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Dynamic Integrated Marine Climate, Biodiversity, Fisheries, Aquaculture and Seafood Market Model (DIVERSE)

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Table of Contents

Executive Summary

Global change drivers, such as population growth, increasing consumption, inequity in resource distribution, overfishing, climate change and pollution, are challenging the sustainability of global coupled human-natural seafood production system. Modelling the linkages between the biophysical and socio-economic components of the seafood production systems is a useful way to explore the interactions between these drivers and policy responses. Moreover, combining the use of models and scenarios can then provide quantitative projections for pathways of changes in ocean human-natural systems.

This report documents a newly developed model, herein called Dynamic Integrated Marine Climate, Biodiversity, Fisheries, Aquaculture and Seafood Market Model (DIVERSE) to project future pathways to seafood sustainability under global change. DIVERSE is supported by a system of linked and harmonised infrastructure of environmental, biodiversity, fisheries and socio-economic databases (Appendix). In parallel, scenarios of direct and indirect drivers of changes in the marine human-natural systems are developed based on the Representative Concentration Pathway (RCP) and the Shared Socioeconomic Pathway (SSP) frameworks.

DIVERSE is grounded in the framework of coupled human-natural systems for the ocean. Chapter 1 describes the basic structure of DIVERSE and its potential applications. Specifically, the different sub-components of DIVERSE and their main interconnections are introduced. Some of the overarching research questions in the context of exploring scenarios and pathways for ocean futures under climate change that can be addressed by DIVERSE are also highlighted.

DIVERSE includes five interconnected sub-components: climate-living marine resources, fishing effort dynamics, mariculture, and global seafood markets. These model sub-components are described in separate chapters. Specifically, Chapter 2 describes the structure of the climate-living marine resources component of DIVERSE. This component includes models and scenarios for changes in ocean conditions and abundance of fish stocks. Ocean conditions are projected by Earth system models while fish stock abundance is projected by the Dynamic Bioclimate Envelope Model (DBEM). The projections of abundance forcing under scenarios of greenhouse gas emissions and marine protected areas are illustrated using four fish stocks as examples.

The projected abundance forcing is subsequently linked to a newly developed fishing effort dynamic model (EDM). The EDM, described in Chapter 3, is a bio-economic model that simulates changes in fishing fleets dynamics based on scenarios of changes in abundance of fish stocks projected from DBEM and fisheries economic variables such as the price of fish and cost of fishing. The main outputs of the EDM are projected changes in fishing efforts, catches, fisheries revenues and profits by countries and fishing fleets (demersal and pelagic). The EDM reproduces historical trends of global fisheries catches and fishing effort, demonstrating its potential utility to make projections for the future.

In addition to capture fisheries, DIVERSE also includes a model for mariculture (marine aquaculture) production. The mariculture production model, described in Chapter 4, accounts for inputs of mariculture production in modelling procedure such as price, suitable marine area for farming, total world fishmeal and fish oil production, and farm species trophic level. These inputs

can also be affected directly or indirectly by climate change. The model then simulates changes in mariculture production potential by countries for the main farmed marine species. The outputs from the EDM and mariculture production model provide inputs into the global seafood market model (GFish).

The GFish model, described in Chapter 5, is a partial equilibrium model of global fish supply and demand. It aims to facilitate the analysis of the supply, demand and trade consequences, associated with different scenarios subject to changing market forces, policy, demographics and environments. The GFish model can be used to assess the impacts of market and non-market forces have on the marine resources and the effects of changing seafood supply from capture fisheries and mariculture on the global seafood markets.

In addition to commercial fishing and aquaculture that are connected to seafood markets, DIVERSE also accounts for fishing for subsistence purposes. Subsistence catches are predicted using an empirical model established based on historical subsistence catches. The model predicted expected subsistence catch for each country based on the average income level of the country, its rural population size, per capita seafood consumption and fisheries resources abundance. The model is able to significantly explain variations in subsistence catches in the world over the last few decades. In DIVERSE, the subsistence model is used to project subsistence catches based on projections of social-economic drivers (income classes and human population) and changes in fisheries resources abundance under SSPs and RCPs.

The last two chapters of this report describe and discuss scenarios of direct and indirect drivers for capture fisheries and mariculture. These scenarios are based on the Shared Socioeconomic Pathways (SSPs) framework to examine the challenges and limits to climate mitigation and adaptation. Three sets of fisheries- and mariculture- focused storylines are developed based on three SSPs (SSP1, SSP3, and SSP5) that describe alternative futures engaged in 'sustainability', 'regional rivalry' and 'fossil-fuel based development' pathways, respectively. Specific quantitative drivers such as population and per capita income under each scenario are provided. These drivers are applied to model future changes in seafood sustainability using DIVERSE.

Overall, this report describes the structure, parameterization and testing of DIVERSE. The report also highlights the strengths, weaknesses and future opportunities for the potential extension of DIVERSE. This report provides the main documentation of DIVERSE that will be useful for future applications of the model and analyses of its outputs

Director's Foreword

UBC's Institute for the Oceans and Fisheries envisions a world where the ocean is healthy and its resources are used sustainably and equitably. We take pride in presenting innovative research that looks at global change drivers - such as population growth, increasing consumption, inequity in resource distribution, overfishing, climate change and pollution - and how they affect our ocean, and the human communities dependent on it.

Nowhere is this more important than on the human-natural seafood production system.

This Report documents the first release of an integrated assessment model that links a variety of scenarios and models developed for marine biodiversity, ecosystems and fisheries through a coupled human-natural system framework. Named the Dynamic Integrated Marine Climate, Biodiversity, Fisheries, Aquaculture and Seafood Market Model (DIVERSE), this approach was developed to address a wide range of fundamental applied research questions, particularly those related to ocean systems, global food security and sustainable ocean development. Further, it has the potential to be linked to other existing Integrated Assessment Models that do not have an explicit representation of the ocean.

This approach should have far-reaching implications for understanding the seafood production system and I congratulate the authors on this significant work.

Evgeny Pakhomov
Director, Institute for the Oceans and Fisheries

Editor's Preface

The future of the ocean, and human communities that are dependent on it are at a crossroads. Understanding what the future ocean would become given different pathways of global society, environmental, policy and cultural changes could generate valuable knowledge that helps identify shared visions about the future ocean. These could also inform decision making related to the governance of ocean-related activities.

One of the main research objectives of the Changing Ocean Research Unit (CORU) at the Institute for the Oceans and Fisheries, The University of British Columbia, is to predict the future of the ocean and human communities that are dependent on it under global change. To achieve this goal, scenarios and models are amongst the major analytical tools that CORU develops and applies. Since 2011, in connection with the Nippon Foundation-the University of British Columbia Nereus Program, CORU has undertaken studies that project future changes in marine biodiversity, fisheries, mariculture, and seafood supplies, globally and in various regions.

This report documents the first release of an integrated assessment model that harmonizes and links the various scenarios and models developed for marine biodiversity, ecosystems and fisheries through a coupled human-natural system framework. This integrated assessment model is called the Dynamic Integrated Marine Climate, Biodiversity, Fisheries, Aquaculture and Seafood Market Model (DIVERSE). DIVERSE is developed to address a wide range of fundamental and applied research questions, including those related to the ocean systems, global food security and sustainable ocean development. It also has the potential to be linked to other existing Integrated Assessment Models that do not have an explicit representation of the ocean.

The development of DIVERSE and this report would not be possible without the advice, data and support from many collaborators and organizations. We would like to acknowledge the following colleagues and research groups who provide us with valuable advice, data or technical support: Thomas Frölicher, Yoshitaka Ota, Deng Palomares, Daniel Pauly, Jorge Sarmiento, Charlie Stock, U. Rashid Sumaila, Max Troell and Dirk Zeller. For chapter 6 we acknowledge insights from the following individuals, which informed the scenario storylines: Patricia Angkiriwang, Jeff Ardron, Jessica Blythe, Natalie Ban, Patrick Christie, Andrés M. Cisneros-Montemayor, John Hampton, Quentin Hanich, Kristina Gjerde, Bethan O'Leary, Guillermo Ortuño Crespo, Juliano Palacios-Abrantes, Daniel Pauly, Graham Pilling, Joyce Samuelu-Ah Leong, Essam Yassin Mohammed, Louise Teh and Glen Wright. We also acknowledge Nesar Ahmed, Patricia Angkiriwang, Rachel E. Cox, Ling Cao and Cecilia Engler-Palma for their participation and contribution in the mariculture scenarios workshop. We also acknowledge funding support from the Nippon Foundation through the Nippon Foundation-UBC Nereus Program, the Natural Sciences and Engineering Research Council of Canada, the Social Sciences and Humanity Research Council of Canada, the Canada Research Chair program, and the Peter Wall Institute for Advanced Studies. The simulations of components of DIVERSE use the High-Performance Computing fallibilities offered by Compute Canada and Westgrid.

We hope that this report will serve as the main reference to explain the principles and assumptions behind the different sub-components of DIVERSE. More elaborated versions of some of the chapters are expected to be published in peer-review journals.

William W. L. Cheung
Muhammed A. Oyinlola

Acronyms used

AIC	Akaike Information Criterion
CMIP5	Coupled Model Intercomparison Project Phase 5
DBEM	Dynamic bioclimate envelope model
DIVERSE	Dynamic Integrated Marine Climate, Biodiversity, Fisheries, Aquaculture and Seafood Market Model
EDM	Effort dynamic model
EEZ	Exclusive economic zone
ENFA	Ecological Niche Factor Analysis
ESM	Earth system model
FAO	Food and Agriculture Organization
FMFO	Fishmeal and fish oil
GAM	General additive model
GFDL-ESM2G	Geophysical Fluid Dynamic Laboratory Earth System Model 2G
GFish	Seafood market model
GLM	Generalized Linear Model
HDI	Human Development Index
HIC	High-Income Countries
HSI	Habitat suitability index
IAM	Integrated assessment model
IPSL-CM5A-MR	Institut Pierre Simon Laplace climate model 5A-MR
LDCs	Least Developed Countries
LIC	Low Income Countries
MCP	Maximum catch potential
MIC	Middle Income Countries
MPA	Marine protected areas
MPI-ESM-MR	Max Planck Institute Earth System Model MR
MPP	Mariculture production potential
RCP	Representative concentration pathway
SDGs	Sustainable Development Goals
SDM	Species distribution model
SSP	Shared Socioeconomic Pathway
TPP	Temperature preference profile

List of Symbols

AE	Active fishing effort
Area	Total suitable marine area for mariculture
B	Biomass
biomass	Resource biomass
bs	String indicating the (penalised) smoothing
CapitalCost	Capital cost of a fishing fleet
CostInc	Cost inflation rate
cr	Cubic regression
D	Capital depreciation rate
EffR	Effort response to profit
Employment	Fisheries-related employment
F	Mortality rate
FCR	Feed conversion rate to farm commodity
FEX	Fish expenditure of all fish commodities
FMFO	Total fishmeal and fish oil production
fs	Smooth factor interactions
gdppc	Gross domestic product per capita
GQXFeed	Global feed supply of a commodity
GSHFeed	National feed supply of a commodity
H	Total catch
H_{comm}	Commercial catches
HSI	Habitat suitability index
H_{sub}	Subsistence catches
I	Reinvestment ratio
i	Population
IFC	Import charges including freight, insurance and other costs of fish type
ij	Fish commodities
K	Carrying capacity
LV	Landed value
M	Marketing cost
MCP	Maximum catch potential
MP	Historical mariculture production
NE	New effort entry
NSHFeed	National (country) supply share of a commodity
o	initial
p	Ex-vessel price
p	Prices
P	Price level which is approximated using Stone price index

PARM	Price of the import-domestic aggregate
PARX	Price of the export-domestic aggregate
PC	Price of fish
PC	Consumer price for fish type
PHI	Fishing effort
P_i	Producer price
pm	Import price of fish type
Pnum	Price of the numeraire good
Price	Farm gate price of the species
PS	Producer price of fish type
PS	Domestic price
PU	Percentage of maximum catch potential used for FMFO
pv	Prevalence
px	Export price of fish type
q	Catchability
QA	Netput supply
QD	Quantity demanded for fish type
QDF	Market demand aggregates
QDFeed	Total feed demand of a country
QH	Foreign component of export
QHM	Combination of total demand for the domestic component
QHX	Domestic component (for domestic consumption)
qinRate	Catchability increase rate
QM	Total demand for imports
Qnum	Numeraire good
QS	National supply of a commodity
QSF	Market supply aggregates
QSFeed	National feed supply of a commodity
QX	Commodity exports of country
r	Intrinsic population growth rate
RE	Retirement of existing effort
ruralpopulation	Rural population size
s	Smooth function
SCatch	Subsistence catches by country
SH	Expenditure share of fish among the fish commodities
t	Year
TA	Tariff imposed on fish type
TaxonBioTL	Trophic level of species
TP	Profit from last-year
uc	Catchability
V	Conditioning variable for fixed input in market model

α, β *and* γ	Model parameters in GFish model
ε	Error term
λ	Proportional change of output of supply fish type
λnum	Expansion for the numeraire fish type
π^*	Normalized profit
ρm	Transformation of the elasticity of substitution
ρx	Transformation of the elasticity

Chapter 1: Dynamic Integrated Marine Climate, Biodiversity, Fisheries, Aquaculture and Seafood Market Model (DIVERSE): introducing the framework

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Abstract

Global change drivers, such as population growth, increasing consumption, inequity in resource distribution, overfishing, climate change, and pollution, are challenging the sustainability of global coupled human-natural seafood production system. Modelling the linkages between the biophysical and socio-economic components of the seafood production systems are useful to explore the interactions between these drivers and policy responses. Such models can be applied to project future scenario of seafood sustainability under global change. This chapter describes the basic framework of an integrated assessment model for the ocean, fisheries, and aquaculture called Dynamic Integrated Marine Climate, Biodiversity, Fisheries, Aquaculture and Seafood Market Model (DIVERSE) and its potential applications. DIVERSE includes four interconnected sub-components: climate-living marine resources, fishing effort dynamics, mariculture, and global seafood market. DIVERSE is supported by a system of linked and harmonized infrastructure of environmental, biodiversity, fisheries, and socio-economic data. In parallel, scenarios of direct and indirect drivers of changes in the marine human-natural system are developed based on the Shared Socioeconomic Pathway (SSP) framework. Some of the main research questions in the context of exploring scenarios and pathways for ocean futures under climate change are also highlighted. The DIVERSE model has the potential to link to other integrated assessment models to explore broader societal challenges related to the future of global (including land, ocean, and freshwater) food systems, and in general biodiversity and ecosystem services.

Introduction

Marine ecosystems and the benefits they provide to human society are important components of sustainable development (Singh et al., 2018; Diaz et al., 2019). However, global change, i.e., planetary-scale changes in the Earth system, is challenging the sustainability of the ocean. The main direct global change drivers in the ocean include fishing, pollution, habitat destruction, and climate change (including ocean acidification). Amongst these drivers, overfishing is already threatening many marine species (Pitcher and Cheung, 2013; Diaz et al., 2019). Most notably, many fisheries are removing fish at a rate considered by many to be unsustainable, with commercially important species being driven to vulnerable levels. In addition, climate change is now exerting massive and long-lasting impacts on marine ecosystems (Pörtner et al., 2014; Bindoff et al. 2019). Driven by greenhouse gas emissions from human activities, the ocean is getting warmer, more acidic, and its oxygen content is declining (Gattuso et al., 2015; Bindoff et al. 2019) causing large-scale changes in marine biodiversity and ocean productivity that ultimately affect marine ecosystems' benefits to people (Cheung et al., 2016a; Bindoff et al. 2019; Sumaila et al., 2019).

