Building confidence in projections of future ocean capacity

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Chapter Outline

7.1 Ocean capacity and ecosystem services

The oceans provide us with ecosystem services such as food provision from fisheries and aquaculture, carbon sequestration, flood control and waste detoxification for people living in coastal communities, and biodiversity provision [1]. These services play a direct role in the composition of the Earth's atmosphere that regulates our weather and climate [2]. The capacity of the oceans to provide these ecosystem services can change over time due to human activities such as fishing, emission of greenhouse gases, pollution, and coastal development [3]. We can measure components of nature to quantify the capacity of the ocean to provide ecosystem services and how capacity changes with time. One component of ocean capacity is the extent and quality of habitats such as coral reefs, mangroves, sea grasses, and kelp forests, which are directly related to the abundance and biomass of species and biodiversity associated with each habitat [4]. Habitats, biomass, and biodiversity respond to human activities such as fishing, habitat destruction, pollution, and sedimentation as well as to environmental conditions that are affected by climate change such as temperature, nutrient flux, pH, and oxygen levels of the oceans. By tracking these

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key aspects of ocean capacity through time, we can understand how ecosystem services respond to human activities and climate change.

7.2 Climate change impacts on ocean capacity

Humans have been impacting the oceans for millennia through fishing, which has reduced the abundance and biomass of many different species worldwide, in turn affecting the structure and function of marine food webs and ecosystems [5,6]. These activities have altered the capacity of the oceans to provide ecosystem services such as food provision. More recently, since the mid-1800s and the industrial revolution, the emission of greenhouse gases has played a transformative role in the Earth's biogeochemical cycle and climate. These effects are already observed in coastal communities, as fishers have noticed traditionally fished species are absent and new species arriving to their waters or that they have to travel farther to fish species than they used to [7,8]. Reducing greenhouse gas emissions has been addressed by policies, technologies, local and regional initiatives, and international agreements such as the Paris Agreement. However, it remains unclear at what rate greenhouse gases will be emitted in the future, and for that reason scientists have been working with a range of greenhouse gas scenarios to make projections about what we might expect for the future capacity of the oceans to provide ecosystem services. Projections about how the oceans, marine biodiversity, marine aquaculture, and fisheries will respond to climate change are used by policy makers, businesses, natural resource producers and users, and insurance companies to plan for future environmental and ecological conditions.

The Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report summarizes the state of the art scientific research addressing how climate change is projected to impact the oceans [3]. This report presented an approach to project how catch potential—the amount of fish in the ocean available to be caught—is expected to change in the future. This analysis relied on a modeling approach developed by Cheung et al. [9], referred to as the Dynamic Bioclimate Envelope Model (DBEM). As with every model, this model is based on assumptions and simplifications of how the world works, and is subject to various uncertainties, biases, limitations, and sensitivities [10]. As a result, projections about the future ocean capacity made by this model may differ from projections made by other models. DBEM is based on a species distribution approach, whereby if environmental conditions for a particular species are favorable, the model will predict that it will occur there. This model does not take into account species interactions, but some models such as EcoOcean [11], a global extension of the popular and foundational Ecopath with Ecosim regional model [12], specify species interactions via predator–prey relationships. At the other end of the spectrum of model architecture are size-based models which do not resolve species or functional groups, but instead focus on size classes of marine life [13,14].

Generally, DBEM and size-based models project greater overall declines in global fish biomass under climate change when compared to EcoOcean [15].

Acknowledging the need to improve our understanding of uncertainties in projections of climate change impacts on the world's oceans, a research group composed of fisheries and ecosystem modelers at both regional and global scales as well as members from the climate and Earth system modeling community was created to address this question. The Fisheries and Marine Ecosystem Model Intercomparison Project (FishMIP) was formed in 2013 to bring together a wide array of modeling approaches and compare them in a meaningful way in order to understand how models project climate change impacts and quantify associated uncertainties, biases, limitations, and sensitivities for model projections of future ocean capacity. The founding coordinators were Heike Lotze, Derek Tittensor, Eric Galbraith, William Cheung, and myself. FishMIP maintains a membership that is open to all who wish to participate, and at present includes more than 50 members.

7.3 The model intercomparison project experience: model ensembles

The Model Intercomparison Project (MIP) approach of using an ensemble of models to run standardized simulations has been applied to many different sectors and fields. An ensemble of models is a group of models that are all capable of making projections about the same thing—such as future land surface temperature or sea surface temperature—but may be built differently. The rationale for using an ensemble of models forced with the same data is because, as above, each model has its own structure, assumptions, uncertainties, biases, limitations, and sensitivities. Most models give different answers when asked the same question, and learning why is important to improve and refine our understanding of how we model systems. Using an ensemble of models accounts for a greater envelope of variability or level of agreement in model projections. Under the IPCC framework to evaluate evidence, the two quantitative criteria that are applied are: the amount of evidence and evidence agreement [3]. To allow for meaningful comparisons among models, it is necessary to standardize how simulations are run as much as possible, thereby elucidating differences that are due to the models themselves. Once a general understanding of ensemble variability under different scenarios has been achieved, whether all models predict the same direction of change (increase or decrease), and how different the magnitude of change varies, a more detailed and controlled experimental design of simulations and analyses of factors contributing to the envelope of variability can be undertaken. For these reasons, the MIP approach has been taken up by many modeling communities worldwide.

