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Special Collection:
Past and Future of Marine Ecosystems

Key Points:
- We present new scenarios and models for simulating fisheries and marine ecosystems, accounting for climate and socio-economic changes
- Our scenario framework extends the SSPs. It can be utilized by any marine ecosystem model and in particular those contributing to FishMIP
- We propose a simulation strategy addressing major research gaps and including policy-targeted simulation experiments

Correspondence to:
O. Maury,
Olivier.maury@ird.fr

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The Ocean System Pathways (OSPs): A New Scenario and Simulation Framework to Investigate the Future of the World Fisheries

O. Maury[1], D. P. Tittensor[2], T. D. Eddy[3], E. H. Allison[4,5], T. Bahri[6], N. Barrier[1], L. Campling[7], W. W. L. Cheung[8], K. Frieler[9], E. A. Fulton[10,11], P. Guillotreau[1], R. F. Heneghan[12,13], V. W. Y. Lam[8], D. Leclère[14], M. Lengaigne[1], H. Lotze-Campen[9,15], C. Novaglio[6,16], K. Ortega-Cisneros[17], J. Rault[18], J. Schewe[9], Y.-J. Shin[1], H. Sloterdijk[19], D. Squires[20], U. R. Sumaila[8,21], A. N. Tidd[1], B. van Ruijven[14], and J. Blanchard[16]

[1]MARBEC, University Montpellier, IRD, CNRS, Ifremer, INRAE, Sète, France, [2]Department of Biology, Dalhousie University, Halifax, NS, Canada, [3]Centre for Fisheries Ecosystems Research, Fisheries & Marine Institute, Memorial University, St. John's, NL, Canada, [4]WorldFish, Bayan Lepas, Penang, Malaysia, [5]Lancaster Environment Center, Lancaster University, Lancaster, UK, [6]Food and Agriculture Organization, Rome, Italy, [7]School of Business and Management, Queen Mary University of London, London, UK, [8]Institute for the Oceans and Fisheries, The University of British Columbia, Vancouver, BC, Canada, [9]Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany, [10]CSIRO Environment, Hobart, TAS, Australia, [11]Centre for Marine Socioecology, University of Tasmania, Hobart, TAS, Australia, [12]School of Science, Technology and Engineering, University of the Sunshine Coast, Petrie, QLD, Australia, [13]Australian Rivers Institute, School of Environment and Science, Griffith University, Nathan, QLD, Australia, [14]International Institute for Applied System Analysis (IIASA), Laxenburg, Austria, [15]Humboldt-Universität zu Berlin, Berlin, Germany, [16]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, TAS, Australia, [17]Department of Biological Sciences, University of Cape Town, Cape Town, South Africa, [18]IFREMER, Centre de Bretagne, Plouzané, France, [19]Christian-Albrechts-University Kiel, Center for Ocean and Society, Kiel, Germany, [20]University of California San Diego, San Diego, CA, USA, [21]The School of Public Policy and Global Affairs, University of British Columbia, Vancouver, BC, Canada

Abstract The Fisheries and Marine Ecosystems Model Intercomparison Project (FishMIP) has dedicated a decade to unraveling the future impacts of climate change on marine animal biomass. FishMIP is now preparing a new simulation protocol to assess the combined effects of both climate and socio-economic changes on marine fisheries and ecosystems. This protocol will be based on the Ocean System Pathways (OSPs), a new set of socio-economic scenarios derived from the Shared Socioeconomic Pathways (SSPs) widely used by the Intergovernmental Panel on Climate Change (IPCC). The OSPs extend the SSPs to the economic, governance, management and socio-cultural contexts of large pelagic, small pelagic, benthic-demersal and emerging fisheries, as well as mariculture. Comprising qualitative storylines, quantitative model driver pathways and a "plug-in-model" framework, the OSPs will enable a heterogeneous suite of ecosystem models to simulate fisheries dynamics in a standardised way. This paper introduces this OSP framework and the simulation protocol that FishMIP will implement to explore future ocean social-ecological systems holistically, with a focus on critical issues such as climate justice, global food security, equitable fisheries, aquaculture development, fisheries management, and biodiversity conservation. Ultimately, the OSP framework is tailored to contribute to the synthesis work of the IPCC. It also aims to inform ongoing policy processes within the United Nations Food and Agriculture Organization (FAO). Finally, it seeks to support the synthesis work of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), with a particular focus on studying pathways relevant for the United Nations Convention on Biological Diversity.

Plain Language Summary The Fisheries and Marine Ecosystems Model Intercomparison Project (FishMIP) has spent 10 years studying how climate change might affect marine life. FishMIP is now getting ready for simulating how climate and socio-economic changes will affect marine fisheries worldwide. For this purpose, FishMIP develops the Ocean System Pathways (OSPs), a new set of scenarios that extend the scenarios used by the Intergovernmental Panel on Climate Change (IPCC) by considering the socio-economic factors related to different types of fishing and mariculture. The OSPs detail what might happen in the future and provide tools that will allow the ecosystem models involved in FishMIP to simulate fisheries in a consistent way. This paper presents the OSP framework and the simulation strategy adopted to explore how ecosystems and fisheries might change in the future, focusing on key issues such as climate justice, food security, equitable fisheries management, and biodiversity conservation. Ultimately, this work will contribute to the IPCC and to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) in understanding how to manage the impacts of climate change. It will also support the Food and Agriculture Organization of the United Nations (FAO) in assessing fisheries policies in the context of global change.

1. Introduction

Projecting the future trajectories of marine social-ecological systems is highly challenging, with many sources of uncertainty. The biophysical system consists of intricate networks of numerous species and processes that span multiple scales and exhibit non-linear responses to changes. These are reciprocally interacting with layered human networks and activities, which are just as complex (e.g., Berkes & Folke, 1998; Redman et al., 2004). There is no single way of modeling this complexity (e.g., Schlüter et al., 2019). However, ensembles of independently developed models can help quantifying the uncertainty associated with climate impact projections (see Box 1 for definitions) under various scenarios of future GHGs emissions (e.g., IPBES, 2016). To do this, sets of projections can be produced by simulating identical scenarios with multiple models, using standardised inputs and producing standardised outputs.

Box 1

There is often confusion between the terms scenarios, storylines, pathways, and projections, which can sometimes be perceived as overlapping. In the present paper we use these terms in the following sense:

- **Scenarios** describe plausible futures of a given system in an internally consistent way. They include qualitative storylines as well as quantitative pathways of relevant variables, which can be either model drivers that are prescribed to derive scenario-based model projections, or simulated trajectories of prognostic variables of the modeled system.
- **Storylines** are qualitative narratives that provide the context and unfolding of events of a given scenario in "words".
- **Pathways** are quantitative time-dependent trajectories of specific variables of the system (either model drivers or simulated prognostic variables) that evolve consistently with the storylines.

A **projection** is a numerical simulation of a future trajectory of the system based on a given model, a given set of drivers' pathways, and a given set of initial conditions. An ensemble of projections (simulated by the same model from an ensemble of initial conditions, or by an ensemble of models from a given initial condition) provides the statistical distribution (ensemble mean and variance) of the future system trajectories.