The direct human drivers that affect the coupled human-natural system of the ocean are the manifestation of indirect drivers including, for example, human population, economic development, consumption patterns, and social equity (Díaz et al., 2015). It is also shaped by policies and interventions that have consequences on the ocean (Gattuso et al., 2018). Therefore, to understand the past and potential future changes in ocean sustainability under global changes, it requires the consideration of the combination and interactions of the direct and indirect drivers and policy responses.

Modelling the linkages between the biophysical and socio-economic components of the seafood production systems is useful to explore the interactions between drivers and policy responses. Specifically, to investigate the implications of over-exploitation and climate change for sustainable development, and examine the effectiveness of societal actions in response to these challenges, we suggest that a formal modelling framework can include four building blocks: (1) climate-living marine resources, (2) fishing effort dynamics, (3) aquaculture (including mariculture) and (4) global seafood trade (Figure 1.1). Such a model can be applied to make projections under different scenarios to support decision-making for ocean governance (IPBES, 2016).

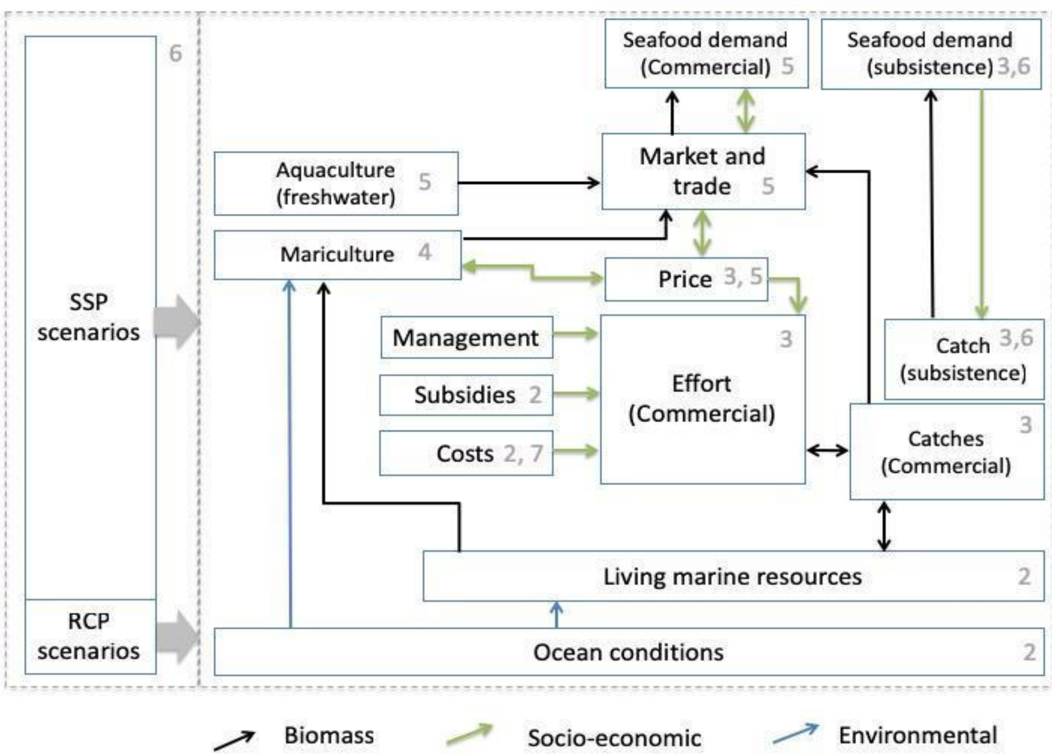

Figure 1.1. Schematic diagram of the Dynamic Integrated Marine Climate, Biodiversity, Fisheries, Aquaculture and Seafood Market Model (DIVERSE) representing a global ocean coupled human-natural system that aims to examine questions related to the future of seafood sustainability under climate change. Different arrows represent the flow of biomass (black) and environmental (blue) and socio-economic (green) influences between different components of the coupled human-natural system. The grey number highlights chapters in this report that describe the various components of the DIVERSE: (Chapter 2) climate-living

marine resources, (Chapter 3) fishing effort dynamics, (Chapter 4) mariculture, (Chapter 5) seafood market, trade and aquaculture (freshwater) and (Chapter 6) scenarios (representative concentration pathways - RCPs and Shared Socioeconomic Pathways - SSPs).

This chapter describes the basic framework of such integrated assessment model (IAM) for the ocean and its potential applications. Specifically, the different sub-components of DIVERSE and their main interconnections are introduced. Also highlighted are some of the main research questions in the context of exploring scenarios and pathways for ocean futures under climate change.

Climate-living marine resource model

The climate-living marine resources model represents the biophysical conditions of marine ecosystems that support biodiversity and the production of fish stocks. The conditions of organisms, biological communities, and their interactions are influenced by the physical and biogeochemical conditions of the oceans (Pörtner et al., 2014). Examples of the key ocean variables that influence the physiology, growth, reproduction, distribution, and trophic interactions of marine species include temperature, oxygen, pH, salinity, nutrients, primary production, ocean currents, eddies, and mixing (Table 1.1).

At the global scale, changes in these ocean variables under scenarios of climate change are projected by earth system models; the outputs of which are then used in projecting changes in biomass production of fish stocks and fisheries (Chapter 2). A range of global scale living marine resources models are available with different structural assumptions (Tittensor et al., 2018). Some of the models are based on energy (or biomass) flows across marine food webs that are structured by body size and/or functional guild of the organisms. Other models explicitly represent dynamics of populations of species and their distribution. This report focuses on a specific living marine resources model called Dynamic Bioclimate Envelope Model (DBEM, Chapter 2). It is a spatially-explicit population dynamic model that simulates changes in abundance, biomass, and potential population production on a 0.5^{o} latitude x 0.5^{o} longitude grid of the world ocean (Cheung et al., 2008; Cheung et al., 2016b). The projected changes in ocean conditions from the earth system models are used as environmental forcings in DBEM. Ocean conditions in the 21st century are dependent on anthropogenic greenhouse gas emissions that are described under different Representative Concentration Pathways (RCPs, see Chapter 6). Driven by the outputs from the earth system models, DBEM simulates the effects of changing ocean conditions on the biology and distribution of exploited marine fishes and invertebrates through changes in the growth, body size, habitat suitability, population dynamics, adult and larval dispersals, and potential production (Cheung et al., 2016b).

Overall, in DIVERSE, the main outputs of the climate-living marine resources model include projected changes in ocean conditions, fish stock abundance, biomass, and maximum potential catches on 0.5^{o} x 0.5^{o} grid of the world ocean. (Table 1.1).

Table 1.1. Cross-domain parameter sets for DIVERSE. Each row represents a sub-component of DIVERSE as described in Figure 1.1 (see Appendix for description of databases).

Sub-model	**Main inputs variables**	**Data sources for the inputs**	**Main output variables**
DBEM	Annual average seawater temperature, dissolved oxygen, pH, net primary production, salinity, surface current advection, sea ice extent	Earth system models	Abundance, biomass, potential catch by exploited species by year
EDM	Relative changes in biomass by exploited species, changes in the price of species, costs and subsidies	DBEM, price and subsidies databases, seafood market model, socio-economic scenarios	Annual total and active fishing (commercial) effort, changes in stock biomass, catches, total revenues and profits.
Mariculture model	Changes in price, fishmeal and fish oil supply, human development index, ocean conditions	DBEM, seafood market model, Earth system model, socio-economic scenarios	Annual mariculture production potential
Seafood market model	Production by seafood commodities, seafood demand, per capita income, tariffs	EDM, mariculture model, scenarios	Seafood trade flows in weight, value, and seafood price.

Fishing effort dynamic model

Fisheries are one of the main ecosystem services from the ocean, supporting economic benefits, livelihood, and provision of food. However, benefits from fisheries are strongly dependent on catches that are affected by the distribution, abundance, and productivity of fish stocks (including fishes and invertebrates), as well as the intensity of fishing activities. On the other hand, fishing activities impact marine species and ecosystems. Overfishing degrades the long-term productivity of the fish stocks and may lead to local or even global extinction (Dulvy et al. 2003). Climate change also affects the distribution and potential catches of fisheries (Cheung et al. 2016a). Moreover, commercial fishing is an economic sector and therefore its dynamics are affected by the benefits fishers get from such activities. Benefits are dependent on catches, their prices, cost of fishing, and policy interventions, such as subsidies and fisheries management. In addition, some fishing activities are for subsistence purposes and are thus driven by the demand for food and nutrients. These human-natural system interactions and their feedbacks together shape the level of fishing, catches, abundance, seafood supply, and the status of fish stocks and biodiversity.

In the DIVERSE framework, the interactions and feedbacks between living marine resources, fisheries (commercial), economic factors and policies affecting fishing activities are modelled through an effort dynamic model (EDM) (Figure 1.1, Chapter 3). The EDM is a bioeconomic model with a simplified biological component and a fisheries economic component that interacts with one another. The EDM is spatially implicit; in the model, the ocean is subdivided into EEZ-ocean units and the high seas (see Chapter 3). The biological component is a biomass dynamic model (based on the assumption of logistic population growth) in which biomass production is a function of the projected changes in total biomass from DBEM and the amount of fishing projected from the fisheries economic component of the EDM. The fisheries economic component describes the dynamics of commercial fishing effort and the projected fishing effort is based on calculated total revenues and profit, and investment into and depreciation/exists of the fishing fleets. The factors affecting fishing effort depend strongly on catches by species, their price, fishing costs, subsidies received changes in catchability of the fish stocks, and the sensitivity of fisher's decisions on fishing to changing benefits from the fisheries. Commercial catches are assumed to be sold to the seafood market where global trade, supply and demand determine seafood prices (see seafood market model, Chapter 5). Seafood prices, in turn, affect the revenues and profits of the fishing fleets and influence fishing behaviour.

Subsistence fisheries catches are modelled separately through an empirical model that is based on population size and its growth, as well as the development status of the society (see Chapter 6). The calculated subsistence catches add to those from commercial fisheries and consequently affect fish stocks that are modelled through the biological sub-component.

Overall, the main outputs from EDM include biomass by exploited populations, their catches, revenues, profits and total and active fishing effort (Table 1.1).

Mariculture model

Seafood production from mariculture has been growing rapidly in recent decades. While mariculture contributes to the global seafood supply, it also has a footprint on wild fish stocks as many feed-based mariculture operations require fishmeal and fish oil as ingredients in aqua-feed from capture fisheries (Cashion et al., 2017). Moreover, changing ocean conditions such as warming, ocean acidification and deoxygenation can affect the suitability of marine area for mariculture. Changes in social-economic factors such as technological development, prices of seafood products and management policies can also affect mariculture production and their operations.

To capture the linkages of mariculture to the coupled human-natural marine system, DIVERSE includes a mariculture sub-model (Chapter 4). The mariculture model has two main components: (i) a species distribution models that projects potential suitable area for mariculture and (ii) an empirical model that calculates mariculture potential production based on the projected suitable mariculture area, price of mariculture products, supply of fishmeal and fish oil (based on projections from DBEM and EDM; Chapter 2 and 3) and other social-economic factors. Changes in price are determined by the global seafood market (from seafood market model; Chapter 5) while other social-economic factors are derived from scenario storylines (Chapter 6).

Overall, the mariculture model projects seafood supply from fish or shellfish farming in the ocean and their demand for fishmeal and fish oil (Table 1.1).

Seafood market model

Seafood is one of the most traded seafood commodities, with traded value exceeding the sum of sugar, maize, coffee, rice, and, cocoa (Asche et al., 2015). Therefore, the global demand and supply of seafood have large influences on their prices in different regions and countries. Seafood demand is shaped by many social and economic factors, particularly their consumption patterns and levels, which is partly dependent on population size, income, and preferences.

Simultaneously, seafood supply is dependent on the abundance and productivity of fish stocks (Chapter 2), as well as fishing effort, their management, and production from mariculture (Chapter 3, 4). The latter is also dependent on seafood prices. Therefore, modelling global seafood trade is an important component of DIVERSE that is interconnected to all aspects of the seafood production chains.

In the DIVERSE framework described here, the global seafood market and trade are modelled explicitly to assess the effects of market and non-market forces on other components of the seafood production system (Chapter 5). The seafood market model (GFish model) simulates supply, demand, prices, and international trade of fish. GFish is a partial equilibrium model as only the quantities and prices of fish commodities are determined within the system. The GFish model is capable of generating dynamic equilibrium on an annual basis, considering the outputs from the climate-living marine resources model (Chapter 2), effort dynamic model (Chapter 3), and mariculture production model (Chapter 4) (Table 1.1). Also, indirect drivers to the seafood market, such as population size and income level, are considered based on socio-economic scenarios (Chapter 6).

Overall, the main outputs from the GFish model include global seafood trade flows (in weight and value) and seafood prices (Table 1.1).

Scenarios

A range of direct and indirect drivers, such as population size, income levels of different segments of the world, country-level population, and global development patterns (e.g., regionalization vs globalization) are not modelled explicitly in DIVERSE. Instead, these drivers are considered exogenous to the model and incorporated through scenarios. For global environmental assessments such as the focus of the DIVERSE, and qualitative and quantitative descriptions of these direct and indirect drivers are available under the Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) scenarios (van Vuuren et al., 2011; O'Neill et al., 2017) (Chapter 6). The RCPs quantitatively describe different pathways of greenhouse gas emissions, while the SSPs describe ways in which the future society might evolve, as indicated by socio-economic factors, including population, economic growth, education, urbanisation, and the rate of technological development. The RCPs provide scenarios of projected changes in terms of radiative forcing that are directly used in the simulation of changes in climate and ocean conditions in the earth system model (Chapter 2). The general storylines described by the SSPs are further contextualized to make them relevant for the ocean, fisheries, mariculture and seafood trade through literature review and expert opinions (see Chapter 6).

Key databases and their harmonization

DIVERSE provides a quantitative framework to simulate changes in ocean conditions, fish stocks, fisheries, seafood trade, and mariculture under scenarios of physical and social-economic changes which requires the support from appropriate data infrastructure. The main databases that are used in DIVERSE include current species distributions, the *Sea Around Us* catch reconstruction database (Pauly and Zeller, 2016), Fisheries Economics Research Unit's fishing price (Tai et al., 2017), cost (Lam et al., 2011) , subsidies (Sumaila et al., 2010), and jobs (Teh and Sumaila, 2013) databases, United Nations' Food and Agriculture organization fish trade database, and data extracted from FishBase (www.fishbase.org) and SeaLifeBase (www.sealifebase) (see Appendix).

These databases are linked to one another either through the taxonomic identity of the exploited species, spatial grid (0.5° x 0.5°), national EEZs, year, and fishing entities.

Key questions and hypotheses

DIVERSE can be used to address questions and hypotheses related to the impacts of global change. The model can also be applied to examine the implications of human responses to these impacts for seafood sustainability at global and regional scales. Examples of hypotheses that DIVERSE can be used to test include:

- Increasing greenhouse gas emission reduces the scope for sustainable development of marine seafood system;
- Improving fisheries management reduces the sensitivity of countries' fisheries to climate change impacts;
- Climate change intensifies the trade-offs between economic and social/ecological objectives in the seafood system in tropical developing countries;
- Regionalization of global trade reduces the scope for sustainable seafood systems.

To test these hypotheses, indicators for sustainable seafood system are needed to help evaluate the projections under various scenarios. Here, sustainability of the seafood system is characterized by three dimensions: ecological, social, and economic. For example, ecological status can be indicated by changes in mean species abundance, which is calculated from the average changes in abundance (or biomass) of species in the assemblages relative to a reference period. For the social dimension, it can be indicated by the number of employments and the amount of subsistence food provided by the seafood sector. Chapter 6 describes empirical models that we developed to predict fisheries-related employments and subsistence catches. For economic, it can be the total value of the seafood system and the revenues and profits from the fisheries/aquaculture sectors.