The Ocean MIP "aims to provide a framework for evaluating, understanding, and improving the ocean, sea ice, tracer, and biogeochemical components of global climate and Earth system models" contributing to the Coupled MIP (CMIP) which also represents terrestrial processes. The fifth iteration of CMIP (CMIP5) was used widely in the IPCC 5th

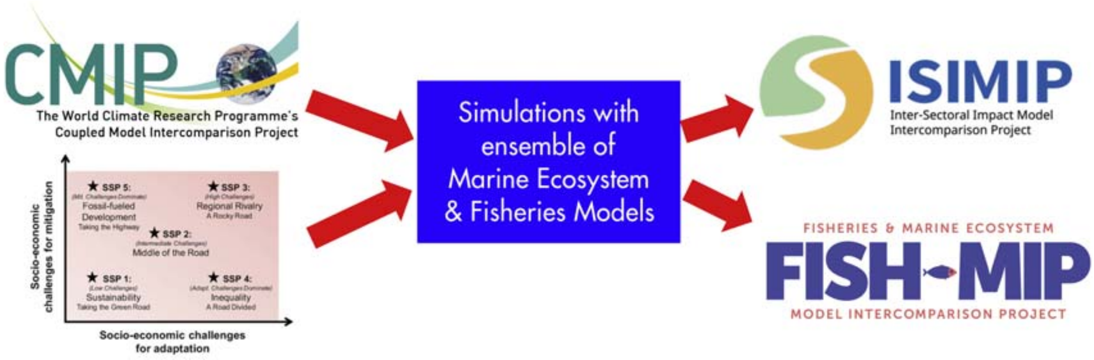

Figure 7.1
Methodological approach of the FishMIP to make projections about future ocean capacity. *FishMIP*, Fisheries and Marine Ecosystems Model Intercomparison Project.

Assessment Report to detail future projections about land and sea temperatures, primary productivity, precipitation, winds and storms, ocean circulation, salinity, acidity, and oxygen concentration under different carbon emissions scenarios [3]. The Inter-Sectoral Impact MIP (ISIMIP) was formed to interface with CMIP in a downstream manner using CMIP outputs as ISIMIP inputs. Outputs from the CMIP ensemble describing projections for physical and environmental variables under climate change scenarios are used as inputs for impact MIPs from different sectors such as agriculture, biomes, coastal infrastructure, energy, forests, water, human health, lakes, permafrost, terrestrial biodiversity, and fisheries and marine ecosystems (Fig. 7.1; [16]). The aim of ISIMIP is not only to standardize climate change simulations among models within sectors but also to standardize simulations among sectors to allow for a broader comparison of climate change impacts [17,18]. In this standardization of simulations lies the challenge of using a MIP approach; by including a wide variety of model structures, and their required inputs, and outputs, compromises have to be made by some models in order to have a lowest common denominator that is inclusive of all models.

7.4 Fisheries and Marine Ecosystem Model Intercomparison Project: projecting future ocean capacity

FishMIP was conceived in response to a question posed by researchers working in the agricultural climate change community about whether the oceans could potentially make up for food losses that were projected to happen on land under climate change. After four years of FishMIP, we were able to answer this question by comparing FishMIP fish projections to crop projections from the Agricultural MIP (AgMIP) under climate change. Unfortunately, countries in the tropics that are projected to experience the biggest losses in agricultural production on land are also projected to have the largest losses in fisheries catch production in the ocean [13,14].

The process of developing a simulation protocol for FishMIP that could be applied by a diverse set of fisheries and marine ecosystem models took many years, workshops, emails, and conference calls and was largely a consensus process among modelers who were interested in the project (https://www.isimip.org/gettingstarted/marine-ecosystems-fisheries/). Models ranged greatly in their data requirements (Table 7.1) and resolution of marine organisms, from size-based modeling approaches such asthe BiOeconomic mArine Trophic Size-spectrum (BOATS) model that resolves all fish in the oceans into three size categories [19] to the DBEM which resolves more than 1000 different species [9]. As a result of this heterogeneity, FishMIP outputs from all models have been disaggregated into three size categories [16,20–22]. An additional level of complexity of FishMIP was that models of both global scale and regional scale were included. While it would have been more straightforward to only include models of global scale, we wanted to be able to address how projections by global models based on first principles and driven by bottom-up processes for individual regions compared to corresponding regional models that were parameterized with local biomass survey and fisheries data and driven by top-down processes such as

Table 7.1: Description of common model inputs and outputs employed by Fisheries and Marine Ecosystem Model Intercomparison Project (FishMIP) model ensemble, as well as the standardized model outputs provided by all models participating in FishMIP.