In this perspective, mirroring the approach of CMIP, which provides global ensemble projections of climate change to facilitate scientific understanding, support policy discussions and in particular contribute to the Intergovernmental Panel on Climate Change (IPCC) assessments, the international FishMIP consortium (https://www.fishmip.org/) is producing sets of ensemble projections of the impacts of climate change on marine ecosystems and fisheries at both global and regional scales (e.g., Blanchard et al., 2024; Tittensor et al., 2018). These are helpful to understand these impacts and contribute to science-policy processes, particularly through the IPCC and IPBES. Since its inception in 2013, the FishMIP program has led to several collective publications (e.g., Bryndum-Buchholz et al., 2019, 2020, 2023; Frieler et al., 2024; Lotze et al., 2019; Tittensor et al., 2018), notably in the areas of food security (Blanchard et al., 2017), trophic amplification of impacts (Guibourd de Luzinais et al., 2023; Heneghan et al., 2021) and climate risks (Cinner et al., 2022; Tittensor et al., 2021). These findings have been included in several national-level climate response plans and major science to policy reports (e.g., IPBES, 2019; IPCC, 2019a, 2019b, 2022; Novaglio et al., 2024).

However, to date, FishMIP simulations have only considered the effects of climate change on marine ecosystems, accounting for the effects of fishing in a very crude way (e.g., assuming either constant fishing effort or no fishing effort in future scenarios) and disregarding the concurrent and dynamically interacting effects of future socio-economic changes on fisheries (e.g., Lotze et al., 2019; Tittensor et al., 2021). For its next round of simulations, FishMIP aims to produce ensemble projections of the future of the world's marine fisheries and mariculture, simultaneously taking into account climate and socio-economic influences along with the intertwined feedbacks between ecological and human components of fisheries dynamics. To this end, the marine ecosystem models (MEMs) participating in FishMIP 2.0 (Blanchard et al., 2024) will be driven by the Ocean System Pathways (OSPs), a new set of fisheries scenarios and associated model framework derived from and extending the Shared Socioeconomic Pathways (SSPs, e.g. O'Neill et al., 2017). Originally developed to represent plausible futures of large pelagic fisheries (Maury et al., 2017), the OSP storylines have been extended by the FishMIP Scenario Working Group to also cover the future of small pelagic, benthic-demersal and emerging fisheries, as well as mariculture. These storylines identify and detail the evolution of the major driving forces in the economic, governance, management and socio-cultural domains, which are expected to shape the future of fishing fleets and seafood markets in the five SSP contexts. In addition to qualitative storylines, the OSPs include quantitative model driver pathways and a "plug-in-model" (PIM) framework designed to allow any ecosystem model to simulate dynamic fisheries, accommodating models that currently lack such functionality. When coupled with ecosystem models, the OSP framework will enable the simulation of marine biodiversity, fishing effort, fishery catch, seafood prices and consumption at global, regional, sub-regional and national levels in response to both climate change and the evolving global socio-economic contexts.

Here we present the OSP framework, including storylines, quantitative drivers and the PIM framework. We also outline the experimental simulation protocol that FishMIP will implement to explore policy-relevant research questions, with a focus on critical issues such as climate justice, global food security, equitable fisheries, aquaculture development, fisheries management and biodiversity conservation. Ultimately, the OSP framework is tailored to contribute to the synthesis work of the IPCC in the political context of the UN Framework Convention on Climate Change (UNFCCC). It also aims to inform ongoing policy processes within the United Nations Food and Agriculture Organization (FAO). Finally, it seeks to support the synthesis work of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), with a particular focus on studying pathways toward the implementation of the Kunming-Montreal Global Biodiversity Framework (GBF) of the United Nations Convention on Biological Diversity (CBD).

2. The Ocean System Pathways

The OSP scenarios extend the Shared Socioeconomic Pathways (SSPs), which are commonly used in climate change research, to cover the marine fisheries and mariculture sectors. They include qualitative storylines and quantitative fisheries model driver pathways that are both fully consistent with the SSPs. They also include three PIMs to represent market and price dynamics, fleet dynamics and aquaculture dynamics in a straightforward and robust way. Specifically designed for online coupling with FishMIP ecosystem models, the PIMs are forced by the OSP drivers to simulate the dynamics of fisheries for each scenario.

2.1. The OSP Narratives and Scope

2.1.1. The OSP Storylines Extend the SSPs to Marine Fisheries

The five OSP storylines were all constructed in the same way by identifying the main driving forces of marine fisheries in the four areas of "fisheries management" (e.g., the targets and tools used to regulate fisheries), "fisheries governance" (e.g., the governmental institutions and non-governmental interests actually shaping fisheries policies), "fisheries economics" (e.g., the drivers of demand, costs and prices) and "socio-cultural environment" (e.g., social structures and cultural values). The OSPs describe the evolution of these forces in a manner consistent with the SSP contexts, and their associated reference climate change scenario (the Tier 1 of the ScenarioMIP, see O'Neill et al., 2016), such that each OSP extends one SSP (Maury et al., 2017). They are therefore all structured in the same way and can be briefly summarized as follows:

- The OSP1 "Sustainability first" extends the SSP1 context of a world where sustainable practices are consistently implemented across multiple sectors. In OSP1, individual preferences for high-quality wild fish remain high in mid- and high-income countries where there is a transition to low-carbon protein sources (fish vs. livestock), and it increases through to 2100 globally, largely driven by increasing demand from currently low-income populations and countries becoming progressively wealthier. At the same time, mid-to low-income populations in upwelling regions (e.g., Chile, Peru, South Africa, Namibia, Senegal, Mauritania…) increasingly consume small pelagic species, while a smaller proportion is used for fishmeal and fish oil, as aquaculture transitions to non-fish food sources and shifts to higher value fish. The emphasis on reducing long-distance transport and encouraging local consumption fosters the prominence of regional and even sub-regional markets. In the OSP1 world, sustainability and biodiversity conservation are guiding principles for fisheries policy. Fisheries management is based on the extensive use of marine protected areas (MPAs) and precautionary and adaptive reference points to ensure ecosystem health, food security and economic viability of fisheries.