Conclusion

The ocean integrated assessment model provides a framework to formally link the coupled human-natural seafood production system at the global scale explore future scenarios of global change. The outputs from DIVERSE can be used to inform the consequences of pathways of human actions on the sustainability of seafood production system under climate change. In the future, DIVERSE can be linked to other integrated assessment models to explore questions related to the future of global (including land, ocean, and freshwater) food systems and the interconnections with biodiversity and ecosystem services.

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Chapter 2: Climate-living marine resources model to project future changes in fish stock biomass and catches

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Abstract

This chapter describes the structure of the climate-living marine resources component of the ocean integrated assessment model called Dynamic Integrated Marine Climate, Biodiversity, Fisheries, Aquaculture and Seafood Market Model (DIVERSE). This component includes two parts: first, models and scenarios for changes in ocean conditions and second, abundance of fish stocks. Changing ocean conditions under scenarios of greenhouse gas emissions are projected using three earth system models. Their outputs are used as environmental drivers for a dynamic bioclimate envelope model that projects spatial and temporal changes in abundance of exploited fish and invertebrates populations. The dynamic bioclimate envelope model is chosen for DIVERSE because of its explicit representation of exploited species and changes in spatial distribution. Abundance forcing for each exploited population is projected from the climate-living marine resources model that are used as drivers for the biological component of the effort dynamic model described in Chapter 3 of this report. Three idealized scenarios of marine protected areas designation (10%, 30%, and 50% of the global ocean in area) are also described and explored. The projection of abundance forcing under scenarios of greenhouse gas emissions and marine protected areas are illustrated using four examples: Atlantic cod (*Gadus morhua*) in the Atlantic coast of the USA, shortfin scad (*Decapterus macrosoma*) in the Philippines, Bonga shad (*Ethmalosa fimbriata*) in Guinea, and Yellowfin tuna (*Thunnus albacares*) in the high seas. The model projects changes in biomass that are generally consistent with other published living marine resources models. In the future, uncertainties on the projections and results of DIVERSE model could be explored by using living marine resource models other than DBEM to generate abundance forcing to explore the effects of model structural uncertainties on the projections and results of DIVERSE model.

Introduction

Increasing greenhouse gas emissions are changing the global ocean conditions (IPCC, 2013). The ocean is absorbing more than 90% of the heat generated from greenhouse effects, and almost 30% of the carbon dioxide emitted from human activities (Gattuso et al., 2015). This absorption has led to changes in ocean conditions, including ocean warming, deoxygenation, and acidification. These environmental changes are projected to continue in the 21st century, with levels that are likely to be significantly higher under 'no mitigation' (Representative Concentration Pathway or RCP 8.5) relative to 'strong mitigation' (RCP 2.6) greenhouse gas emissions.

Ocean warming, deoxygenation, and acidification affect fish stock distribution, physiology and their potential fisheries catch (Cheung et al., 2013; Pinsky et al., 2013; Jones and Cheung, 2015; Cheung et al., 2016a; Cheung et al., 2016c). In responses to warming, marine species shift their distributions towards higher latitudes, deeper waters or track environmental temperature gradients to areas with their preferred environmental conditions. A decrease in oxygen further increases the stress on marine fishes and invertebrates, leading to reduction in growth and body size. Also, ocean acidification affects the acid-base balance of marine species, with species that form exoskeletons being particularly vulnerable. Acidification also impacts the neuro-sensory system of some marine species that can indirectly increase their mortality rate. Ocean warming increases stratification of the water column, reduces sea ice extent and alters nutrient availability that, in addition to the direct effects of warming on marine microbes, alter primary production. The effects of these ocean changes impact species composition, interactions and potential biomass production of exploited marine fish stocks.

Modelling of future changes in fish stock biomass and catches under climate change, therefore, requires two components. First, we need models and projections of future changes in ocean conditions that affect distribution, biomass, and production of fish stocks. The main ocean physical and biogeochemical drivers that generally affect the biology of fish stocks include temperature, oxygen, pH, primary production, salinity, and current advection. Second, we need models and projections of changes in biology and population dynamics of exploited fish stocks. Such changes in fish stocks are driven by the changing ocean conditions and other important non-climatic human activities such as fishing.

In this chapter, we describe the models that we use to project future changes in environmental drivers and distribution, abundance and maximum potential catches of global fish stocks. In the dynamic integrated marine climate, biodiversity, fisheries, aquaculture, and seafood market model (DIVERSE) framework (Chapter 1), the ocean and fish stock models are then linked to the effort dynamic model (Chapter 3), seafood market model (Chapter 4), and mariculture model (Chapter 5) to project future scenarios of global change (Chapter 6).

Model descriptions

Earth System Models

Earth system models (ESM) or coupled ocean-atmospheric physical and biogeochemical climate models represent the global dynamics of climate system and their interactions with part of the biological systems such as primary production on land and ocean. ESMs describe the earth's atmosphere, land, and ocean on three-dimensional grids and their resolution varies between models. In almost all the ESMs with the ocean component, basic physical properties such as heat content, advection, and sea ice are modelled. In many ESMs (specifically in the three models that we use in the ocean integrated assessment modelling, Table 1.1), the ocean component of the model includes dynamics of oxygen, carbon, nutrients (e.g., phosphorus, silica and iron), phytoplankton, and zooplankton.

The Coupled Model Intercomparison Project Phase 5 (CMIP5) provides outputs from ESMs developed by research institutes around the world under a common set of greenhouse gas emissions scenarios. These scenarios are described under different Representative Concentration Pathways (RCP). Specifically, the DIVERSE model described in this report uses outputs from three ESMs: the NOAA Geophysical Fluid Dynamic Laboratory Earth System Model 2G (GFDL-ESM2G), the Institut Pierre Simon Laplace climate model 5A-MR (IPSL-CM5A-MR) and the Max Planck Institute Earth System Model MR (MPI-ESM-MR) (Table 1.1). The performance of each model has been assessed and reported (LaufKoötter et al. 2015; Kwiatkowski et al. 2017). These three ESMs are used in this report because all the oceanographic variables that are required for the simulation of the fish stock model are available for these ESMs from the CMIP5 data portal. The GFDL-ESM2G and IPSL-CM5A-MR are also used in the Fisheries and Marine Ecosystem Impact Models Intercomparison Project (FISHMIP), thus allowing for potential intercomparison of outputs from marine and fisheries impact models.

The ESMs outputs of interest in DIVERSE include seawater temperature (surface and bottom), oxygen concentration (surface and bottom), pH (surface and bottom), salinity (surface and bottom), sea ice, surface current advection and net primary production. The original model outputs generally have a grid resolution of approximately 1.0 latitude x 1.0 longitude. The data are regridded onto a 0.5° x 0.5° grid using a bi-linear interpolation method.

Fish stock model - Dynamic Bioclimate Envelope Model

We used the Dynamic Bioclimate Envelope Model (DBEM) to simulate changes in distribution, abundance, and catches of exploited marine fishes and invertebrates. The structure of the DBEM is described in Cheung, et al. (2016c) and the pertinent aspects of the model were summarized here.

a. Current species distribution

The current distributions of commercially exploited species, representing the average pattern of relative abundance in recent decades (i.e., 1970-2000), were produced using an algorithm developed by the *Sea Around Us* Project (see www.seaaroundus.org). The algorithm predicts the relative abundance of a species on a 0.5_{o} latitude x 0.5_{o} longitude grid based on the species' depth range, latitudinal range, Food and Agriculture Organization (FAO) statistical areas and polygons encompassing the species' known occurrence regions. The distributions were further refined by assigning habitat preferences to each species, such as affinity to shelf (inner, outer), estuaries, and coral reef habitats. The required habitat information was obtained from FishBase (www.fishbase.org) and SeaLifeBase (www.sealifebase.org), which contains key information on the distribution of the species in question, and on their known occurrence region.

b. Predicting future habitat suitability

Based on the relation of a given species with the climatological average ocean conditions (average of 1971-2000) such as temperature (bottom and surface temperature for demersal and pelagic species, respectively), bathymetry, salinity and sea ice, an index of habitat suitability for each species (P) is computed for each marine cell using ESMs outputs . DBEM estimated the temperature preference profile (TPP) of each species by overlaying the estimated species distribution with annual seawater temperature and calculated the area-corrected distribution of relative abundance across temperature for each year from 1971 to 2000, subsequently averaging annual temperature preference profiles (TPP). The estimated TPP was used to predict the thermal physiological performance of a species in each area.

c. Predicting carrying capacity

Population carrying capacity in each spatial cell is a function of the unfished biomass of the population, the habitat suitability, and net primary production. We assumed that the average of the top-10 annual catches was roughly equal to the maximum sustainable yield (hereafter called the maximum catch potential or MCP) of the species. The carrying capacity (K) of the species is approximated from the estimated MCP and the intrinsic population growth rate (r) ($K = MSY*4/r$, see Cheung et al. 2016c). The total K is then spatialized according to the predicted current habitat suitability index. The model also predicts the equilibrium relative abundance-at-size class based on a size-based population matrix sub-model. Growth is described by a generalized von Bertalanffy growth function. The characteristic mean weight of the population is then calculated based on the outputs from the size-based population model. Population abundance of the species is also predicted by dividing biomass by the species' mean weight.

d. Simulating changes in biomass and distribution

The model simulated changes in abundance and biomass of a species based on changes in population carrying capacity, intrinsic population growth, the population mean weight and the advection-diffusion of the adults and larvae of the population. DBEM calculates a characteristic weight representing the average mass of the individuals of a population in a given spatial cell given projected habitat temperature and oxygen concentration. The model simulated how changes in temperature and oxygen content would affect growth and body size of the individuals using a sub-model derived from a generalized von Bertalanffy growth function. The outputs of this sub-model are then used to simulate changes in the characteristic mean weight of the population in each spatial cell. Population growth is calculated using a logistic function. Movement of adults between spatial cell is driven by diffusion (as a function of their motility), abundance, habitat suitability, and carrying capacity. For species that produces pelagic larvae, larval dispersion is based on advection with ocean current and diffusion of pelagic larvae and their pelagic larval duration.

The model had a spin-up period of 200 years using the climatological average oceanographic conditions from 1971 – 2000, thereby allowing the population to reach equilibrium. To calculate maximum catch potential and assuming logistic population growth, fishing mortality is set to be equal to natural mortality rate M in order to have maximum equilibrium surplus production.

Scenarios of marine protected areas (no-take marine reserves) are implemented by assuming no fishing for all species in spatial cells that are intended to be designed as protected areas (Figure 2.1) (Cheung et al., 2017). Idealized scenarios of protected areas of 0%, 10%, 30%, and 50% of the area of high seas were developed (Figure 2.1). The locations of the protected areas are randomly assigned (based on a random number generator). If a 30_o x 30_o spatial cell is selected, the whole pixel is assumed to be protected from fishing. The total number of protected pixels are then based on the total area that is intended to be protected. Also, the protected area is proportional to the area of each exclusive economic zones and the high seas. For the high seas, it is further prorated to the area of each ocean basin (represented by the United Nations' FAO statistical area). In these idealized scenarios, we assume that all the marine protected areas are designed in year 2020.

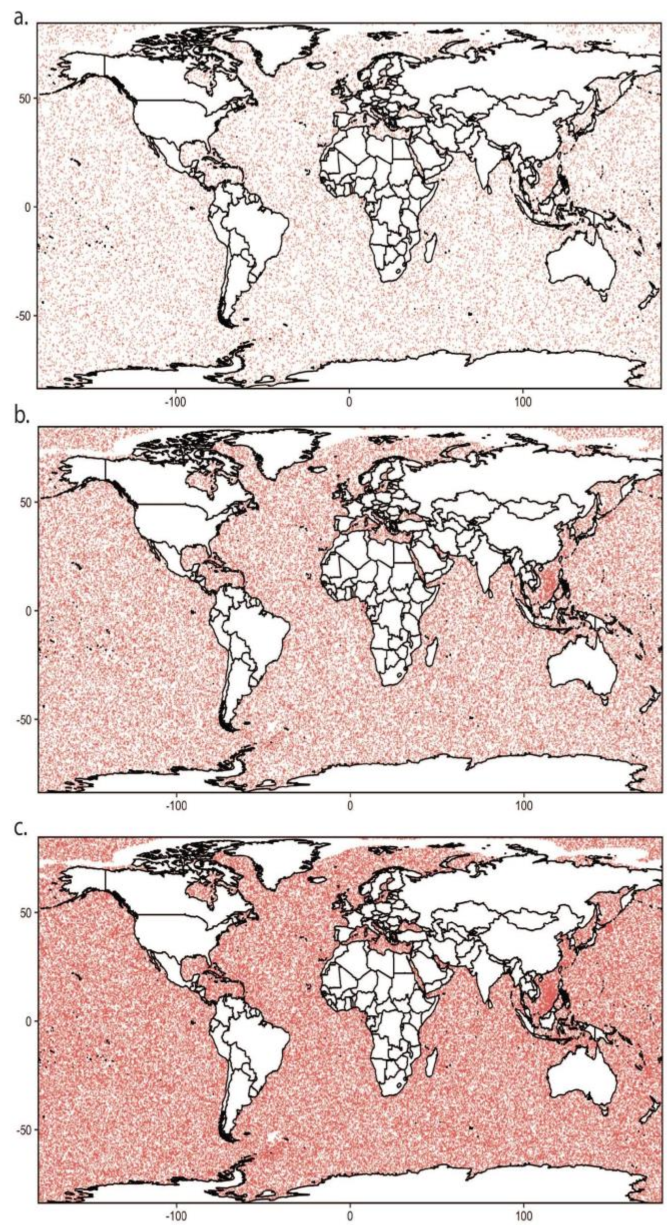

Figure 2.1. Maps of scenarios of marine protected areas when (a) 10%, (b) 30% and (c) 50% of the ocean is randomly selected for protection from fishing (red pixels).

Finally, the projections of biomass by DBEM is compared against an ensemble of 10 combinations of earth system model-upper trophic level models projections that are available from the Fisheries and Marine Ecosystems Impact Models Intercomparison Project (FishMIP) (Lotze et al., 2019).

Projected abundance forcing

The projected changes in abundance of exploited fish stocks are used as forcing for the simulation of changes in fishing effort, catches, and revenues and profits from fishing (Chapter 3). The abundance forcing is calculated from the total annual abundance of each species across the spatial cells within each EEZ-ocean basin/high seas boundary from 1951 to 2099 under two contrasting

Representative Concentration Pathways (RCP2.6 and RCP8.5). The projected changes in abundance are normalized to the average of the 1951 to 2000 period.

The diversity of pattern of forcing between fish stocks, scenarios and earth system models is illustrated through three examples: Atlantic cod (*Gadus morhua*) in the USA, bigeye scad (*Selar crumenophthalmus*) in the Philippines, and bonga shad (*Ethmalosa fimbriata*) in Guinea (Figure 2.2). For Atlantic cod in the USA, the model projected a large (>50%) decrease in abundance forcing by the end of the 21st century, relative to 1951-2000 under both RCP2.6 and RCP8.5. The high greenhouse emissions scenario resulted in a large decline in USA's cod (<25% relative to 1951-2000). Such contrast between RCP2.6 and RCP8.5 scenarios is also observed in the case of bigeye scad and bonga shad although the magnitude of the differences varies between species. While the sensitivity of the projected changes in abundance forcing varies between earth system models, the direction of changes remains consistent (Figure 2.2).

