hunger, 8 Decent Work and Economic Growth, 12 Responsible Production and Consumption, 13 Climate Action, and 14 Life Below Water).
2. Inform climate-resilient Marine Protected Areas to effectively protect and restore marine ecosystems (SDGs 14 Life Below Water and 13 Climate Action).
3. Test climate intervention scenarios (e.g., geoengineering) to determine their potential impacts on ecosystem and fisheries and avoid unintended and irreversible consequences (SDGs 13 Climate Action, 14 Life Below Water).

Table 2
Summary Key Advances Contributing to the Development of FishMIP 2.0 and Relevant Publications

Feature	Key advance	Reference
Fishing	Global standardized fishing effort and reconstructed historical forcing	Novaglio, Rousseau, et al. (2024), Rousseau et al. (2024); this paper
	Standardized dynamic fishing effort implementation tools	Maury et al. (2024)
	Future fishing scenarios linked to Shared Socioeconomic Pathways (SSPs)	Maury et al. (2024)
Climate	Higher spatial resolution of Earth system model variables	Liu et al. (2019)
	Inclusion of changing coastal land-based nutrient inputs	Liu et al. (2019)
	Updated re-analysis-based climate forcing	Liu et al. (2019), Lengaigne et al. (2024)
	Bias corrected future climate forcing	Lengaigne et al. (2024)
Community	Workflow for regional marine ecosystem application and extension	Ortega-Cisneros et al. (2024), Murphy et al. (2024)
	Model skill assessment and evaluation tools	Rynne et al. (2024), Steenbeek et al. (2024), Ouled-Cheikh et al. (2024)
	Use of global marine ecosystem projections at regional scales	Eddy et al. (2024), Mason et al. (2024), Murphy et al. (2024), Bryndum Buccholz et al. (2023)
	Model-specific advances and development	P. D. van Denderen et al. (2024), Guiet et al. (2024), Steenbeek et al. (2024), Barrier et al. (2024), Boot et al. (2024)
	Continued contribution to the Intersectoral Impact Model Intercomparison Project (ISIMIP)	Frieler et al. (2023)
	Wider policy-relevant impacts and alignment	Blanchard and Novaglio (2024), Novaglio et al. (2024), Novaglio et al. (2024), Maury et al. (2024), this paper

4. Compare future changes among biodiversity, water, food and health interdependencies (nexus assessment), to examine trade-offs 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) (e.g., 2 Zero Hunger, 6 Clean Water and Sanitation, 14 Life Below Water, 15 Life on Land, and 13 Climate Action).

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., 2024), 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, 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 (Table 2). 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 to underpin skill assessments.

The integrated ensemble modeling of marine ecosystems has advanced rapidly over the past decade (Novaglio et al., 2024). 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, with its many benefits for people, will respond to accelerating global change.

Acknowledgments
JLB, CN, LFA and EO acknowledge support from the Australian Research Council Future Fellowship Project (FT210100798) and computational support from the Australian Research Data Commons Nectar Research Cloud via the University of Tasmania. JLB and KJM acknowledge support from the Australian Antarctic Centre of Excellence and the Australian Antarctic Program Partnership (AAPP). OM acknowledges support from the European Union's Horizon 2020 research and innovation program under Grant agreement N° 817806. DPT acknowledges support from the Jarislowsky Foundation and NSERC. D.B. and J.G. acknowledge support from the US National Aeronautics and Space Administration (NASA) Grant 80NSSC21K0420, and computational resources by the Expanse system at the San Diego Supercomputer Center through allocation TG-OCE170017 from the Advanced Cyber infrastructure Coordination Ecosystem: Services and Support (ACCESS) program, which is supported by National Science Foundation Grants 2138259, 2138286, 2138307, 2137603, and 2138296. MC acknowledges support from the Spanish project ProOceans (Plan Estatal de Investigación Científica, Técnica y de Innovación, 2020, PID2020-118097RB-I00) and the "Severo Ochoa Centre of Excellence" accreditation (CEX2019-000928-S) to the Institute of Marine Science (ICM-CSIC). CMP was supported by NOAA-CPO-MAPP Grants NA20OAR4310438, NA20OAR4310441, and NA20OAR4310442. KOC acknowledges support from the National Research Foundation of South Africa (Grant 136481), MISSION ATLANTIC Horizon 2020 Research and Innovation Program (862428) and the Centre for High Performance Computing (CHPC), South Africa, for providing computational resources. K.J.N.S is funded by the Norwegian Research Council, project 326896. YJS and ROR acknowledge support from the European Union's Horizon 2020 research and innovation programme under Grant agreement No 869300 (FutureMARES), the Horizon Europe research and innovation programme under Grant agreement No 101060072 (ActNow), France Filière Pêche, and the Pew marine fellows programme. CSH and KR acknowledge funding from US National Oceanic and Atmospheric Administration Climate Program Office, and US National Science Foundation awards 2218777 and 2149890. This paper was discussed at the ISIMIP Prague 2023 workshop supported by COST Action CA19139 PROCLIAS (PROcess-based models for CLimate Impact Attribution across Sectors), supported by COST (European Cooperation in Science and Technology; https://www.cost.eu), a FishMIP 2022 workshop in St John's Newfoundland,

Data Availability Statement

All forcing data for FishMIP 2.0 protocols can be accessed by following instructions here: https://www.isimip.org/outputdata/isimip-repository/. Climate forcing variables for Track A are available from Liu et al. (2022) and Novaglio, Rousseau, et al. (2024). Additional tools, including Shiny apps for marine ecosystem modellers and end-users, can be found here: https://fishmip.org/tools.html. Further documentation of FishMIP 2.0 protocols is available here: https://fishmip.org/protocols.html.

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Canada (partially supported by the Belmont Forum project: SOMBEE) and a joint NOAA-FishMIP workshop in Honolulu, 2023, partially supported with funding from NOAA. We thank all FishMIP members and participants who have provided valuable inputs in these and other workshops. We are grateful to the ISIMIP project and coordination team for their ongoing support of FishMIP. Open access publishing facilitated by University of Tasmania, as part of the Wiley - University of Tasmania agreement via the Council of Australian University Librarians.

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