- The OSP2 "Conventional Trends" extends the SSP2, which depicts a world continuing on current trajectories, marked by both progressive deterioration and moderate improvement in various areas. Following the demographic and economic trends in SSP2, the demand for fisheries and mariculture products continues to grow in globalized but unevenly distributed fish markets, putting more pressure on already fully exploited or over-exploited fish stocks. Fisheries management is largely based on quotas despite some progress in spatial management approaches and the implementation of MPAs. Management is unevenly effective as research, monitoring and enforcement capabilities remain low in many countries, and fisheries governance continues to disproportionately benefit high-income countries and firms (e.g., through access and subsidies). Although mariculture's share of global marine fish production has been increasing since the 1970s, its growth rate has been decreasing due to the detrimental effects of global warming and other environmental impacts, limitations that are anticipated to increase throughout the century in OSP2.
- The OSP3 "Dislocation" unfolds in the SSP3 context of heightened nationalism, economic rivalries, geopolitical conflicts and very large regional economic disparities. It describes the fragmentation of markets for aquatic products down to the national level, the failure of fisheries management and the dismantling of international cooperation. In OSP3, increased economic competition between countries leads to heavy subsidies for distant-water fishing fleets to exploit the High Seas, where exploitation is no longer regulated. However, the fragmentation of markets significantly reduces the ability of coastal industrial fisheries and aquaculture businesses to invest and cover their operational costs, in contrast to less capitalized artisanal forms of production. In this scenario, demand remains high because fish is a primary source of protein and other essential nutrients in many countries. However, despite the predominantly local consumption of fish, widespread food security challenges are common in many countries due to a lack of trade and cooperation, the failure of management institutions, and non-compliance by fishers focused on short-term survival.
- The OSP4 "Global elite and inequalities" is consistent with SSP4 techno-optimism, robust economic growth and pronounced global intra- and international inequalities. It depicts a world where high-value fisheries and aquaculture products are accessible only to the elite. Low-quality products supply high-standard aquaculture firms and the remaining volume of seafood products is too limited to feed the vast majority of the population, who cannot afford expensive fish and rely instead on cheap industrial animal commodities. Multinational corporations dominate the global economy, favoring transnational elites. Developing countries are largely excluded from decision-making and fisheries management is designed to maximize corporate profits, utilizing advanced monitoring and enforcement technologies to ensure compliance, and maintaining high environmental standards to meet certification labels.
- The OSP5 "High technology and market" extends the SSP5 scenario, which describes a world of rapid economic growth and technological progress fueled by cheap fossil energy and increasing reliance on globally connected markets. Although fishing costs are low, growing global fish consumption is increasingly decoupled from wild capture fisheries due to the development of productive aquaculture industries. Wild-caught fish remains a preference for the wealthy, while aquaculture caters to the needs of low- and middle-income consumers. Despite ecological damages, emerging fisheries targeting mesopelagic resources develop to complement small pelagic fisheries in supplying fishmeal and fish oil to the aquaculture industry. In SSP5, global governance aims to maintain economic cooperation and expand the consumer base of markets. This reduces economic disparities between low-income and high-income countries as low-income ones benefit more from economic growth. However, geopolitical tensions arise over increasingly limited natural resources, blocking international governance of the High Seas and coastal waters of states with low capabilities, which are in a virtually open access situation. Technological advances enhance enforcement due to the generalization of remote monitoring systems, but the global emphasis on market-driven measures often hinders effective fisheries management by prioritizing consumers' immediate interest in low-cost products at the expense of biodiversity conservation.

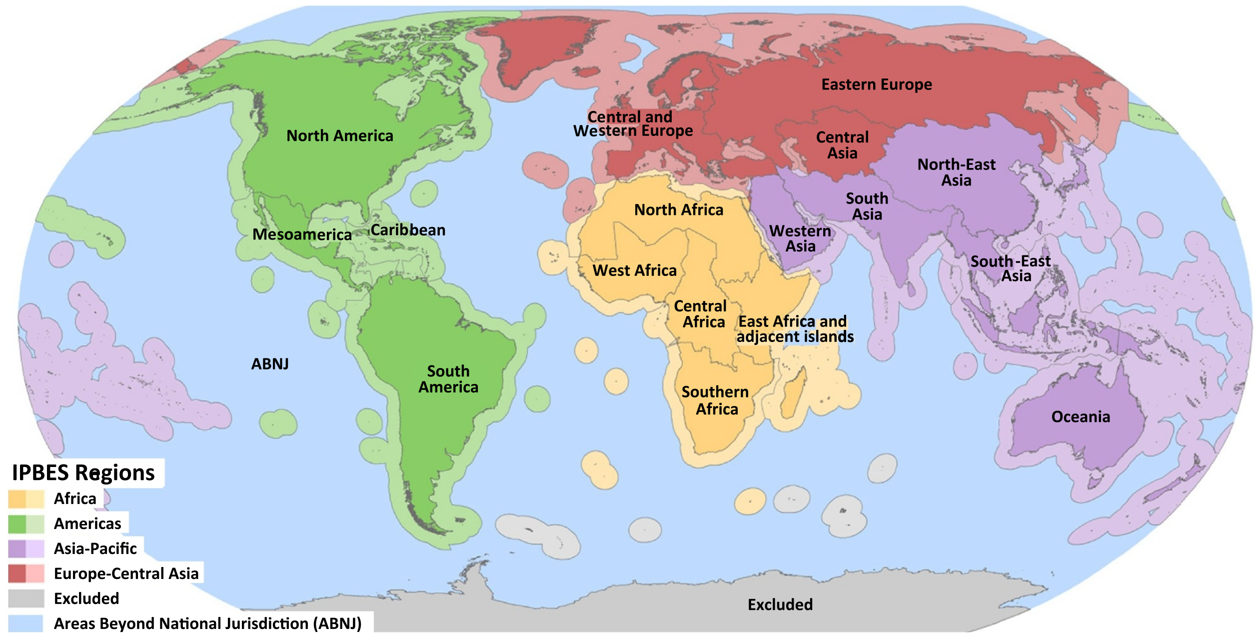

Figure 1. The 4 IPBES regions and 17 sub-regions (modified from Brooks et al., 2016).

2.1.2. The OSPs Cover All Global Marine Fisheries and Mariculture

Initially developed to characterize plausible future evolutions of oceanic fisheries (Maury et al., 2017), the OSP storylines have been extended to cover all global marine fisheries and the aquaculture production of sea products. These extended OSPs (now the Ocean System Pathways) include storylines and driver pathways for large pelagic fisheries (tuna and tuna-like species), demersal and benthic fisheries, small pelagic fisheries, emerging fisheries (mesopelagic fish, krill, etc) and marine aquaculture.

Industrial fisheries, characterized by large-scale profit-driven operations, employ advanced technologies to harvest significant quantities of fish, usually for regional or global markets. In contrast, artisanal fisheries, based on smaller community-oriented companies, often rely on traditional fishing methods and small boats. Operating locally, they prioritize subsistence, support small communities, and contribute to local markets, although they may sometimes target high-value species for the export market (e.g., Short et al., 2021). For the sake of realism and because their scales, gears, economic organization, social roles, purposes, impacts, and management differ widely, the OSPs explicitly distinguish artisanal from industrial fleets and provide distinct driver trajectories for each.

2.1.3. The OSP Storylines Specify the Spatial Integration of Markets

The spatial integration of markets (SIM) is a critical factor in economic dynamics. In the OSP framework it defines the geographical extent of markets within which demand functions are calculated, assuming that the law of one price holds and that commodities circulate easily within these integrated regions. In the OSPs, the fish markets are supposed to be either fragmented to the country level or operating at a broader scale (sub-regional, regional or global), based on the IPBES geographic partitioning (Figure 1). The degree of spatial integration of fish markets (the SIM) is a crucial characteristic specified for each OSP storyline. It determines demand functions and commodity flows, playing a significant role in the economic profitability of both fishing and aquaculture industries, thus influencing their dynamics.