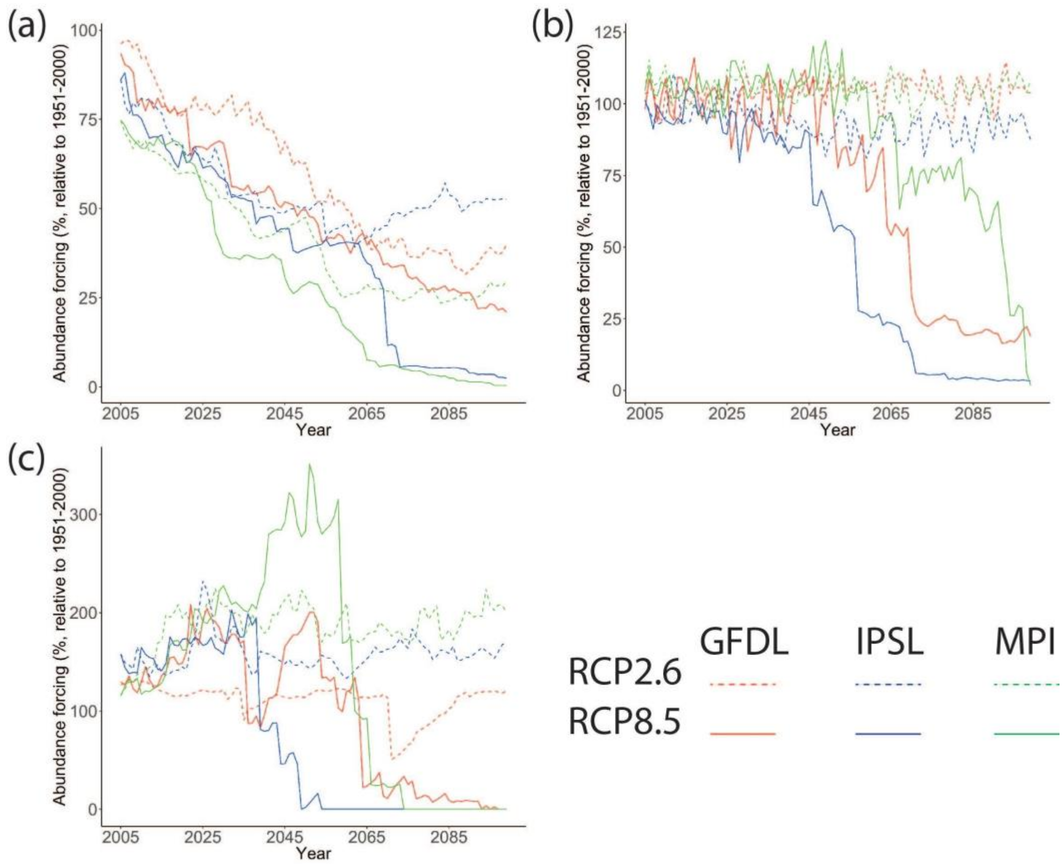

Figure 2.2. Projected changes in annual abundance from 2005 to 2099 (relative to the mean level between 1951 and 2000) for (a) Atlantic cod (*Gadus morhua*) in the USA, (b) shortfin scad (*Decapterus macrosoma*) in the Philippines, (c) Bonga shad (*Ethmalosa fimbriata*) in Guinea under RCP2.6 (blue lines) and RCP8.5 (red lines). The projected changes in relative abundance are driven by outputs from two earth system models: GFDL-ESM2G (solid lines) and IPSL-CM5-MR (dashed lines).

The incorporation of marine protected area scenarios into the simulation of abundance forcing is illustrated using the populations of yellowfin tuna (*Thunnus albacares*) in the high seas and the EEZs of Fiji and the Atlantic coast of USA as examples (Figure 2.3). Without protected areas, yellowfin tuna populations in the high seas and the Atlantic coast of USA are projected to increase by the end of the 21st century relative to the present day under RCP2.6 and RCP8.5. In contrast, yellowfin tuna in Fiji is projected to remain stable or decrease by around 20% during the same period under the low and high greenhouse gas emissions scenarios, respectively. Protecting larger areas in the high seas (implemented starting in year 2020 in the model) from fishing increases the overall abundance of yellowfin tuna relative to the present-day across all populations and greenhouse gas emission scenarios.

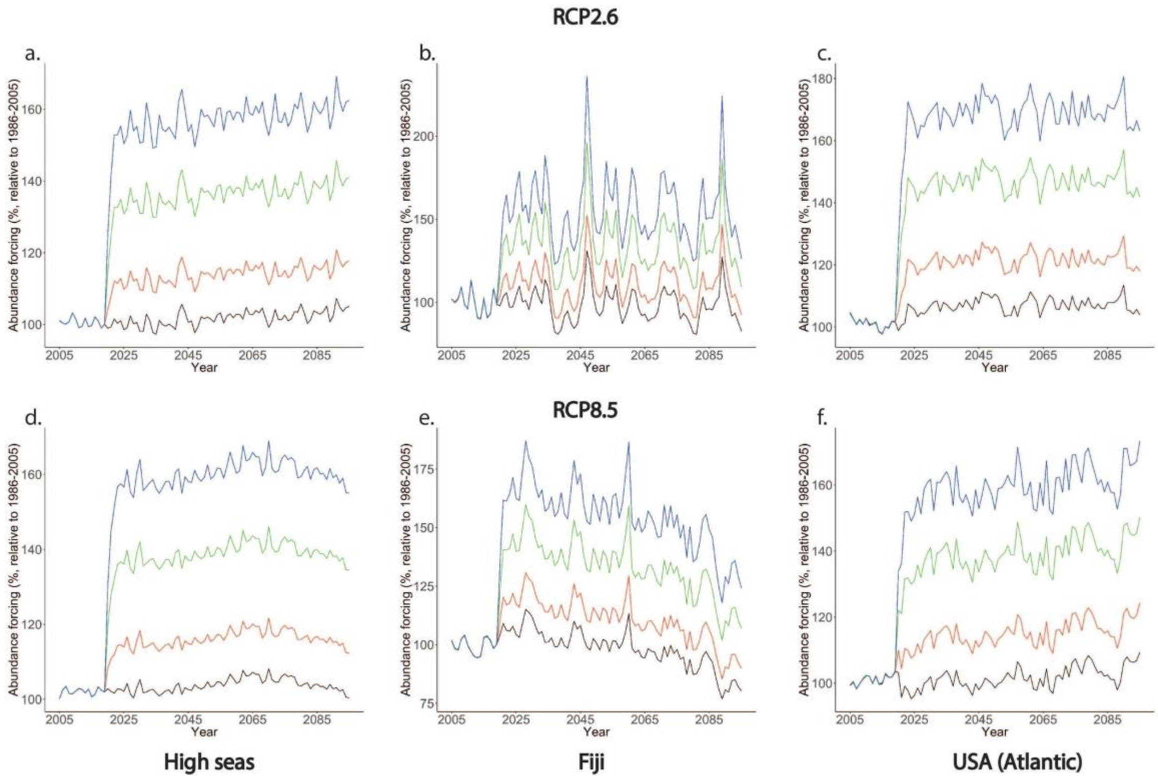

Figure 2.3. Projected changes in relative abundance forcing of yellowfin tuna (*Thunnus albacares*) on the high seas (a, d), in the exclusive economic zones of Fiji (b, e) and Atlantic coast of USA (c, f) in the 21st century under (a - c) RCP2.6 and (b - f) RCP8.5 under different scenarios of marine protected areas (MPAs): 0% (black line), 10% (red line), 30% (green line) and 50% (blue line) of the ocean is protected. Projections are driven by ocean conditions simulated from GFDL ESM2G.

The projected changes in total animal biomass by the dynamic bioclimate envelope model under RCP2.6 and RCP8.5 are consistent with the FishMIP ensemble projections (Figure 2.4). Specifically, dynamic bioclimate envelope model is projecting a relatively larger contrast in relative biomass changes between the two greenhouse gas emissions scenarios (decrease of 4% and 20% under RCP2.6 and RCP8.5, respectively, by 2100 relative to 1986-2005).

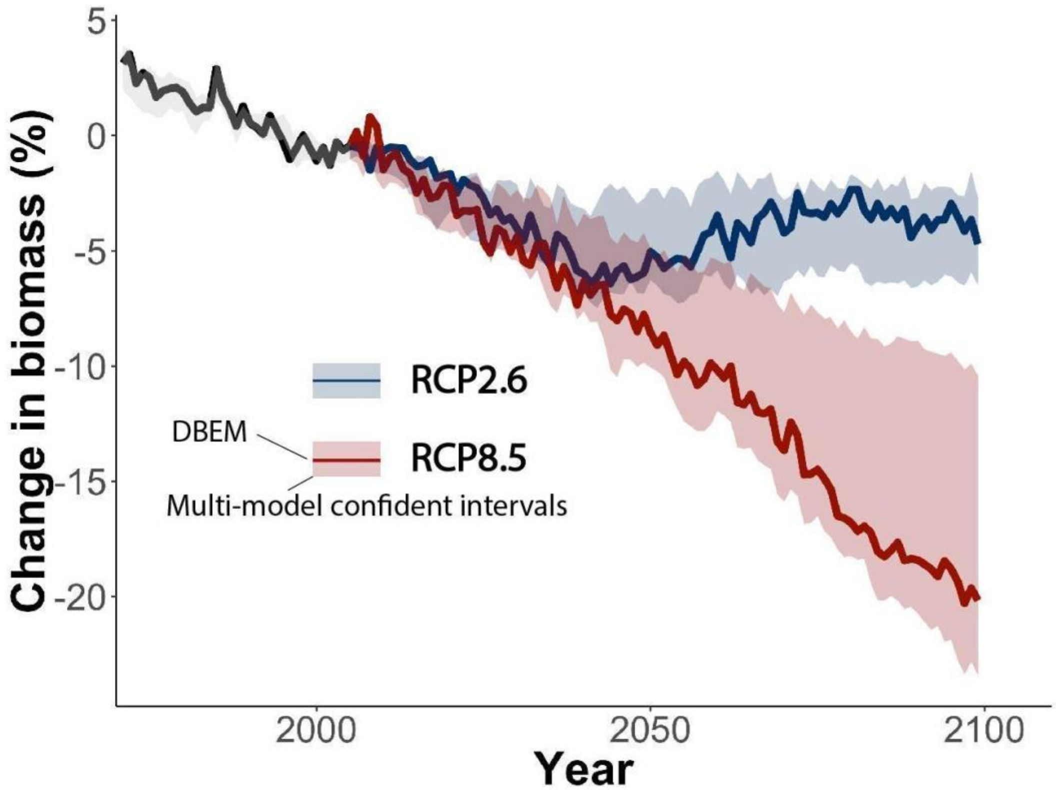

Figure 2.4. Projected changes in total animal biomass by the dynamic bioclimate envelope model (DBEM) relative to projections from an ensemble of 10 earth system model-marine ecosystem model combinations (Lotze et al., 2019) under RCP2.6 and RCP8.5. The reference period is average of 1986-2005.

Discussion

The dynamic bioclimate envelope model described in this chapter simulates spatial and temporal changes in abundance of exploited fish populations under scenarios of climate change and marine protected areas. To link this to DIVERSE, changes in total abundance is expressed as an index representing the proportional changes relative to the present-day period (1986-2005). The results are then used as forcing functions for the biological component of the effort dynamic model described in Chapter 3.

The key uncertainties associated with the projection from the dynamic bioclimate envelope model are highlighted in the following:

- Earth system models have substantial biases in coastal regions, particularly in upwelling regions where biological productivity is often very high. Therefore, projections for abundance in EEZs that are predominantly operating in the near-shore and upwelling regions have low confidence; similarly, potentially important features like regime shifts and tipping points are not always captured by these models, particularly where these are triggered by regional mesoscale dynamics.
- The variability among model realizations in the projected response of the ecosystem to climate change of the driving simulations is considerable, particularly at the regional level, and often equals or exceeds the average change itself.
- The dynamic bioclimate envelope model does not incorporate mechanisms related to the capacity of fish species to adapt to climate change. Such adaptation would be possible through

selection operating on standing genetic diversity in traits associated with temperature sensitivity and changes in food availability, as well as evolutionary or trans-generation adaptation in these traits. These mechanisms have the potential to reduce the sensitivity of marine species and ecosystems to climate change.
- Trophic feedbacks from upper trophic levels to biogeochemical properties of the climate and ocean systems are not considered. Although the effects of such trophic feedbacks on future catch potential are currently not clearly understood and may have relatively smaller contributions to changes in future catch compared to the direct effects of climate change, the lack of understanding contributes to the general uncertainty of the projections.
- The scenarios represent hypotheses of greenhouse gas emission pathways at the global level; they do not include hypotheses of specific mitigation or adaptation strategies by individual countries or organisations.
- The marine protected areas scenarios are idealized and should be considered as a 'null' model as the spatial locations of the protected areas were randomly assigned and were not based on any criteria in relation to management and conservation objectives.

Despite these uncertainties, the dynamic bioclimate envelope model is chosen to project abundance forcings under climate change and protected areas scenarios for DIVERSE because of its explicit representation of exploited species and changes in spatial distribution. The high taxonomic resolution greatly facilitates the harmonization with global fisheries data e.g., catches and prices, and the economic components of the DIVERSE (effort dynamic model and market model) that also require explicit taxonomic representation (see Appendix for description of databases). The model also projects overall changes in biomass that are consistent with other global-scale climate-living marine resources models (Lotze et al., 2019), although there are more substantial regional variations between models (Bryndum-Buchholz et al., 2019). In the future, other climate-living marine resources models can be used as alternative models to generate abundance forcing to explore the effects of model structural uncertainties on the projections and results of the DIVERSE (Cheung et al., 2016b).

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Chapter 3: Dynamics of fishing effort

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Abstract

This chapter describes a fishing effort dynamic model (EDM) that aims to project the effects of climate change and bioeconomic dynamics on regional fisheries catch. The EDM is a dynamic bio-economic model that simulates changes in fishing effort, fisheries catches, revenues, and profits under scenarios of climate change and fisheries management. Parameter values of the effort dynamic model are estimated for each EEZ-ocean basin unit using available databases, empirical equations, and time-series of fisheries catches data from 1950 to 2014. The model included a total of 13,831 stocks in the world ocean. Across all the fisheries stocks, annual catches predicted by the effort dynamic model were consistent with observed catches including estimates of unreported catch. The predicted fishing effort for the historical time period by the model increased substantially from 1950 to the present. Projecting into the future, fishing effort and climate change scenarios can have substantial effects on fish stock abundance. This chapter suggests that the EDM is suited for simulation of changes in fishing dynamics at the global scale. The EDM could be applied to all EEZs and high seas of the world and enables projection for future changes in fishing based on scenarios and projections of resource abundance, prices, fishing costs, subsidies and fishing efficiency from other components of the Dynamic Integrated Marine Climate, Biodiversity, Fisheries, Aquaculture and Seafood Market Model (DIVERSE).

Introduction

The future production of marine capture fisheries will be impacted by changes in the oceans' physical properties, biochemical processes, and primary productivity that are subjected to climate change. Indeed, there is already evidence for such changes in many fisheries (Cheung et al. 2013; Free et al. 2019). Changes in ocean conditions, such as temperature, sea ice extent, salinity, pH, oxygen levels, and circulation, leads to change in survival rates and shifts in the distribution range of marine species (Cheung et al. 2009; Pinsky et al., 2013), changes in primary and secondary productivity, and shifts in timing of biological events (Pörtner et al. 2014). Warmer temperatures may also lead to decreases in maximum body sizes of marine fishes (Pauly and Cheung 2018). The combined effects of these predicted distributional shifts and changes in ocean primary productivity under climate change are expected to lead to changes in species abundance and composition (Beaugrand et al. 2014; Lotze et al. 2019) and hence global redistribution of maximum catch potential (MCP), with projected increases in maximum catch potential (MCP) in high latitudinal regions and decreases in the tropics (Cheung et al. 2016a, Lam et al., 2016).