Common model inputs	**Units**
Ocean current speed	m/s
Sea temperature or potential temperature	K
Dissolved O_2 concentration	mol/m^3
Primary organic carbon productivity	mol/m^3/s
Zooplankton carbon concentration	mol/m^3
pH	Unitless
Salinity	psu
Common model outputs	
Fish species and functional group carbon biomass density	g/m^3/month
Fisheries metrics	Various
Relative species and functional group abundances	Unitless
Trophic level	Unitless
Production of carbon	g/m^3/month
Production and biomass ratio	Unitless
Mortality rate	month^{-1}
FishMIP standardized outputs	
Total system carbon biomass	g/m^2
Total consumer carbon biomass density	g/m^2
Carbon biomass density of consumers $>$ 10 cm	g/m^2
Carbon biomass density of consumers $>$ 30 cm	g/m^2
Total catch (all commercial functional groups or size classes)	g wet biomass/m^2
Total landings (all commercial functional groups or size classes)	g wet biomass/m^2

fishing. Additionally, we included different socioeconomic scenarios, often referred to as shared socioeconomic pathways (SSPs) of future fishing pressure, not to try to predict the future, but to provide an exploratory approach to a range of possible ocean futures (Fig. 7.1).

During each iteration of the FishMIP process, we learned more and more about other models in the project, the model(s) that we work with and develop directly, and why they give different answers. Initial results indicate that global mean fisheries productivity is projected to decrease under climate change, with greater declines under higher carbon emissions scenarios [15,22]. There is however, a lot of spatial variation in projected changes, and there is less agreement among regional and global models for specific regions compared to agreement among global models. We are now in a position to run controlled experiments of changes in the two primary climate drivers—sea surface temperature and primary productivity—to pinpoint the mechanisms in each model that lead to variability in projections. For example, in the AgMIP, the main factor leading to differences in projections of crop production under climate change was if models included CO_2 fertilization or not (increased crop production due to increased CO_2 in the atmosphere under climate change; [23]). These comparison exercises lead to a better understanding of how different representations of models respond to climate change drivers, to further refine projections of future ocean capacity.

7.5 Socioeconomic drivers of future ocean capacity

It has been shown in a number ofinstances that while climate change may reduce future fisheries productivity in some regions, the most important factors to consider when projecting future fish biomass are socioeconomic in nature. For example, a recent study that used satellite tracks from vessels and machine learning algorithms to differentiate fishing behavior from transit behavior quantified the global footprint of fishing effort—and found that the largest reduction in fishing effort annually occurred during the holidays of Chinese New Year [24]. A fishery that is aiming to fish at maximum sustainable yield typically reduces the biomass of the stock by about half. While some species may be more susceptible to climate change impacts than others, typically the projected changes in biomass due to climate are much less severe when compared to potential changes due to fishing activities—even for sustainable fisheries reference points. Therefore any projections of climate change impacts on fisheries need to take into account how fishing effort will change in the future.

While there have been some efforts to qualitatively map out future exploratory ocean scenarios related to the SSPs [25,26], at present there is a lack of the types of socioeconomic scenarios that can be run with FishMIP models. For these reasons, FishMIP used two different fishing scenarios in combination with different climate emissions scenarios: hold fishing constant at 2005 levels to be consistent with ISIMIP protocols (and due to data availability) and a no-fishing scenario. While highly unrealistic, the no-fishing scenario is a control run that allows for an analysis of how much climate change affects future ocean capacity in the absence of fishing. In future iterations of FishMIP we aim to be able to incorporate more detailed socioeconomic scenarios. The goal of these exploratory scenarios is not to predict the future, but to try to encompass the extremes in terms of the range of how fishing effort might change to understand the range of future ocean capacity under different socioeconomic and climate scenarios.

7.6 Summary

Overall, an ensemble or MIP approach to project ocean capacity has its strengths in being able to partition uncertainty according to choice of the Earth system model, fisheries/ ecosystem model, climate scenario, and socioeconomic scenario. We can also find out how dependent our projections are on different components of model projections, such as choice of Earth system model, ecosystem model, climate scenario, and fishing scenario. By comparing projections of models of varying philosophy and structure, we can learn more about the models themselves, where their sensitivities lie, what mechanisms and processes lead to variation in projections, how to improve them, and where to focus efforts to build confidence in ocean capacity projections moving forward. This process has been developed with the goals of not only improving modeling of ocean ecosystems and fisheries, but to provide information for developing management and adaptation strategies and policies to climate change.

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