2.2. Simulating the OSPs

2.2.1. The Need for Coupling Models From Climate to Markets

FishMIP seeks to simulate the intertwined impacts of climate and socio-economic changes on marine biodiversity and fisheries evolution. In this integrative social-ecological perspective, process-based models need to be coupled

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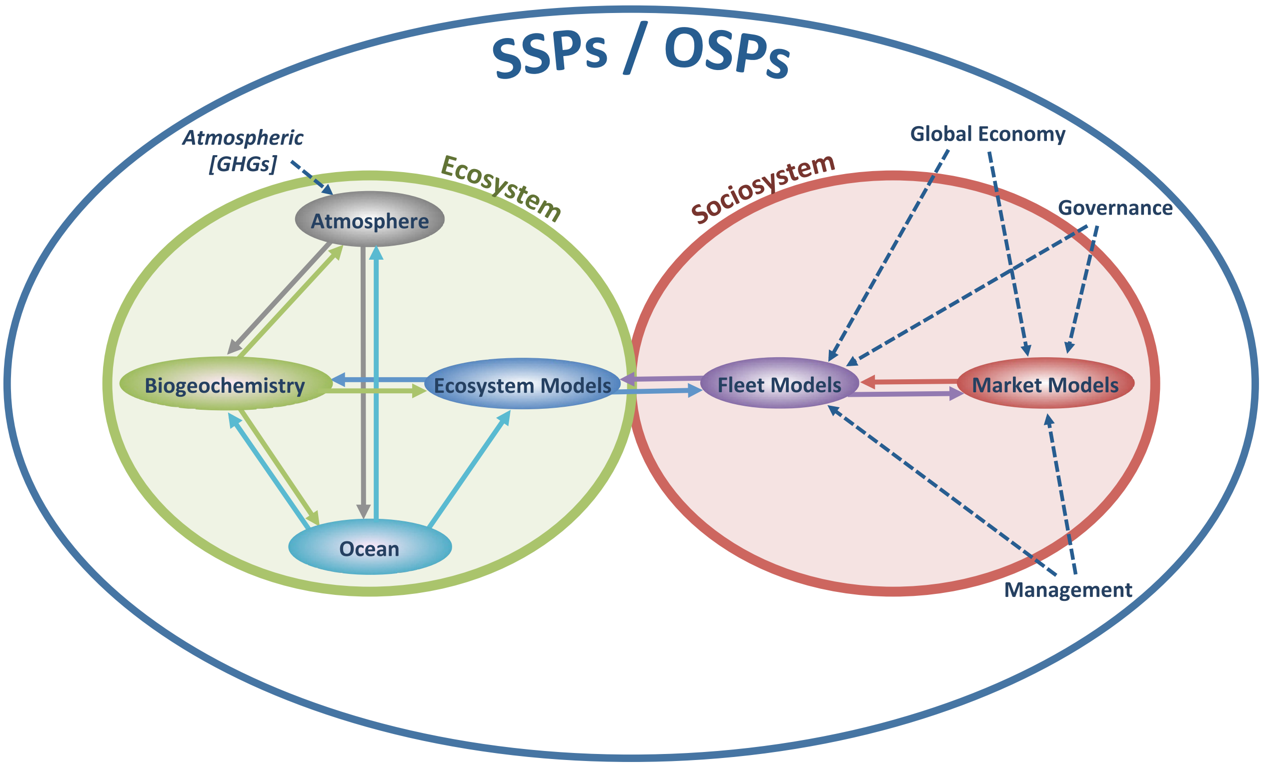

Figure 2. The social-ecological model coupling and scenario approach used in FishMIP.

together, one-way or two-ways, from climate to fish markets (Figure 2). Different research groups in the international Earth system and marine ecosystem modeling communities follow the same approach. While the representation of processes differs between models, their coupling architecture remains similar. Climate models (Earth System Models: ESMs), with their atmospheric, oceanic and biogeochemistry components, influence marine ecosystem models (MEMs), which need to be simultaneously coupled with bio-economic models representing the dynamics of fishing fleets and fish markets (Figure 2). Key variables that are not explicitly modeled are prescribed as boundary conditions, or drivers. The SSP and OSP scenarios provide the time-evolution of these boundary conditions, according to the different storylines considered (Figure 2). Consistency across the climate and socio-economic drivers is maintained through the connection and alignment between the SSP/RCP framework (O'Neill et al., 2016) and between the SSP and the OSP scenarios that prescribe the socio-economic drivers of fisheries in the "economy", "governance" and "management" domains (Figure 2).

The MEMs used in the FishMIP community to project the impact of climate change simulate ecological, bioenergetic, and/or behavioral processes that underpin ecosystem dynamics. Only a minority of these models also include dynamical coupling with bio-economic fishing fleet models that simulate the dynamics of fishing effort (Christensen et al., 2015; Galbraith et al., 2017), as well as market models that simulate the dynamics of prices and commodity trade through supply chains (Cheung & Oyinlola, 2019). However, in order to simulate fisheries in a way that responds to both market and ecological dynamics and captures feedbacks between these two components across all MEMs in FishMIP, it is necessary to incorporate fleet and market dynamics modules into the ecosystem models that do not represent these processes. This is the aim of the PIM strategy.

2.2.2. The 'Plug-In-Model' Strategy

The OSP framework includes three concise PIMs that represent the dynamics of fishing effort, aquaculture and prices. These PIMs are designed to be influenced by the OSP drivers and to interact with the ecosystem models (Figure 3). They offer an easy-to-implement mechanistic modeling framework that will allow the diversity of FishMIP models to simulate the dynamics of fisheries according to the OSP scenarios in a coherent way. They will be provided to the FishMIP community along with the quantitative OSP drivers pathways (see below) and

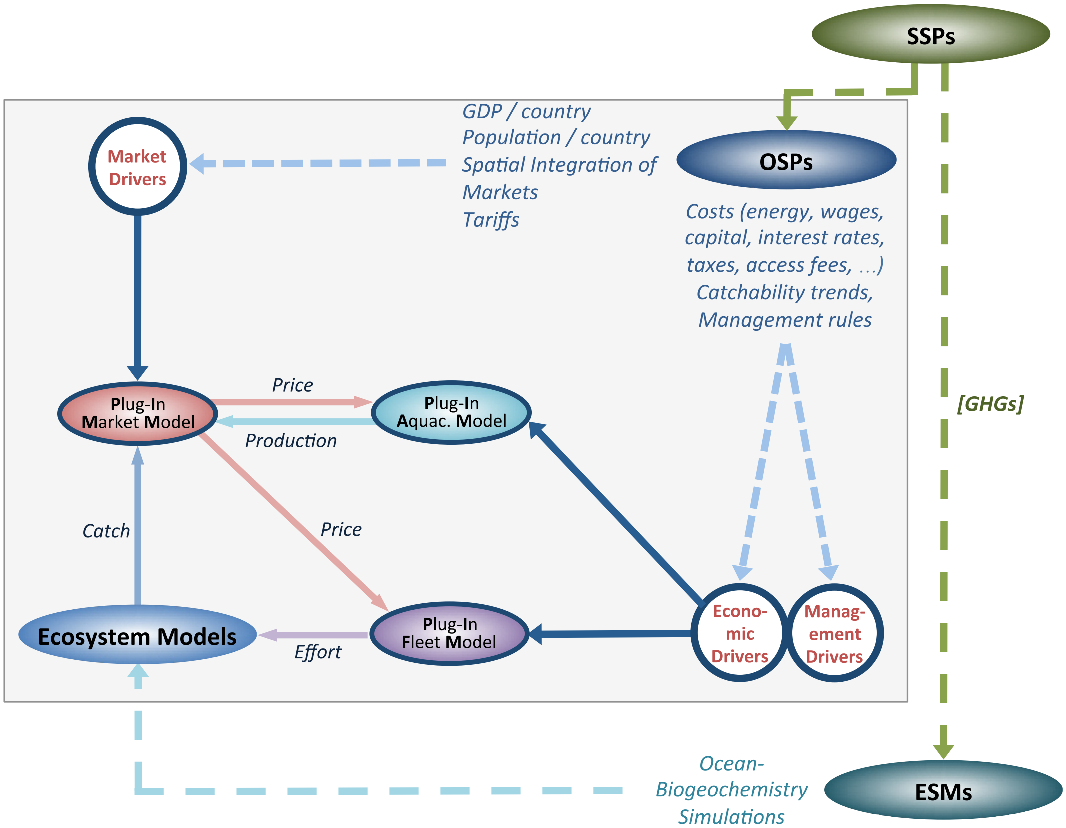

Figure 3. Schematic structure of the information flow from the shared socioeconomic pathways (SSPs) to the "plug-in-models" and their coupling to marine ecosystem models (MEMs). Dashed arrows represent the drivers of the MEM-PIM complex.

documented in detail in a forthcoming publication. Those MEMs that already include some of these elements (e.g., dynamic models of fishing effort, mariculture or seafood prices) will be able to keep their own sub-models instead of the corresponding PIMs, and use the OSP drivers to force them.