Concurrent with climate variability and directional change, the continued increase in fishing pressures on species and habitats also poses threats to marine ecosystems and wild capture production (Pauly et al., 2002). While there are limitations to global data on fisheries effort and total catch (Pauly and Zeller, 2016), in general, global fishing effort is driven by increasing demand for seafood worldwide (Swartz et al., 2010, Anticamara et al., 2011) and commercial fishers adjust their effort based on their observed catch volume and profits. Thus, for any given time period, commercial fishers will aim to maximize profits from accessible species. As such, the synergistic effect of both climate change and response of fishers to changes in catch adds more complexity and uncertainty to future seafood production. These changes have severe implications for people who depend on fish for food and income, and for the contribution of fisheries to the global economy (Sumaila et al., 2011, Barange et al., 2014).

This chapter describes a model that aims to project the effects of climate change and bioeconomic dynamics on regional fisheries catch.

Model structure

The effort dynamic model (EDM) is a dynamic bio-economic model that simulates changes in fishing effort, fisheries catches, revenues and profits under scenarios of climate change and fisheries management. The model includes two main components: a biomass dynamic model and a fisheries economic model (Figure 3.1).

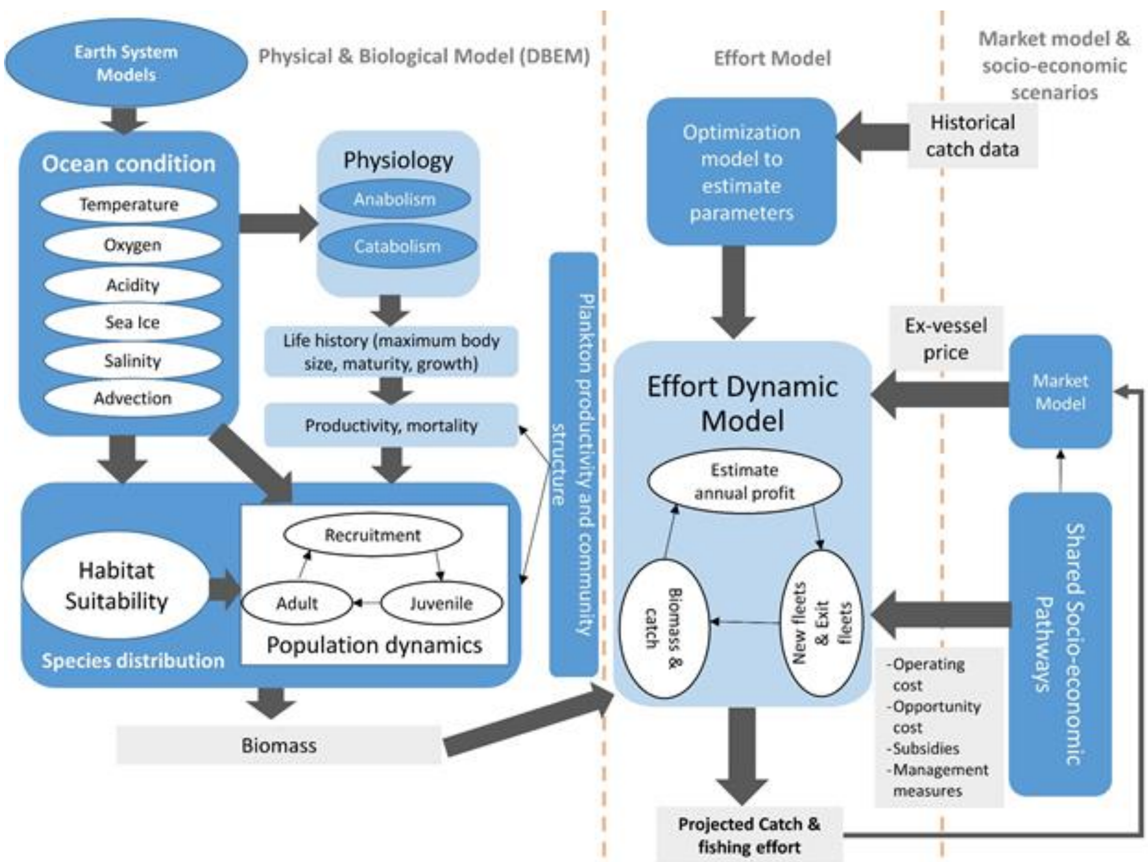

Figure 3.1. Conceptual diagram of spatial fishing effort dynamics model components.

The biological component of the EDM is a biomass dynamic model that assumes logistic population growth. The biomass dynamic model is initialized with two parameters: the intrinsic population growth rate (r) and the carrying capacity (K) of the population (equation 1). The spatial units for populations in the model are delineated by the boundaries of the exclusive economic zones (EEZ), and the high seas (Figure 3.2). In some cases, the EEZ includes multiple ocean basins (e.g, the Pacific, Atlantic, and Arctic Ocean of the Canadian EEZ). In these cases, the part of the EEZ in each ocean basin forms a different population (for example, Canada Pacific, Canada Arctic, Canada Atlantic). The model is driven by two variables that relate to climate change effects on biological production (BP) and changes in fishing mortality rate (F) for each exploited population (i) (Table 3.1).

$$B_{t+1} = \left(B_t + B_t \cdot r \cdot \left(1 - \frac{B_t}{K}\right) - H_t\right) \cdot \ BP_t \qquad (3.1).$$

Total catch (H_t) is the sum of both subsistence (H_{sub}) and commercial (H_{comm}) catches.

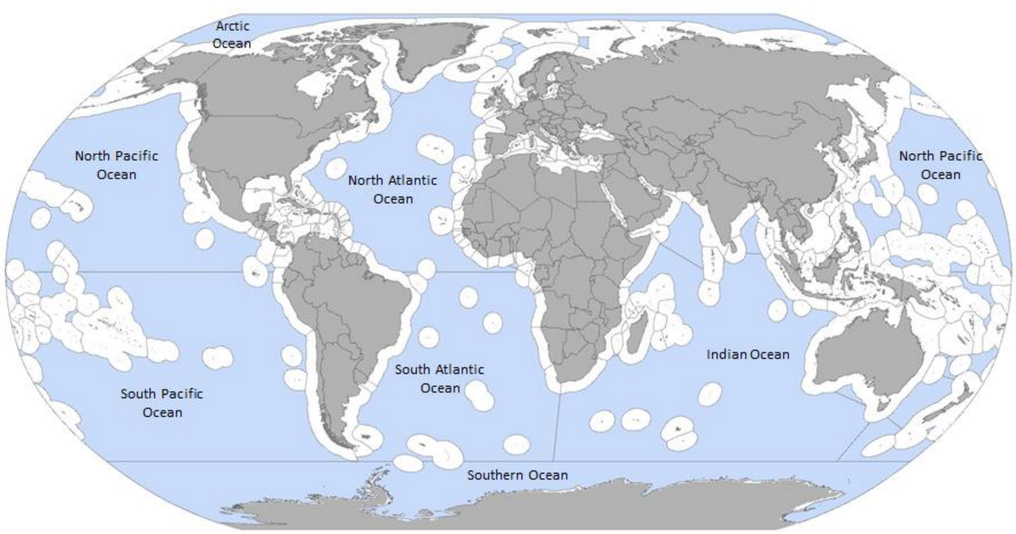

Figure 3.2. Delineation of population boundaries based on exclusive economic zones (EEZ) and ocean basins.

Distributional shifts and abundance of exploited marine species are based on estimates using the dynamic bioclimate envelope model (DBEM, described in Chapter 2). For climate change effects, the DBEM simulates changes in biomass of each species on a 0.5_{o} latitude x 0.5_{o} longitude grid of the world ocean under scenarios of climate change. Changes in ocean conditions in the 21st century are projected by three earth system models (GFDL-ESM2M, IPSL-CM5-MR, MPI-ESM-MR) and under two Representative Concentration Pathways (RCP2.6 and RCP8.5) scenarios. For each species, projected annual total biomass from DBEM under each scenario and from each earth system model is subdivided by the population boundary (Figure 3.2). For each population, annual relative change in biomass (BF) is calculated and then applied to the biomass dynamic model to simulate the effect of changes in abundance and production as a result of climate change.

Changes in catchability and fishing mortality are calculated from the active fishing effort that is an output from the fisheries economic component of the effort dynamic model (EDM). The fisheries economic sub-model assumes fishers to seek to maximize their profit according to the Gordon-Schaefer model (Schaefer, 1957). The model is based on four key parameters: the effort response to profit coefficient (*EffR*), reinvestment ratio (*I*), capital depreciation rate (*D*), and the catchability coefficient of the fishing fleet. Changes in fishing effort are also driven by annual profit that is dependent on the catch of the exploited stocks, ex-vessel price of fish, fishing cost and subsidies received.

Table 3.1. Key parameters and variables in the effort dynamic model, their definitions and sources or methods of estimation.

Parameters and variables	**Definition**	**Sources and methods of estimation (see Appendix for description of data sources)**	**Units**
K	Carrying capacity	Initial values calculated from 4*MSY/r_0 is based on historical catch and parameters from DBEM	Tonnes by fish population
B_t	Biomass at year t	Calculated from the biomass dynamic model	Tonnes by fish population
r_0	Intrinsic population growth rate	Based on parameter from DBEM	year^{-1}
P	Ex-vessel price	Historical price is based on the global ex-vessel price database; future price is projected using the seafood market model (see Chapter 5)	USD/tonne
CostInc	Cost inflation rate	For historical simulation, cost inflation rate is estimated by the model; future rate is modified depending on the social economic scenario (see Chapter 6)	year^{-1}

Uc	Unit cost of effort	Historical fishing cost is based on estimated ratio of fishing cost relative to total landed value (Lam et al. 2016) that is then divided by the initial fishing effort. Annual unit cost of fishing is modified according to the inflation rate.	USD/vessel
q_0	Catchability	Initial catchability coefficient is estimated from the model. Catchability coefficient is modified based on the catchability increase rate (*qinRate*).	
qinRate	Catchability increase rate	In historical period, *qinRate* is estimated from the model; for future period, although previous study suggested that the technological efficiency is about 2-4% (Palomares and Pauly 2019), the future *qinRate* is based on the shared socioeconomic pathway scenario (Chapter 6).	$year^{-1}$
AE	Active fishing effort	Calculated from the model based on total fishing effort, profit, and effort response ratio (see equation 8)	Relative effort unit
NE	New effort entry	Calculated from the model based on total simulated revenue, profit, active effort and fishing cost (see equation 10)	Arbitrary effort unit
RE	Retirement of existing effort	Calculated from the model based on current fishing effort and an effort depreciation rate	Arbitrary effort unit
EffR	Effort response to profit - Response of latent effort to expected profit. (Or, how fast do existing boats "activate" into the fishery.)	Model estimate based on observed data	Arbitrary effort unit/USD
I	Reinvestment ratio – Proportion of profit reinvested into fishery	Model estimate based on observed data	
D	Capital depreciation	Model estimate based on observed data	$year^{-1}$

Subsidies	Total subsidies given to the fisheries expressed as the proportion relative to total fishing cost	Subsidies in the historical period is based on the global subsidies database from Sumaila et al. (2010, 2016). Future changes in subsidies are based on shared socioeconomic pathway (see Chapter 6)	
H_{comm}	Commercial catches (sold to the seafood market).	Commercial catches are calculated from the model for both historical and future periods.	Tonnes
H_{sub}	Subsistence catches (consumed without being sold in market)	For historical period, subsistence catches are from the *Sea Around Us* catch database. For future period, subsistence catches are dependent on shared-socioeconomic pathway.	Tonnes

Specifically, for each time step (year), catch (*H*) at time step *t* is calculated from:

$$F_t = q_t \cdot AE_t \quad (3.2)$$

$$H_{t,i} = F_t \cdot B_{t,i} \quad (3.3)$$

where q_t and AE_t are the catchability coefficient and active fishing effort at time *t* and biomass (*B*) of population *i*.

Catchability coefficient can change over time (e.g., due to technological improvement). Thus,

$$q_t = q_o \cdot (1 + qinRate)^t \quad (3.4)$$

where catchability is dependent on the initial catchability coefficient (at time step 0) and the rate of increase in catchability (*qinRate*).

Total landed value (*LV*) is calculated from the unit prices (*p*) and their catches across all species exploited by the fisheries:

$$LV_t = \sum_i^n p_{t,i} \cdot H_{t,i} \quad (3.5)$$

Total profit of the fleet is calculated from the difference between landed value, unit cost of fishing (*uc*) and active fishing effort (*AE*):

$$TP_t = LV_t - uc_t \cdot AE_t \quad (3.6)$$

Unit cost of fishing changes over time (e.g., because of inflation, increase in fuel prices, increase in opportunity cost of fishing) that is expressed as a function of the initial unit cost of effort and the annual rate of increase in unit cost:

$$uc_t = uc_o \cdot (1 + CostInc)^t \quad (3.7)$$

Active fishing effort is dependent on the total fishing effort, the profit from last-year (*TP*) and the rate of effort response to the profit (*EffR,* i.e., how fast the effort responds to the change in biomass):

$$AE_t = \frac{E_{t-1}}{(1+e^{(TP/EffR)})} \quad (3.8)$$

Total effort is determined by current fishing effort and the difference between new entry (NE) and retirement of fishing effort (RE):

$$E_{t+1} = E_t + NE_t - RE_t \quad (3.9)$$

$$NE_t = \frac{I \cdot TR_t/(1+e^{-(TP/AE)/EffR})}{CapitalCost} \quad (3.10)$$

where I is the investment rate (i.e., the fraction of the profit that is reinvested into purchasing new fleets) and *Capital Cost* is the capital cost of a fishing fleet:

$$RE_t = E_t \cdot (1-D)^t \quad (3.11)$$

where D is the effort exit/depreciation rate.

Estimation of parameters

Parameter values of the effort dynamic model are estimated for each EEZ-ocean basin unit (Figure 3.2) using available databases, empirical equations and time-series of fisheries catches data from 1950 to 2015 (Appendix).

For the biomass dynamic model, the initial parameter values for the intrinsic population growth rate and carrying capacity are based on those estimated for DBEM (see Chapter 2). Specifically, carrying capacity of each exploited population is based on the average maximum catch of the catch time-series from the *Sea Around Us* (SAU) database (www.seaaroundus.org) and the intrinsic population growth rate (see Chapter 2 and Appendix, Cheung et al. 2016b). Population biomass in 1950 is assumed to be at carrying capacity and the fishing mortality rate is approximated by Catch/Biomass in which catch is based on the SAU catch dataset (Appendix).

For each EEZ-ocean basin unit, some initial parameters for the fisheries economic model are estimated based on published datasets while others are estimated by fitting the model with catch data reported in the *Sea Around Us* catch database. Unit ex-vessel price of catch is from the Fisheries Economic Research Unit price database (Tai et al. 2017) (Appendix). Initial (first year) fishing cost is estimated based on a cost per unit of total revenue that is calculated from the reported total fishing cost from Lam et al. (2011) and the total revenue from Lam et al. (2016). Subsidies, expressed as a proportion of the total fishing cost, is estimated based on the global subsidies database (Sumaila et al. 2010). Initial fishing effort is calculated from catchability coefficient to be estimated by fitting the effort dynamic model with data. Other parameters that are estimated by model-data fitting include the rate of increase in catchability (*qinRate*), the effort to profit response ratio (*EffR*), the effort exist/depreciation rate (D), the effort investment rate (I), the cost inflation rate and the initial capital cost (*CapitalCost*) expressed as a percentage of total revenue. A numerical optimization algorithm (using the R function nlminb) is used to search for the set of parameter values that minimize the sum-of-square error between the predicted total catch from the effort dynamic model and the reported catch from the *Sea Around Us* database.

The catch data by fishing locations (within or outside Exclusive Economic Zones (EEZs)), taxon, fishing sector (industrial, artisanal, subsistence), catch type, and reporting status from 1950 to 2015 were extracted from the SAU catch reconstruction database. Catches from industrial and artisanal fleets are considered to be for commercial purpose (sold in seafood market). The catch reconstruction process utilizes a wide range of data and information sources to estimate catch data for all fisheries components, such as artisanal, subsistence, and recreational fisheries, which are missing from the official reported data. The *Sea Around Us* reconstructed data are found to be 50% higher than the FAO reported data from 1950 to 2015, and the trend of global catches are declining more strongly since they are peaked in the 1990s (Pauly and Zeller, 2016). The catches of each country are reconstructed using the same methodology with variations in types of data collected and the analysis of such data (for country-specific estimates see www.seaaroundus.org). We tested the goodness-of-fit between the predicted and reported catches using linear regression without intercept. Specifically, we used the lm function in the statistical software R. We tested the goodness-of-fit for annual catch records from all EEZs and specifically for each EEZs.

Fishing scenario with management started in year 2005

We illustrated the EEZ-specific model projections with three countries' fisheries: Pacific Canada, China and Fiji. These three examples represent fisheries with contrasting ecological (temperature to tropical) and socio-economic (developed to developing) context. For each case examples, we also made projections under two fishing scenarios: open access and with fisheries management. In the latter case, we applied a hypothetical harvest control rule:

1. If $Biomass/Biomass_{unexploited}$ = 0.60 to 0.75 then limit to 80% of active fishing effort
2. If $Biomass/Biomass_{unexploited}$ = 0.50 to 0.60 then limit to 50% of active fishing effort
3. If $Biomass/Biomass_{unexploited}$ = 0.25 to 0.50 then limit to 10% of active fishing effort
4. If $Biomass/Biomass_{unexploited} < 0.25$ then close all fishing

Scenarios of subsistence catch by country were projected using an empirical model described in Chapter 6. In short, the model was developed using the estimated subsistence catch by countries from 1970 to 2014 in the *Sea Around Us* database. The independent variables of the model include total biomass of fish stocks in the EEZ of the country, the level of per capital income of the country (four categories: very low, low, medium and high), rural population size and per-capita seafood consumption. Projection of subsistence catch by country into the future was based on the projected changes in social, demographic and economic variables for each country under different Shared Socioeconomic Pathways.

Results

The model included a total of 13,831 stocks in the world ocean with total reported catches increased from around 15 million tonnes to around 60 million tonnes from 1951 to 1990 (Figure 3.3a). Catches then decreased gradually to around 50 million tonnes by 2014. These catches only included records that had been reported at the species level (i.e., not broader groups such as "Groupers"); thus, they represented a subset of the global catches (totalled around 130 million tonnes in the 1990s) (Pauly and Zeller 2016). Subsistence catches only contributed a small proportion relative to those from commercial fisheries.

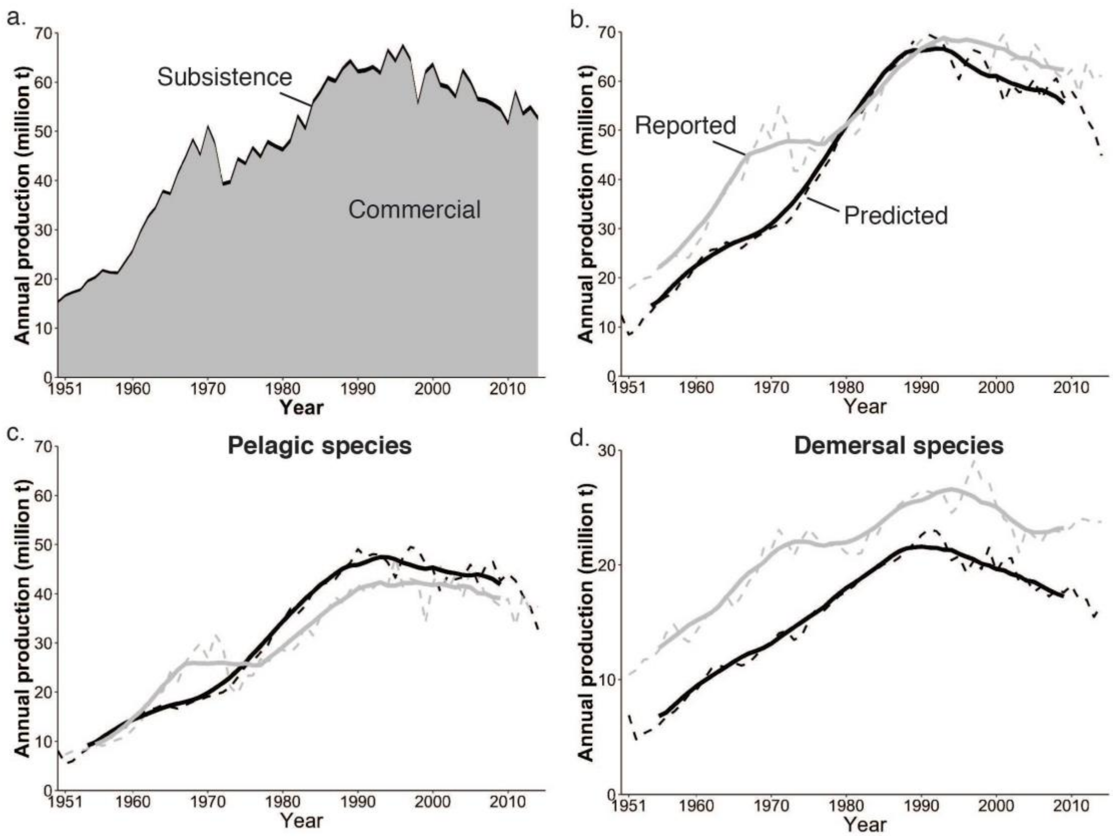

Figure 3.3. Reported and predicted catches of exploited species in the world ocean: (a) reported commercial and subsistence catch from the *Sea Around Us* catch reconstruction database; (b) reported (grey lines) and predicted (black lines) commercial catches from the effort dynamic model; (c and d) reported and predicted commercial catches for pelagic and demersal species only, respectively. Solid lines represent 10-year running mean while the dashed line represents the trend without smoothing.

Across all the fisheries stocks, annual catches predicted by the effort dynamic model were consistent with the reported catches (Figure 3.3b). Considering all the annual catch records from 1950 to 2014, the predicted catches were significantly correlated with observed catches ($p<0.001$, R2 = 0.70, linear regression with intercept = 0, Table 3.2). However, the peak between 1960s to 1970s could not be seen in the predicted catch. The exceptionally high level of catch during this period was due to the strong upwelling effect especially along the Peruvian coast. The predicted annual catches of pelagic species were also significantly correlated with observed catches ($p<0.001$, R_2 = 0.65, linear regression with intercept = 0, Table 2.2). Although predicted annual catches of demersal species were also significantly correlated with observed catches ($p<0.001$, R_2 = 0.88, linear regression with intercept = 0, Table 2.2), the predicted catches were systematically underestimated. The underestimated catches in our model were due to several reasons, including lower intrinsic growth rate and the carrying capacity of the demersal species that we used in our model. Since trophic interactions were also not incorporated into our model, the impacts of the change in other trophic levels on the whole ecosystem and the biomass of demersal species were not considered. Finally, the initial fishing effort that input into the model was set too low because we assumed the fisheries has not been well developed before 1950.

Table 3.2. Test statistics of linear regression between observed and predicted catches using models with and without an intercept (test statistics of the intercept term are presented in parentheses)

Stocks included	**Estimate**	**Standard error**	**t-value**	**p-value**	**R^2**
Linear regression without intercept					
All	1.123	0.004	269.0	<0.001	0.701
Pelagics	1.116	0.007	164.1	<0.001	0.645
Demersal	1.142	0.003	338.6	<0.001	0.878
Linear regression with intercept					
All	1.112 (24,900)	0.004 (1,625)	263.4 (15.3)	<0.001 (<0.001)	0.692
Pelagics	1.103 (3,800)	0.006 (3,194)	160.8 (11.9)	<0.001 (<0.001)	0.653
Demersals	1.133 (12,221)	0.003 (994.1)	330.0 (12.3)	<0.001 (<0.001)	0.873

The predicted fishing effort for the historical time period by the model increased substantially from 1950 to the present (Figure 3.4). Currently there is still no systematic way for recording the fishing capacity (the number of vessels participating in fisheries), which is used as the proxy of fishing effort here, and effort for many countries. A few previous studies have attempted to fill the missing gaps of the global fishing effort data by using the available information (Anticamara et al. 2011, Bell et al. 2017, Greer et al. 2019). The previously developed fishing effort database showed that the fishing effort (in total kilowatt days) remained more or less constant from 1950 to 1960 and then it increased at an annual rate of 1.1% after 1960 until 2010 (Anticamara et al. 2011). At the global scale, the fishing capacity and fishing effort have been increasing continuously since 1950s. As expected, our model predicted that the effective fishing effort, which accounts for changes in fishing efficiency that is due to factors such as improvement in fishing technology and fishers' knowledge, increased at a much faster rate than nominal fishing effort. The rate of increase in fishing effort of pelagic fisheries is also faster than that of demersal fisheries.

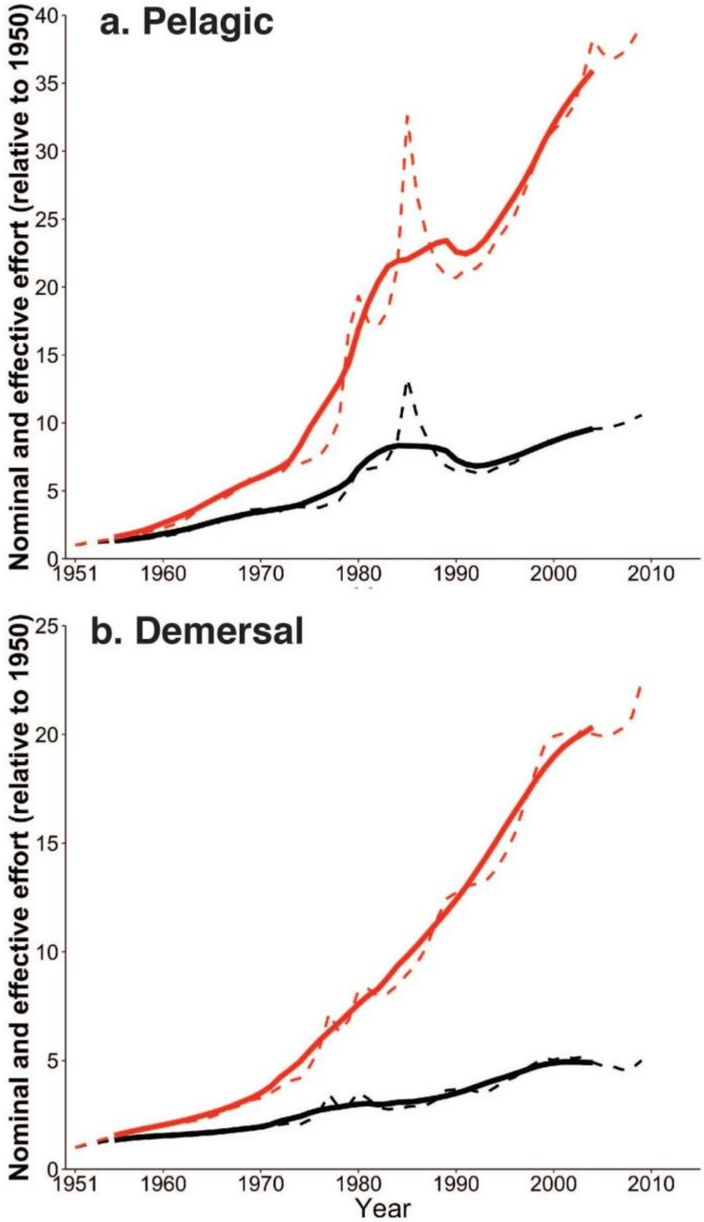

Figure 3.4. Simulated global fishing effort for the (a) pelagic and (b) demersal fleets. Nominal fishing effort (black) and effective fishing effort (red) are presented. Solid line represents 10-year moving averages.

The predicted changes in catch and fishing effort varied amongst countries with general patterns that reflect their history of fisheries development and level of fisheries management, as illustrated by the three case study fisheries (Figure 3.5). Pacific Canada which is considered fully-developed, and a relatively more effectively managed fisheries in the world, with total catches peaking in the 1990s and then decreasing driven, by over-exploitation of some fish stocks as well as more stringent quota. This pattern is reflected in the predicted increase in effective fishing effort that peaks in the 1990s and declines subsequently. In contrast, fisheries in Chinese waters intensified rapidly since the 1970s with substantial increase in predicted catches and fishing effort. However, predicted catches have decreased since the mid-2000s, although reported catches level off. This may be due to the mis-reporting of fisheries landings in China (Watson and Pauly 2001) and/or the effects of increased productivity of low trophic level species due to the depletion of predatory fishes (Szuwalski et al. 2017). Both the nominal and effective fishing effort in the Chinese EEZ have continued to increase since 1950s and they continue increasing even though the predicted catch decreases. Large-scale fishing in Fiji developed relatively more recently compared to Pacific Canada and China. This is reflected in the sharp increase in the predicted fishing effort from the 1990s and the rapid increases in predicted catches since this period.

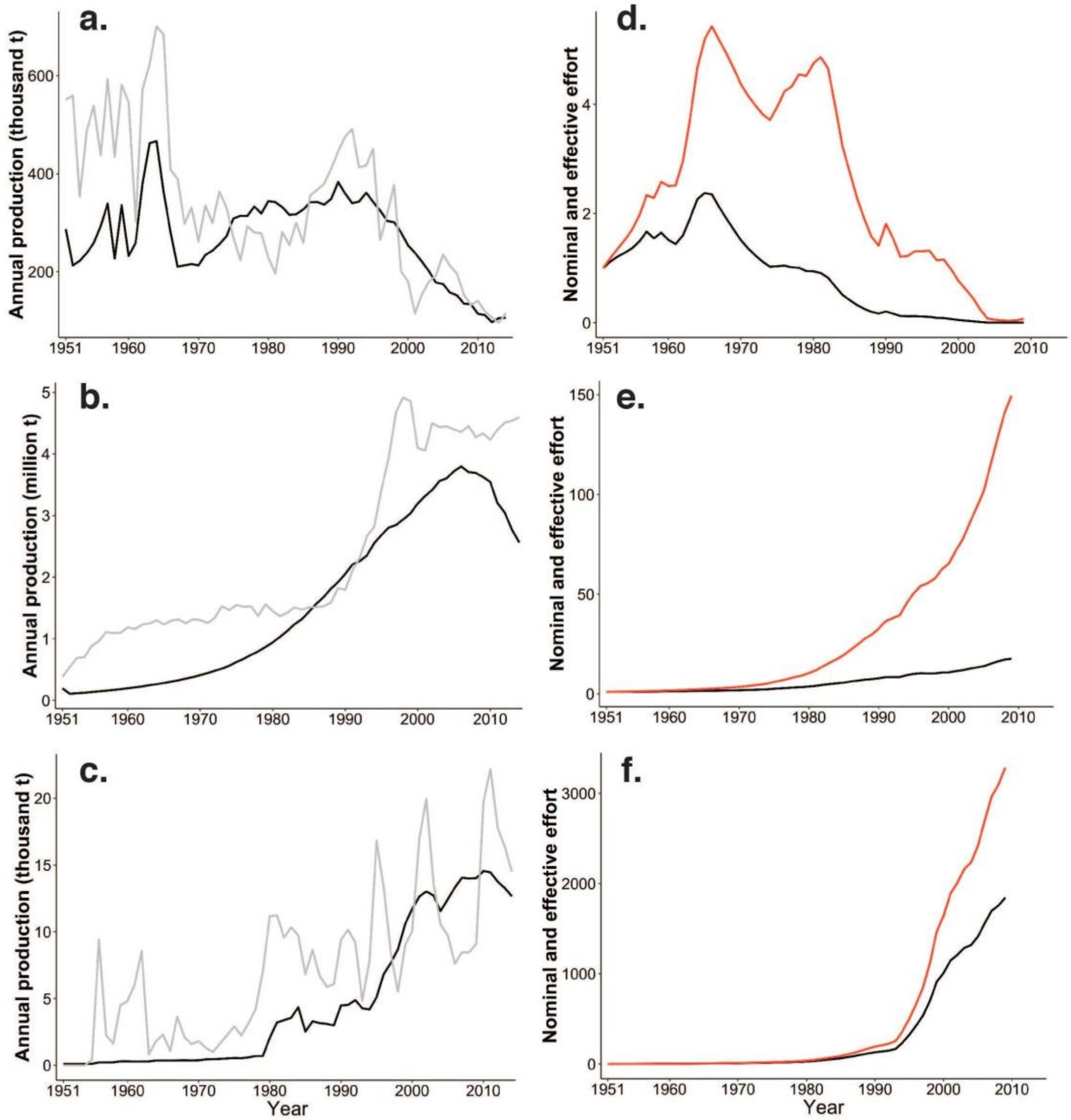

Figure 3.5. Predicted changes in catches (a, b, c) and fishing effort (d, e, f) for the historical period for Pacific Canada (a, d), China (b, e) and Fiji (c, f). The grey lines represent observed catches, solid lines represent predicted catches and nominal fishing effort, the red lines represent effective fishing effort.