The plug-in-market-model (PIMM) is a GDP- and population-driven inverse demand function that accounts for the well-established fact that the per capita demand for food increases with GDP per capita and saturates due to satiation, while declining with price (Bodirsky et al., 2015; Rathu Manannalage et al., 2023; Valin et al., 2014). The PIMM also considers the intermediate demand for fishmeal by the aquaculture industry, which affects the market equilibrium price of small pelagics, and the substitutability between farmed fish and wild-caught demersal fish, which affects the price of both products simultaneously. It calculates the price P of the different commodities i considered (e.g., large pelagic, benthic-demersal, coastal small pelagic, emerging, aquaculture) at time t in all countries c belonging to the national, sub-regional, regional or global region Ω (the SIM that is specified by every OSP storyline) given fisheries yield $Y_{t,i,\Omega}$, aquaculture production $A_{t,i,\Omega}$ and the OSP market drivers $D^{m}_{t,i,\forall c\in\Omega}$ in every country belonging to region Ω. It has the following general form:

$$P_{t,i,\Omega} = \text{PIMM}(Y_{t,i,\Omega}, A_{t,i,\Omega}, D^{m}_{t,i,\forall c\in\Omega}) \tag{1}$$

with the market drivers $D^{m}_{t,i,\forall c\in\Omega}$ being non-linear functions of the population and GDP at time t in every country c belonging to the region Ω.

The plug-in-fleet-model (PIFM) assumes that a fraction of the profit from the sale of fish (the revenue minus the fixed and variable costs considered in the OSPs) is used to invest in new fishing capital that will depreciate over time. This vessel capital is then converted into fishing effort accounting for technical change, and applied according to the fisheries management drivers of the OSPs (e.g., biological reference points and compliance levels).

Technically, the PIFM integrates a first-order ordinary differential equation that determines fishing effort evolution for the different fleet j registered in region Ω (but possibly fishing beyond) at time $t+1$, given fishing effort $f_{t,j}$, catches $Y_{t,j}$, price of the commodity fished $P_{t,i,\Omega}$, as well as the economic drivers $D_{t,j}^{F,e}$ of fishing effort and the fisheries management drivers $M_{t,j}$ that are both prescribed by the OSPs at time t. It has the following general form:

$$f_{t+1,j} = \text{PIFM}\left(f_{t,j}, P_{t,j}, Y_{t,j}, D_{t,j}^{F,e}, M_{t,j}\right) \quad (2)$$

Once calculated by the PIFM, the fishing effort is distributed spatially in the MEM according to a simple gravity model, assuming that local fishing effort is proportional to the relative density of the selected biomass within each EEZ for coastal resources, or globally for oceanic resources. Compliant vessels, whose proportion is specified in the OSPs, are assumed to avoid the location of MPAs according to the OSP management rules.

Aquaculture production $A_{t,\Omega}$ is calculated with the plug-in aquaculture model that is functionally very similar to the PIFM:

$$K_{t+1,c\in\Omega}^{A} = \text{PIAM}\left(K_{t,c\in\Omega}^{A},\ P_{t,\Omega}^{A},\ A_{t,\ \Omega},\ D_{t}^{A,e}\right) \quad (3)$$

with $K_{t,c\,\in\,\Omega}^{A}$ the amount of productive capital of the aquaculture industry at time t in the country c belonging to region Ω, $P_{t,\Omega}^{A}$ the price of aquaculture products, $A_{t,\Omega}$ their quantity, and $D_{A,t}^{A,e}$ the economic drivers for aquaculture prescribed by the OSPs at time t.

2.2.3. From Storylines to Quantitative Meta-Driver Pathways

To produce OSP-consistent future fisheries projections with the PIMs embedded into the MEMs (MEM-PIM), the qualitative OSP storylines need to be transformed into quantitative driver trajectories. To ensure alignment with the SSPs and limit assumptions, the OSP drivers include several variables that are directly provided by the SSPs, including country-level GDP per capita and population, as well as global-level energy prices. The trajectories of the other OSP drivers were determined by the FishMIP Scenario Working Group. This was done either solely through expert knowledge and data analysis to ensure consistency with the OSP storylines, or by supplementing these assumptions with relationships to country-level GDP per capita from the SSPs to modulate their trajectories at the country-level (cf. Table 1). For all drivers, a smooth sigmoidal transition period is assumed between the current trends and the trends characterizing the OSP scenarios.

The OSP MEM-PIM simulation framework has to be capable of simulating the historical dynamics of world fisheries (1850–2022) in addition to its use for projections (2023–2100). To achieve this, the GDP and population from the SSPs are substituted with their historical evolution reconstructed at the national level from 1850 to 1957 and observed from 1958 to 2022. The other OSP drivers have been reconstructed by the FishMIP Scenarios Working Group over the historical period, using available observations and assumptions similar to those used for the projections.

3. Future OSP-Based Simulation Protocols

3.1. A General Strategy in the IPCC, IPBES and FAO Perspective

The development of the OSP scenarios and the implementation of the associated simulation tools, including a database of drivers and PIMs, represent a significant investment for the FishMIP program and the community of modellers contributing to it. These efforts also mark a first step toward a holistic assessment of the synergistic impacts of climate and socio-economic changes on future marine ecosystems and fisheries. The use of these tools to simulate global fisheries as part of the ISIMIP3a (model evaluation, detection and attribution of observed impacts; https://www.isimip.org/protocol/3/) and ISIMIP3b (quantification and projection of impacts at different levels of climate change) simulation protocols is the subject of a medium-term (5 years) strategy. This strategy can be further refined and adapted during its implementation, in particular when ISIMIP4 will start in or around 2027, and indeed extended at a later stage.

From a science-policy perspective, we propose to base this strategy on three main objectives in the climate, food security, and biodiversity domains (Figure 4):

Table 1
List of OSP Drivers for the "Plug-In-Models" in the "Market", Economic", and "Management" Categories

Driver type	Driver name	Resolution	Structure	Origin
Market	GDP per capita	Country	/	SSP
	Population	Country	/	SSP
	Diet preference	Country	/	OSP
	Aquaculture Fish In Fish Out index (FIFO)	Global	/	OSP
	Spatial Integration of Markets	Country/Sub-reg./Reg./Global	Artisanal/Industrial	OSP
Economic	Oil price	Global	/	SSP
	Electricity price	Global	/	SSP
	Proportion of oil in the energy mix	Global	Fisheries/Aquac. Artisanal/Industrial	OSP
	Investment ratio *(Fraction of profit invested in capital growth)*	Global	Artisanal/Industrial	OSP/SSP
	Depreciation rate	Global	Artisanal/Industrial	OSP/SSP
	Price of productive capital	Country	Fisheries/Aquac. Artisanal/Industrial	OSP/SSP
	Interest rates	Global	/	OSP
	Taxes	Country	Artisanal/Industrial	OSP
	Access fees	Global	DWFN/Riparian	OSP
	Labor costs	Country/Sub-reg./Reg./Global	Artisanal/Industrial	OSP/SSP
	Maintenance costs	Country	Artisanal/Industrial	OSP/SSP
	Subsidies and other incentives	Global	Artisanal/Industrial	OSP
	Technical change	Country/Sub-reg./Reg./Global	Artisanal/Industrial	OSP/SSP
Management	Management target	Global	Artisanal/Industrial	OSP
	Compliance rate of the fleet	Global	Artisanal/Industrial	OSP
	Total surface of protected areas	Global	Artisanal/Industrial	OSP

Note. Drivers in red are provided by the SSPs, drivers in green are provided by the OSPs and drivers in blue are provided by the OSPs and calculated using GDP per capita from the SSPs.