The estimated biomass with fishing also reflects the status of fisheries (Figure 3.6). In the case of Pacific Canada, relative biomass is estimated to have decreased by approximately 50% since the

1950s. In contrast, relative biomass in Chinese waters is estimated to have decreased largely since the 1970s to around 20% of the 1950s level. Relative biomass in Fiji is estimated to have decreased more rapidly since the 1990s to around 50-60% of the 1950s level.

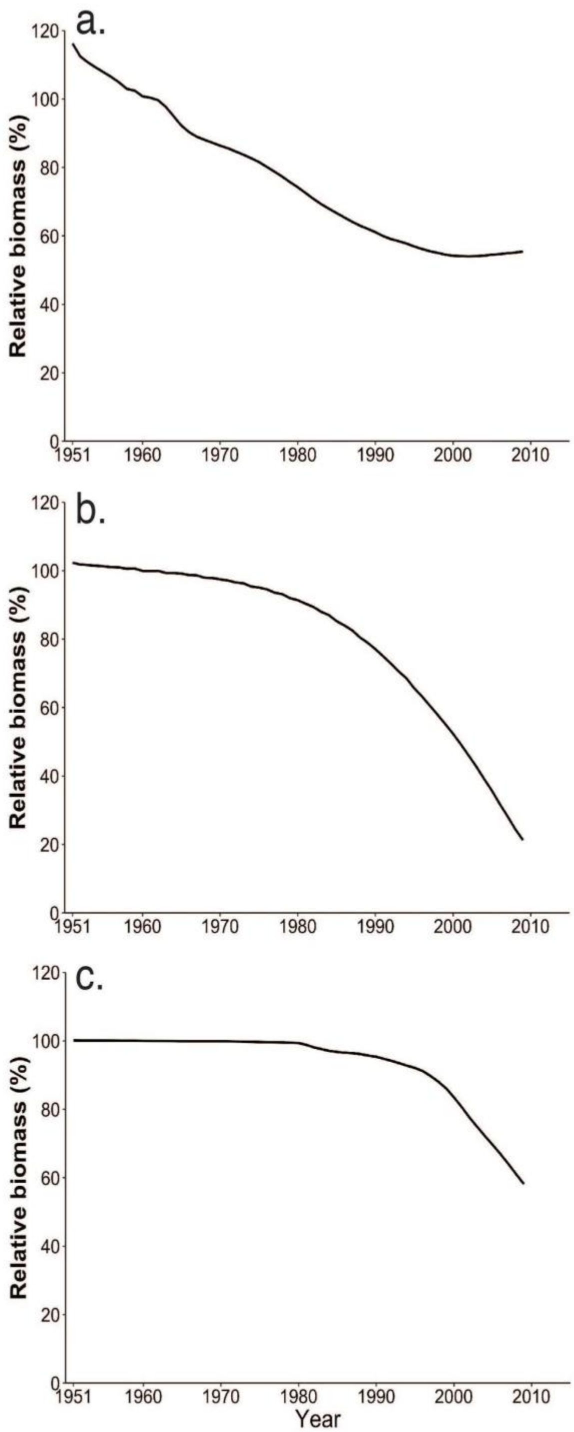

Figure 3.6. Predicted total biomass (pelagic and demersal) for the historical period in (a) Pacific Canada, (b) China and (c) Fiji. Biomass is expressed relative to the average between 1951-1970.

Fishing scenarios can have substantial effects on the projected changes in future fisheries that interacts with climate-driven changes in fish stock abundance (Figure 3.7). In all case examples, open access fishing scenario resulted in substantial loss of revenues relative to the 1986-2005 level. When the hypothetical harvest control rule was implemented, catches decreased initially but then increased gradually. However, in the case of Fiji, fisheries revenues decreased again from the 2005 level. Projected revenues were still lower by the end of the 21st century relative to the 1986-2015 under all cases and scenarios except for China under the fisheries management scenario.

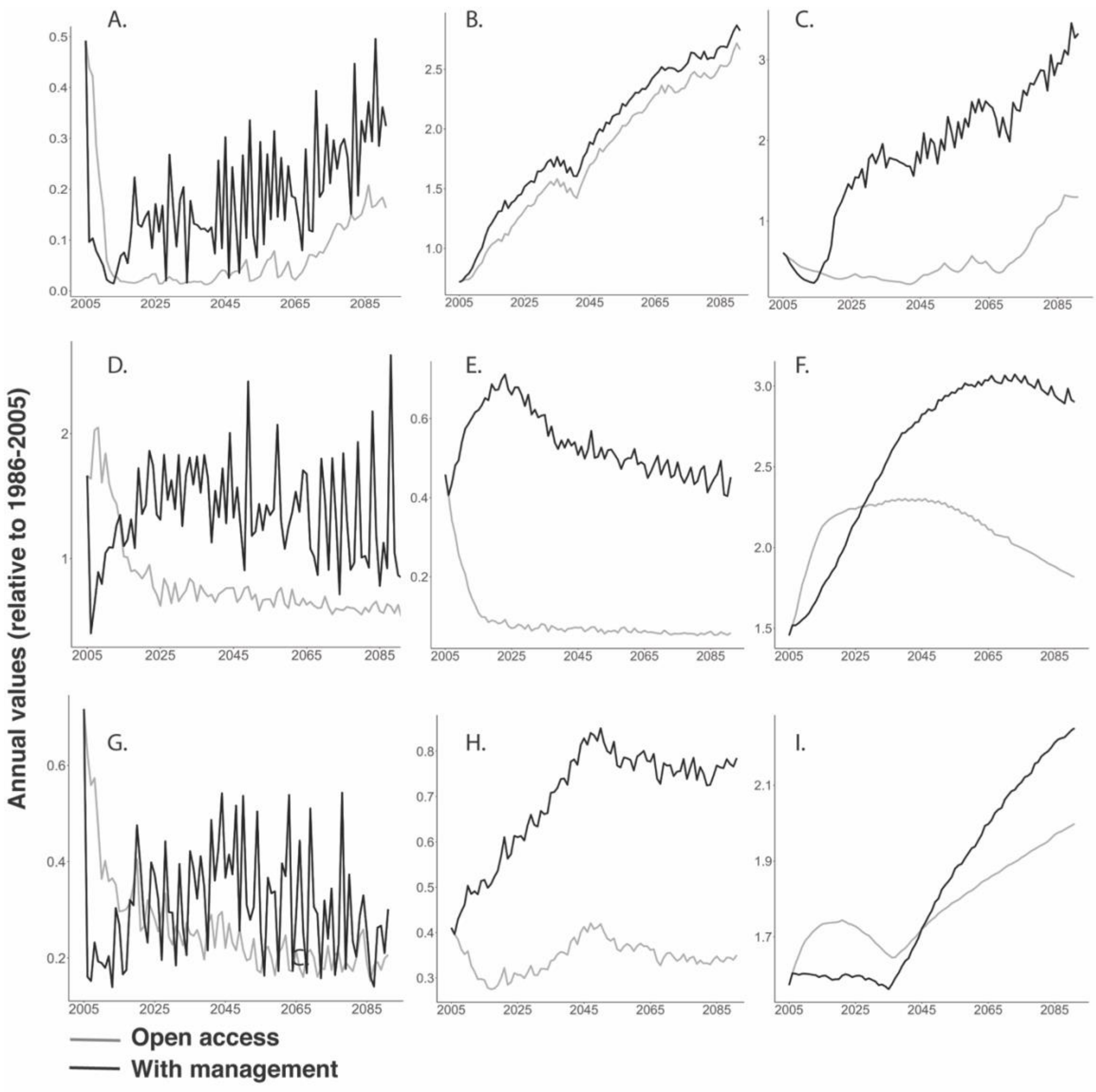

Figure 3.7. Projected future revenues (A, D, G), biomass (B, E, H) and effective fishing effort (C, F, I) from the effort dynamic model for the three case examples: (A – C) Pacific Canada, (D – F) China and (G – I) Fiji. Two fisheries scenarios are considered: open access (grey lines) and with fisheries management (black lines).

Projected biomass shows large contrast between case example fisheries and scenarios. Overall, the fisheries management scenarios lead to high biomass by the end of the 21st century relative to 1986-2005. Particularly, for Chinese and Fijian EEZs, the model projected several factors of differences in biomass between the two scenarios. Effective fishing effort is projected to have initially lower fishing effort and then higher by the end of the 21st century under the fisheries management scenario relative to the open access scenario in all three examples.

Discussion

The EDM simulates reasonable changes in fisheries catches, fishing efforts and the economics of fishing with consideration of fisheries management strategies and climate-induced changes in fisheries resource abundance that generally agree with observations. The outputs from the EDM agree with the observed changes in fisheries catches in the historical period. There is some systematic underestimation of catches for demersal fisheries by the EDM. However, the application of the EDM in the context of DIVERSE is mainly through the predicted relative changes in catches, reducing the impacts of such systematic prediction bias on the overall projection of DIVERSE. Also, the overall increases in fishing effort qualitatively agree with observed records (Anticamara et al. 2011; Rousseau et al. 2019).

The simulated fishing effort and biomass levels also match with expectations based on qualitative and quantitative understanding of the exploitation status of the fisheries, as illustrated by the three case studies. In general, the inclusion of a harvest control rule (HCR) that would reduce active fishing effort would result in higher biomass in the longer term relative to the open access scenario. The higher resource biomass could then support more fishing in the longer term. However, the HCR may lead to short term reduction in fisheries catch, revenues and profits. Hence, there is a trade-off between the short-term loss and the long-term benefits.

The EDM is suited for simulation of changes in fishing dynamics at the global scale. Particularly, the model is grounded on widely used fisheries bioeconomic theory that has been applied to study fisheries at different scales. We constrained the number of parameters so that the parameter values are either based on publicly available datasets or estimated by fitting the model to data. Thus, the EDM could be applied to all EEZs and high seas of the world. Moreover, the EDM enables projection for future changes in fishing based on scenarios and projections of resource abundance, prices, fishing costs, subsidies, and fishing efficiency from other components of the DIVERSE. Open access is assumed for all the fisheries in the base scenario of this model. However, parameters will be adjusted according to different fisheries management and policy scenarios. For example, we can impose a harvest-control rule that limits fishing effort based on specific target and limit reference points such as the ratio of current year biomass relative to unexploited level.

Limitations and caveats

The application and interpretation of the outputs from the EDM should account for its main limitations. Firstly, the EDM accounts only financial benefits that determine investment into fisheries and changes in active fishing effort while non-financial benefits are not accounted for. However, the model framework is able to consider non-market data such as scenarios of subsistence catches. Similarly, the EDM does not account for seasonal non-fishing employment and benefits that change fishing effort in the real world. Moreover, the EDM only accounts for non-trophic interactions between fish stocks within regional fisheries e.g., bycatch. Historical simulations assume that selectivity of the fisheries remains constant (i.e., applying the same fishing mortality on all exploited species). This assumption is considered robust given the highly aggregate level of the fisheries that the EDM represents (grouping all demersal or pelagic fisheries). Future extensions of the EDM will adopt more fisheries-specific selectivity. When using the EDM for projecting future catches, the new invasive marine species are assumed to be taken by the fisheries. However, their contribution to the total projected landed values will depend on whether they have a value in the current seafood market (i.e., an ex-vessel price data of that species), and on any price effects from change in supply (Sumaila et al. 2019). In addition, individual fisher's decisions have not been accounted for. Other than maximizing their profits, fishers may also make decisions based on other factors such as fuel-saving, safety issues linked to travel times and weather, traditional preferences, etc. However, this kind of individual-based model is hard to implement at the global scale; future application of the EDM at much smaller scales may consider incorporating elements of fishers' behavior into modelling fisheries dynamics that are more appropriate for local decision-making.

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Chapter 4: Model for global mariculture production under climate change

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Abstract
Previous studies have reported projections of climate change impacts on seafood production from mariculture. However, these models fail to include other mariculture production considerations, for instance, fishmeal and fish oil or price in the modelling procedure. Here, we describe a predictive model that accounts for some inputs of mariculture production in the modelling procedure such as price, suitable marine area for farming, total world fishmeal and fish oil production, as well as farm species trophic level. Also, these inputs could be affected directly or indirectly by climate change.

Introduction
Food fish supply is facing challenges in the present day, and these challenges will continue over the next century. With the projected increase in population, we expected that these challenges would increase. Also, climate change is projected to further obscure future food fish production, mostly because of the response of marine biota to ocean warming and acidification. These changes will impact their distribution, phenology, body size (Pauly and Cheung, 2018), and abundance leading to a decline in maximum catch potential (Cheung et al., 2010; Cheung et al., 2013). A consequence of which is the decrease in food fish supply from capture fisheries for the growing population. However, current global food fish production and supply is growing as a result of increased contribution from aquaculture. It plays a significant role in filling the supply gap created by capture fisheries, with both freshwater and marine sector contributing about half of the current global food fish production (FAO, 2018). Nevertheless, climate change poses a risk to this contribution.

In this chapter, I describe a model that aims to project future change in mariculture production potential under two climate change scenarios. Here, mariculture production potential (MPP) is defined as some marine species that could be farmed at a particular marine area. The model projects habitat suitability index (HSI) based on the realized niches of the farmed species. Together with other environmental and social-economic constraints, the model identifies the present and future suitable marine area for mariculture. Such model outputs are then linked and applied to project changes in future seafood production from mariculture. I then discuss how the projected changes in mariculture production is used in the DIVERSE modelling framework.

Model structure

We developed a model framework to project Mariculture Production Potential (MPP) under different climate change scenarios (Figure 4.1). This framework includes four main components with outputs from each component that sequentially feed into another one. First, for each farmed species, we predicted the marine areas within the Exclusive Economic Zone (EEZ) where they are suitable for mariculture activities. We used species distribution models (SDMs) to quantify the ecological niche of each species for the present-day period (1970-2000) and calculate a habitat suitability index (HSI). Second, the model applies spatial filters informed by physical and social-economic constraints of marine aquaculture location to generate potential suitable area for mariculture. Third, the model project the future potential suitable area for mariculture under climate change. Last, using a general additive model (GAM), we developed an empirical relationship between the potential suitable area for mariculture with the species' price, suitability of the habitat as indicated by the predicted HSI, the fishmeal and fish oil (FMFO) potential production, and species' trophic level to estimate the mariculture production potential.