1. Contribute to the synthesis work of the IPCC in the perspective of the UN Framework Convention on Climate Change (UNFCCC). This will be done by projecting the impacts of climate change and socio-economic changes in the five OSPs on (a) marine ecosystems and fisheries, (b) the distribution of gains and costs from fisheries between countries, (c) the availability of seafood and its accessibility to people, and the assessment of (iv) climate-driven fisheries-related losses and damages.
2. Inform ongoing policy processes within the United Nations Food and Agriculture Organization (FAO), which provides advice to governments and intergovernmental fisheries bodies, including through policy recommendations to its 193 member states through its Committee on Fisheries. Specifically, we plan to assess the impact of policy-relevant fisheries management strategies on food security and fisheries livelihoods in the context of the OSP2 "Conventional Trends" scenario. It will also be possible to contribute to cross-sectoral studies (e.g., food security trade-offs between fisheries, aquaculture, and agriculture under climate change) and to analyze strategies to adapt fisheries to climate change.
3. Contribute to the synthesis work of IPBES on the impacts of climate change on biodiversity and nature's contributions to people, with a focus on the implementation of the Kunming-Montreal GBF of the United Nations CBD. This entails analyzing policy and management tools such as spatial marine conservation and policy processes such as the biodiversity beyond national jurisdiction framework. This will involve developing and comparing projections for three alternative versions of the OSP1, which correspond to the alternative sustainable and desirable futures described in the IPBES Nature Futures Framework (NFF, e.g. Durán et al., 2023; Kim et al., 2023; Pereira et al., 2020), namely "Nature for Nature", "Nature for Society" and "Nature as Culture". This will, in particular, involve assessing the effects of various levels of MPA implementation, and weighting up trade-offs in the biodiversity space (Kim et al., 2023).

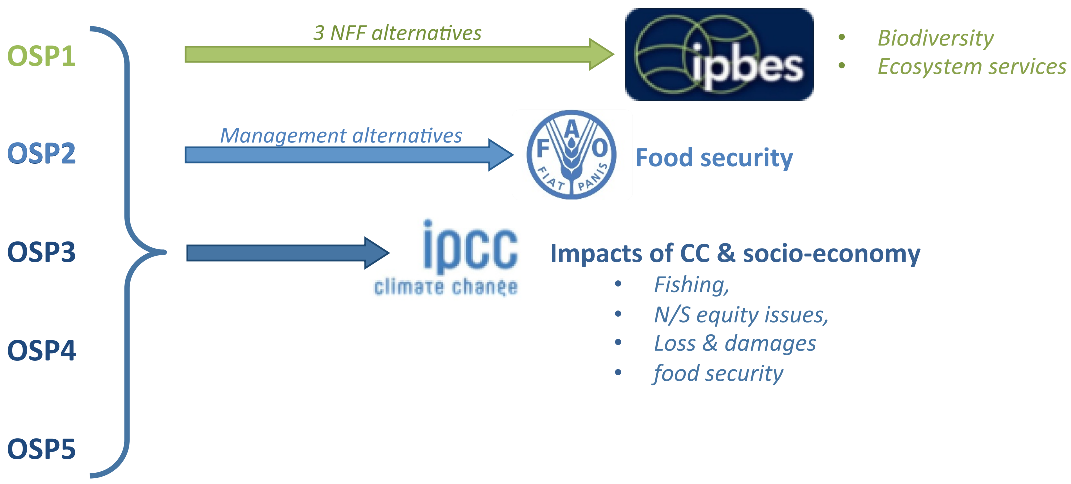

Figure 4. Schematic mid-term (5-year) strategy of the forthcoming rounds of Ocean System Pathway (OSP) simulations from the Intergovernmental Panel on Climate Change (IPCC), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), and the United Nations Food and Agriculture Organization (FAO) perspectives (see text). CC: climate change, NFF: Nature Futures Framework, N/S: North/South.

In line with this general Science-Policy strategy, the simulation protocol outlined in Section 3.2 aims to answer the following broad categories of research questions:

- How well do our social-ecological models perform when evaluated against existing historical data? What improvements can be made to these models? Which processes require focus?
- What are the distinct contributions of climate and socio-economic factors in shaping the historical development of marine ecosystems and fisheries?
- What are the combined effects of different future climate and socio-economic changes on marine ecosystems, fisheries, and the benefits they provide to societies worldwide? What are the associated risks?
- What kinds of non-linearities can social-ecological coupling lead to? What future conditions could precipitate sudden system changes? Can we identify tipping points and delineate pathways to avoid dangerous evolutions?
- How far can fishery management contribute to food security worldwide in a climate change context? What are the risks associated with ineffective fishery management, and what benefits can we expect from a fully compliant MSY management on food security?
- How do different routes to sustainability, aligned with the perspectives on Nature outlined in the IPBES NFF, compare with each other and perform in terms of biodiversity conservation and contributions of nature to people?

3.2. Simulation Protocols

One of the most important outcomes of FishMIP is the development of common standardised simulation protocols (Blanchard et al., 2024; Tittensor et al., 2018) that the community of modellers can follow to contribute to multi-model ensemble projections of climate change impacts on marine ecosystems (e.g., Lotze et al., 2019; Tittensor et al., 2021). With this in mind, we present below the broad outline of how the future OSP simulation protocol will align with the overall OSP strategy described in Section 3.1 and the current development of ISIMIP.

3.2.1. Climate Forcing Used for the OSP Scenarios

As a baseline, each OSP is paired with the corresponding SSP reference climate change scenario (Tier 1) identified in the ScenarioMIP (O'Neill et al., 2016). The baseline climate association retained for the OSPs is therefore OSP1-SSP1-2.6, OSP2-SSP2-4.5, OSP3-SSP3-7.0, OSP4-SSP4-6.0, and OSP5-SSP5-8.5.

The climate forcing used as a reference in the OSP simulation protocol is based on the debiasing methodology proposed by Lengaigne et al. (2024), potentially complemented by other climate simulations as used in previous FishMIP simulation rounds (e.g., GFDL and IPSL climate models as in Lotze et al., 2019; Tittensor et al., 2021).

Earth system Models (ESMs) often exhibit strong regional biases in their representation of present-day climate (e.g., Wang et al., 2014). In contrast, ocean-biogeochemistry models, when forced by observation-based atmospheric reanalyzes, usually exhibit considerably weaker biases and simulate the ocean and marine biogeochemistry satisfactorily (e.g., Barrier et al., 2023). The debiasing methodology of Lengaigne et al. is therefore based on the use of an ocean-biogeochemistry simulation (we will use NEMO-PISCES but other models could be used at a later stage) forced by the JRA atmospheric reanalysis (e.g., Harada et al., 2016; Kobayashi et al., 2015) over the period 1958–2022 as a "realistic" simulation (here too we will start using JRA but other reanalysis could be used in the future). The pre-industrial control (pi-control) simulation is obtained by forcing the ocean-biogeochemistry model with the "repeated year forcing" climatological JRA simulation (Stewart et al., 2020) over 250 years, to which are added the CMIP6 atmospheric heat flux and wind stress interannual anomalies simulated by a single member of the IPSL-CM6A-LR climate model pi-control experiment (again we will start with IPSL-CM6-LR but the methodology could be extended to other members, other models or combinations of models later). Heat fluxes-SST feedbacks are simulated online in the forced ocean-biogeochemistry model. The same methodology is used for generating the historical (1850–2014) and the scenarios (2015–2100) simulations, forcing the ocean-biogeochemistry model with the "repeated year forcing" climatological JRA simulation and adding anomalies simulated by a single member of the IPSL-CM6A-LR climate model for "historical" and each SSP "scenario."

This debiasing strategy offers several advantages. Firstly, it considerably reduces the systematic biases found in ESMs, resulting in "historical" ocean-biogeochemistry simulations that closely align with observations compared to free-running ESM simulations. Secondly, the "realistic-baseline" simulation accurately captures inter-annual and decadal variability, allowing for tuning and evaluation of the OSP framework (i.e., the coupled MEM-PIM) against observations such as fishery catches, fishing effort, and seafood prices. Thirdly, this "realistic-baseline" simulation used for model calibration and evaluation is fully consistent with the "pi-control," "historical" and "scenarios" simulations, eliminating the need for recalibration of the coupled MEM-PIMs, thus dramatically reducing the number of MEM-PIM simulations required. Finally, this debiasing strategy is consistent with both the ISIMIP3a protocol (model evaluation plus detection and attribution of observed impacts), which uses climate reanalysis as forcing (Frieler et al., 2024), and ISIMIP3b (ESM-based quantification of impacts at different levels of climate change), which uses de-biased climate change projections.

3.2.2. Outline of the OSP Simulation Protocol

In line with the general strategy outlined Section 3.1, and the FishMIP 2.0 roadmap (Blanchard et al., 2024), the forthcoming OSP simulation protocol that we propose entails four threads that are presented below and summarized Figure 5.

1. **OSP-baseline:** This first thread is designed to initialize and evaluate the MEM-PIM simulation framework against available data. It also seeks to identify and disentangle the respective roles of climate and socio-economic factors in the historical evolution of marine ecosystems and fisheries. It includes components corresponding to the **ISIMIP3a** (e.g., the Realistic-baseline) and the **ISIMIP3b** (e.g., the Spin-up, Reference, Historical) protocols. It involves running:
   - A 100-year **Spin-up** of the MEMs without fishing and using the pi-control climate forcing.
   - A 1850–2100 **Reference** simulation without fishing, following the spin-up and using the pi-control climate forcing.
   - Three 1850–2014 **Historical** simulations:
     - **Historical-a** with 1850–2014 historical climate forcing and fishing with 1850–2014 OSP drivers based on reconstructed and observed GDP and population. This simulation provides the 1957 initial conditions for the Realistic-baseline simulation.
     - **Historical-b** with 1850–2014 historical climate forcing and without fishing.
     - **Historical-c** without climate change (pi-control climate) and with fishing according to 1850–2014 OSP drivers based on reconstructed and observed GDP and population.
   - A 1958–2022 **Realistic-baseline** simulation with the reanalysis-driven "realistic" climate forcing and fishing with 1958–2022 OSP drivers based on observed GDP and population. This simulation branches off from the Historical-a simulation after 1957.

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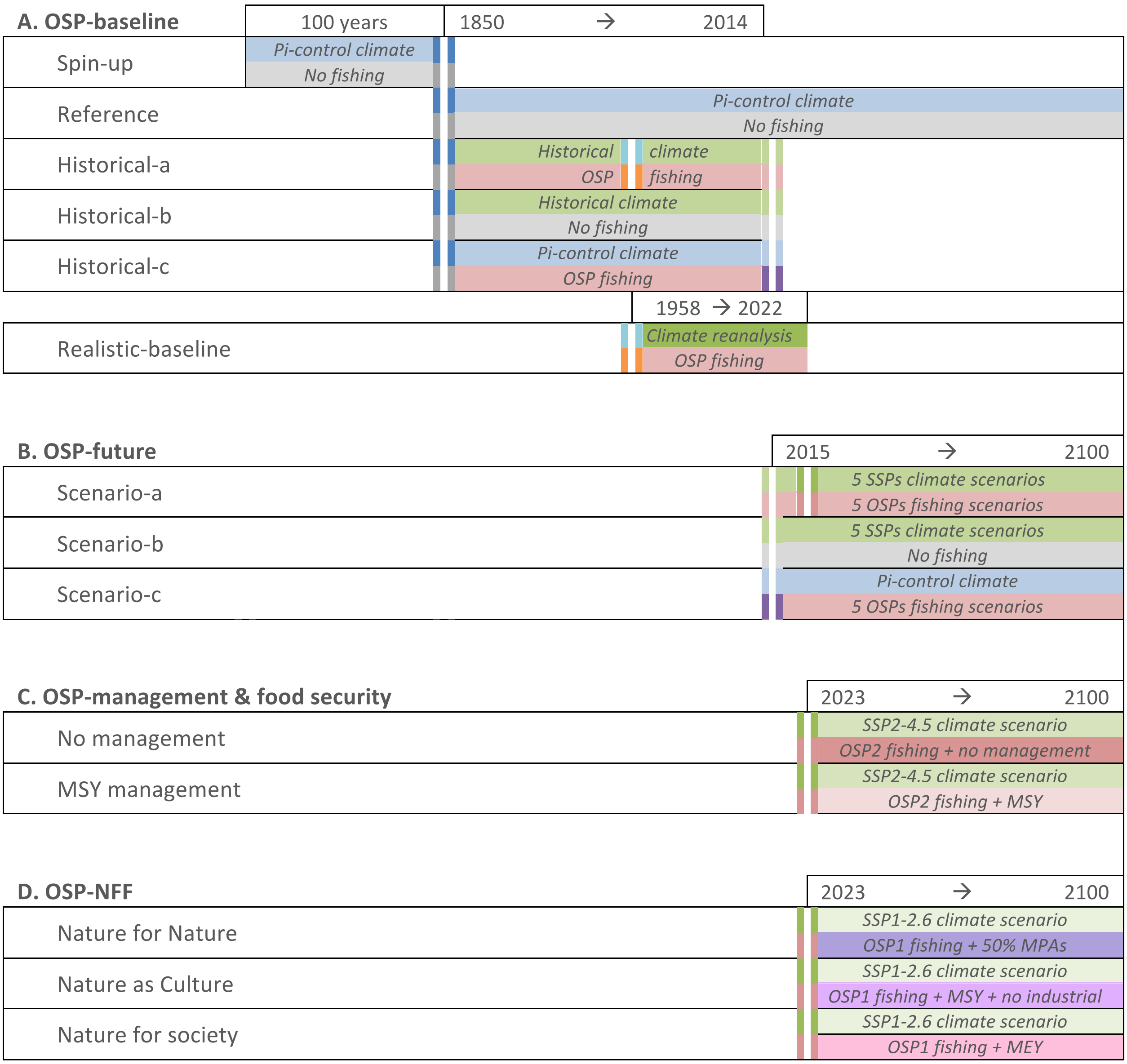

Figure 5. Overview of the proposed OSP simulation protocol, which includes four threads: OSP-baseline, OSP-future, OSP-management and food security and OSP-Nature Future Framework. The various simulations proposed are listed for each thread, with the corresponding time period, the climate forcing (1st line) and the fishing forcing (2nd line), as well as the initial conditions (color of the double bars: for instance the last year of the Historical-a simulation is used as initial conditions for the Scenario-a simulation, the year 1957 of the Historical-a simulation provides the initial conditions of the Realistic-baseline simulation, or the Scenario-a simulation in 2022 initializes all C. and D. simulations). See text for more details.

The Realistic-baseline simulation will be used to evaluate the simulation framework against fishery catches (FAO, 2020, 2024a), reconstructed fishing effort (Rousseau et al., 2024) and observed prices (FAO, 2024b).

To attribute climate effects, fishing effects and their potential interactions (whether antagonistic or synergistic), a counterfactual approach will be employed. The difference between the Historical-b and the Reference simulation over the same time period will allow the identification of historical climate effects on the ecosystem. The difference between the Historical-c and the Reference simulation over the same time period will allow the identification of historical fishing effects on the ecosystem. The difference between the Historical-a simulation and the sum of the climate and fishing effects (Hist-a minus Historical-b minus Historical-c plus 2 Reference) will provide the interactive effects of climate and fishing on the ecosystem.

Further to this, the difference between the Historical-a and the Historical-b simulations will enable the identification of fishing impacts on the ecosystem experiencing climate change, and the difference between the Historical-a and the Historical-c simulations will allow the identification of climate change impacts on the coupled social-ecological fishery system.

2. **OSP-future:** This second thread is dedicated to carrying out scenario simulations from the perspective of the IPCC. The aim is to estimate the impact of climate change and the socio-economic context on marine ecosystems, fisheries and the benefits they provide to societies worldwide. It contributes to ISIMIP3b, which focuses on assessing the climate change impacts, and involves running:
   - **Scenario-a**: The five OSP scenarios (2015–2100) with fishing and SSP climate change, starting from the Historical-a simulation. This simulation is designed to simulate the impacts of climate change on fishery and food consumption in the different socio-economic OSP contexts.
   - **Scenario-b**: The five OSP scenarios (2015–2100) without fishing but with SSP climate change, starting from the Historical-b simulation. This simulation is designed to simulate the impacts of different levels of future climate change on marine ecosystems.
   - **Scenario-c**: The five OSP scenarios (2015–2100) with fishing but no climate change (pi-control climate), starting from the Historical-c simulation. This simulation is designed to highlight the effects of the various socio-economic OSP contexts on fisheries.

Comparing the Scenario-a and Reference simulations during the same time period will allow for the identification of the combined effects of different climate change and socio-economic contexts. Comparing the Scenario-b and Reference simulations will allow for the assessment of climate impacts on the ecosystem at different levels of climate change. Additionally, comparing Scenario-c and the Reference simulation will enable the characterization of the impact of distinct socio-economic contexts on the social-ecological fishery system. The interactive effects of climate and the socio-economic context on the social-ecological fishery system can be determined by calculating the difference between the Scenario-a simulation and the sum of the climate and fishing effects (Scenario-a minus Scenario-b minus Scenario-c plus 2 Reference).

Finally, the difference between the Scenario-a and the scenario-b simulations will enable the identification of fishing impacts on the ecosystem experiencing different levels of climate change, and the difference between the Scenario-a and the Scenario-c simulations will allow the identification of climate change impacts on the coupled social-ecological fishery system.

3. **OSP-management & food security:** This third thread is devoted to scenario simulations from the FAO perspective. It aims to focus on the effects of fishery management on food security, in the "conventional trends" context of OSP2. While the definitive setup of this set of simulations has not yet been fully determined, it would involve running:
   - The OSP2 scenario (2023–2100) with fishing, no management, and climate change (RCP4.5).
   - The OSP2 scenario (2023–2100) with fishing, fully compliant MSY management, and climate change (RCP4.5).

Comparing these two simulations with the OSP2 Scenario-a simulation (with present-day management) will provide insights into the risks of fishery management failure and the potential gains of fully compliant MSY management on global food security.

4. **OSP-Nature Future Framework:** This fourth thread is dedicated to mapping the OSP scenario simulations to the IPBES perspective and the NFF. The aim here is to compare three ways of envisioning the "Sustainability First" OSP1 scenario, corresponding to the three perspectives on Nature of the "Nature Futures Framework" from the IPBES ("Nature for Nature", "Nature as Culture", and "Nature for Society", Pereira et al., 2020; Kim et al., 2023). While the definitive setup of this set of simulations has not yet been fully determined, it would involve running:
   - The OSP1 scenario (2023–2100) with fishing, management transitioning to 50% of the ocean in fully protected MPAs, and moderate climate change (SSP1-2.6). This simulation corresponds to the IPBES NFF "Nature for Nature" pathway.
   - The OSP1 scenario (2023–2100) with fishing, artisanal fisheries managed at MSY and no industrial fisheries, and moderate climate change (SSP1-2.6). This simulation corresponds to the IPBES NFF "Nature as Culture" pathway.

- The OSP1 scenario (2023–2100) with fishing, the management of both artisanal and industrial fisheries at Maximum Economic Yield, and moderate climate change (SSP1-2.6). This simulation corresponds to the IPBES NFF "Nature for Society" pathway.

Comparing these three simulations will bring insights into the performances of the three NFF strategies, in terms of food supply, biodiversity conservation, employment and economic benefits generated in the context of the OSP1 mild climate change.

4. Conclusion

The OSP scenario framework provides a formal and operationalizable basis for exploring the future of marine social-ecological fisheries systems from regional to global scales. Simulation of the OSP scenarios will be at the heart of the next stage of the FishMIP program, focusing on the interplay between climate, biodiversity and food security challenges and associated policy-relevant questions (Blanchard et al., 2024). This endeavor will require significant effort from the FishMIP modeling community, including the technical challenges of integrating the PIM framework into existing MEMs, fitting the resulting coupled MEM-PIM social-ecological models to historical observations, and projecting the impacts of both climate and socio-economic changes along scientifically meaningful and policy-relevant experimental protocols. Yet it will also provide tangible benefits to the community of modellers and beyond. By allowing fisheries to be simulated dynamically, and in a fully integrated manner in line with the SSPs, the OSP framework will significantly broaden the scope of the FishMIP projections, in the context of the ISIMIP 3a and 3b simulation rounds. It will allow ensemble projections of fisheries to be carried out consistently with ongoing international climate and biodiversity policy processes, as well as FAO's efforts to promote sustainable capture fisheries and aquaculture.

The coherence of the OSP storylines with the SSPs, the simplicity of the OSP drivers-PIM package, its mechanistic nature and the fact that it will be made available to the scientific community in an open source format, provide the foundation for an evolving framework that can be easily updated, improved, and adapted to the future needs of FishMIP and the evolution of the science-policy interface to which it aims to contribute.

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Data Availability Statement

The FishMIP tools and protocol informations used in the study are available at https://fishmip.org/tools.html.

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