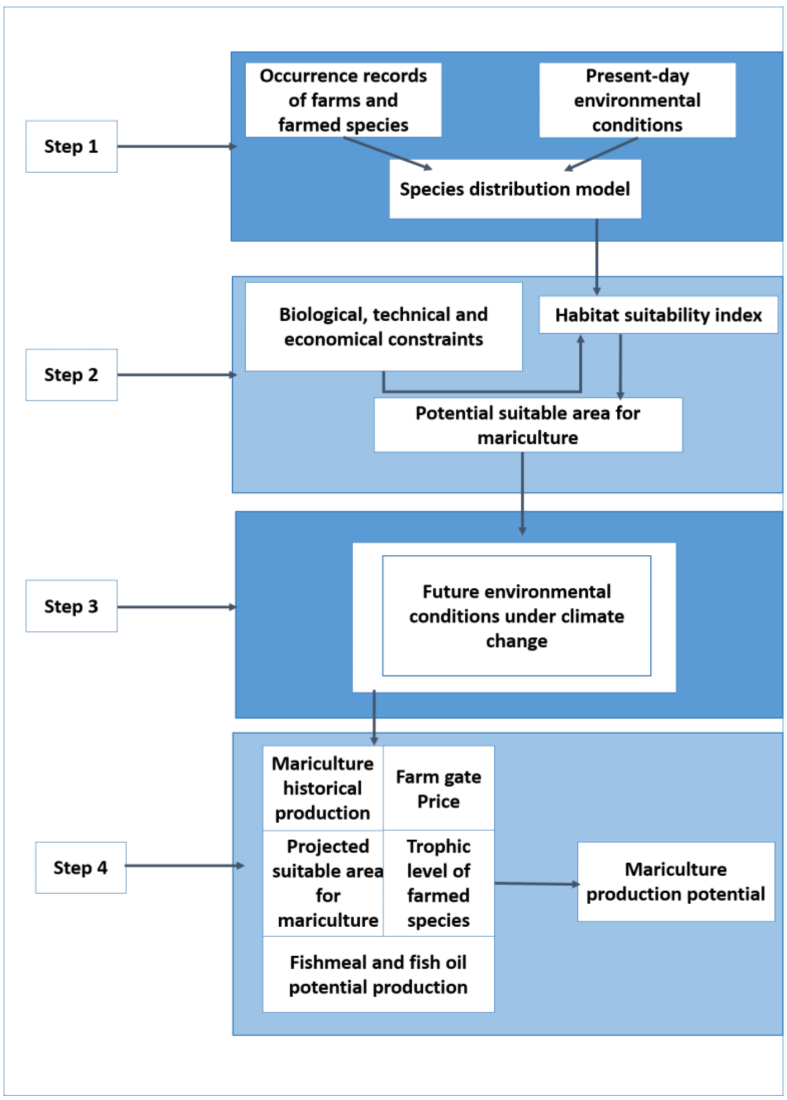

Figure 4.1: Schematic representation of the structure of the model described in this chapter.

Assumptions and specifications

Species distribution modelling and present potential mariculture area

We obtained geo-referenced locations of farmed mariculture species as described in Oyinlola et al., (2018). Each species mariculture location records were converted to a binary of presence or absence and rasterised on a regular spatial grid of 0.5° latitude by 0.5° longitude over the global ocean.

We assembled eight environmental parameters datasets; these include sea surface temperature, dissolved oxygen concentration, chlorophyll-*a* concentration, salinity, pH, silicate concentration, current velocity, and euphotic depth. 10-year averaged ocean current velocity data (1992-2002) was obtained from Estimating the Circulation and Climate of the Ocean (ECCO) Project (http://www.ecco-group.org). Values for temperature, pH, dissolved oxygen concentration, salinity, silicate concentration, and chlorophyll-*a* concentration were gathered from three Earth system models (ESMs) that were part of the Coupled Models Inter-comparison Project Phase 5 (CMIP5): (1) the Geophysical Fluid Dynamics Laboratory Earth System Model 2M (GFDL-ESM2M); (2) the Institute Pierre Simon Laplace coupled model version 5 (IPSL) (IPSL-CM5-MR); and (3) the Max Planck Institute for Meteorology Earth System Model (MPI-ESM-MR). These were then averaged over the period 1970-2000 for each ESM. All environmental data were interpolated using bilinear methods (Legendre and Legendre, 1998) over the global ocean (189.75 °W to 179.75 °E and 89.75 °N to 89.75 °S) on a regular spatial grid of 0.5° latitude x 0.5_{o} longitude (the same as occurrence rasterized data) and for two vertical layers: surface (0-10m) and sea bottom depth, where available.

We further determined the vital environmental parameters; seawater temperature, dissolved oxygen concentration, chlorophyll-*a* concentrations, salinity, pH, silicate concentration, and euphotic depth to model the farmed marine species' distribution using the eigenvalue diagram implemented in Ecological Niche Factor Analysis (ENFA) (Basille et al., 2008). The diagram was constructed based on the departure of the ecological niche from the mean habitat for each species, thus identifying the species' preference for particular environmental parameters among the whole set of parameters. All data was interpolated using bilinear methods (Legendre and Legendre, 1998) on a regular spatial grid of 0.5° latitude x 0.5_{o} longitude and for two vertical layers: surface (0-10m) and sea bottom depth where available. We then used SDM to compute the present mariculture potential area. The model estimates HSI of each species for each gridded cell of the ocean (i.e. 0.5° x 0.5°). The HSI scales from 0 to 1 (low to high) to indicate the environmental suitability of the selected environmental conditions for each species in each spatial cell.

Defining the potential mariculture area

We defined a potential area for mariculture using two criteria:

a. The ecological criterion: Marine area to be suitable for marine aquaculture is defined here as ecologically suitable area for the farmed species (i.e., environmental condition within its tolerance range). The suitable area is further defined here as waters with HSI above minimum ecological requirement for optimal growth conditions. Such minimum requirement was described by the minimum threshold "prevalence" (i.e., the fraction of spatial cells at which the species is present given specific environmental conditions) (Phillips et al., 2009, see Oyinlola *et al.* 2018 for details). We estimated the "prevalence (pv)" for each species by comparing the estimated HSI of the known farm location with estimates for a predicted new location.

$pm_i = 1.$, if $HSI_i \geq pv_i$ (4.1a)

$pm_i = 0.$, If $HSI_i < pv_i$ (4.1b)

where pm_i is the potential for mariculture in spatial cell i.

b. The technical criterion: Following Oyinlola et al., (2018), we assumed that mariculture does not expand to beyond the area of national jurisdiction. Thus, we limited the potential mariculture area to be within countries' Exclusive Economic Zone (EEZ). We also set the current velocity range between 10 cm s^{-1} and 100 cm s^{-1}. This is to ensure sufficient water current to transport new water to farmed species, especially for oxygen input and waste transportation (Jansen et al., 2016). Also, low current below 10 cm s^{-1} would result in less particulate organic matter flow and efficient production, particularly in shellfish aquaculture (Ferreira et al., 2007), less waste removal (feed and organic waste), and high benthic impact in finfish aquaculture (Borja et al., 2009). In contrast, strong currents above 100 cm s^{-1} can damage farm structures and holding facilities (Benetti et al., 2010; Kapetsky et al., 2013) and can lead to skeletal malformations in fish (Chatain, 1994). We also assume that mariculture cannot operate within marine protected areas (MPAs).

Projection of future mariculture area and habitat suitability

We projected future marine area suitable for mariculture under climate change using the three Earth System Models (ESMs): GFDLESM2M, IPSL-CM5-MR, and MPI-ESM-MR. HSI for each species on 0.5^{o} latitude by 0.5^{o} longitude grid cell of the world ocean was estimated for each year from 1990-2100. Two climate change scenarios were considered: Representative Concentration Pathway (RCP) 2.6 and RCP 8.5, representing the low ('strong mitigation') and high ('no mitigation') greenhouse gas emission scenarios, respectively.

Projecting future changes in fishmeal and fish oil production

The future availability of FMFO was estimated based on the projected catch of the major forage fish species and their contribution to FMFO uses. Firstly, annual catches of the 106 major forage fish species that were caught for FMFO production were projected from the effort dynamic model (EDM) (see Lam et al. this volume) under two climate change scenarios: Representative Concentration Pathways (RCP) 2.6 ("strong mitigation") and RCP 8.5 ("business-as-usual") for the period 1950 to 2100. For the simulation period (2015 to 2100), we assumed that the percentage used as FMFO relative to total catches per EEZ would remain constant as the recent five-year average percentage (2010-2014).

$$FMFO_{EEZ,t} = \sum_{EEZ,t} Y_{EEZ,t} \cdot PU_{EEZ,t} \qquad (4.2)$$

Where $FMFO_{EEZ,t}$ is the total fishmeal and fish oil production in per EEZ at year t, Y is catch per EEZ at time t, PU is the percentage of the catches used as FMFO per EEZ at year t.

Modelling potential mariculture production

We quantified an empirical relationship between mariculture potential and related ecological and economic factors across EEZs in the world. Specifically, these factors included the farm gate price of each species (*Price*, USD), the total suitable marine area for mariculture of the species per EEZ (*Area*, km^2), the average habitat suitability index (*HSI*), trophic level and the annual total fishmeal and fish oil production (*FMFO*, tonnes) (see equation 3). We applied a generalised additive model (GAM) using the "gam" function in R package "mgcv" to quantify the relationship between historical mariculture production for each species by EEZ and these drivers of mariculture production. We fitted a gamma family and log link function to the model. Since mariculture of molluscs does not require feed from FMFO, we included different smoothing interaction functions for each species based on whether their farming operations require FMFO. Temporal auto-correlation (1st order) was accounted for as specified by the "CorAR1" term in equation 3. A multi-model comparison framework was used to select the best model with the lowest generalised cross-validation (GCV). The best model has two terms; the parametric and smooth terms. The full GAM model is (Table 4.1):

$$MP_{et} \sim HSI_e + s\,(Price_e, bs = "cr") + s\,(FMFO_t, Fac, bs = "fs") + s\,(TaxonBioTL, bs = "cr") + Area_e + s\,(Year_t, bs = "cr"), \; correlation = corAR1(0.1113718, form = \sim 1|Species) \quad (4.3)$$

Where MP - the historical mariculture production in tonnes for each EEZ ($_e$) at Year ($_t$)

HSI - the EEZ mean habitat suitability index
Price - the farm gate price of the species
FMFO – global fishmeal and fish oil production per year
TaxonBioTL – the trophic level of species
Area – total suitable marine area for mariculture
s – smooth function
cr – cubic regression
fs - smooth factor interactions with FAC as an identifier
bs - string indicating the (penalised) smoothing basis to use

Using the developed GAM, we predicted the MPP using the "predict.gam" function in the R package "mgcv" (Wood, 2017) with projected changes in HSI, FMFO and suitable marine area for mariculture for farmed species.

Table 4.1. List of model variables and data source

Variable	Symbol		Unit	Source
Dependent	MP	Mariculture production	Tonnes	Global mariculture database (http://www.seaaroundus.org/)
Independent	Price	Farm gate price of the species	USD	Global mariculture database (REF, thesis)
	HSI	the EEZ mean habitat suitability index		The output from the species distribution model
	FMFO	global fishmeal and fish oil production per year	Tonnes	Reduction fisheries database (Cashion et al., 2017) and Output from dynamic bioclimatic envelope model (Cheung et al., 2016)
	TaxonBioTL	the trophic level of species		FishBase (http://www.fishbase.org/); SealifeBase (http://www.sealifebase.org/)
	Area	total suitable marine area for mariculture	km_2	Estimate from the species distribution model

Model evaluation

The GAM model was evaluated for robustness to predict historical mariculture production by randomly selecting 75% of all historical mariculture production records to develop the GAM and keeping the remaining 25% for model testing. We then examined the correlation between predicted values and test dataset using linear regression.

Illustrative example

This section provides an illustration of the described model using Gilthead bream (*Sparus aurata)* as an example. We used the Maximum Entropy model (MAXENT) version of our predictive model. First, we extracted the Gilthead bream geo-referenced farm locations from the database described in the method section. Second, we projected the current distribution of farmed Gilthead bream representing the average marine area environmentally suitable for Atlantic salmon farming in recent decades (i.e. 1970 to 2000), using the vital environmental parameters for farming Gilthead bream. This estimates the Habitat Suitability Index (HSI) for the species. We then projected the HSI and the total suitable marine area from 1990 to 2100 under two scenarios of future changes in greenhouse gases (GHG) using the GFDL ESM2M. Third, we applied constant ecological and technical criteria to the projected suitable marine area across the year 1990-2100. Finally, the model predicted MPP for each year from 1990-2100 using the historical production (tonnes), the farm gate price of Atlantic salmon (US $), the total suitable marine area per EEZ (Area, Km_2), the average habitat suitability index (HSI) per EEZ, trophic level, and the total global fishmeal and fish oil (FMFO) production per year. For 2016-2100, we assumed a constant farm gate price (last five-year average 2011-2015). For model testing purpose, annual catches of species used for fishmeal and fish oil were calculated using the maximum catch potential projected from the Dynamic Bioclimate Envelope Model described in Cheung (this volume: Chapter 2).

Results

Predicted MPP for Gilthead bream

We found a significant and positive linear relationship between the mariculture production potential (MPP) (x) and historical production (tonnes) (y) of Gilthead bream (y = -2.95+ 1.11x, $p < 0.001$, $R^2 = 0.52$) (Figure 4.2).

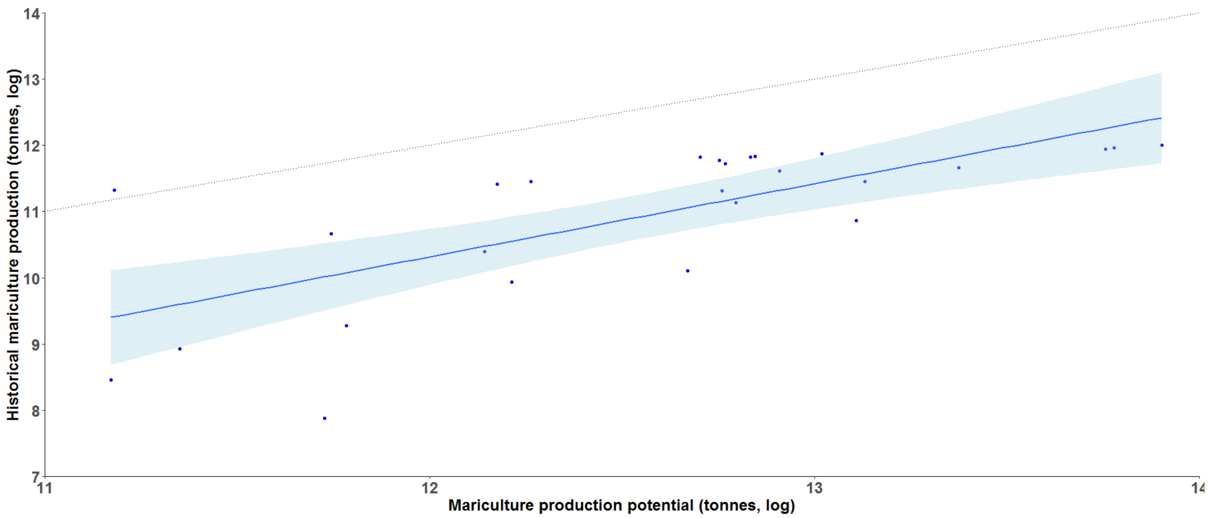

Figure 4.2. The plot of the predicted mariculture production potential for Gilthead bream and the average historical (1990-2015) mariculture production ($R^2 = 0.52$, $P < 0.001$). The production data were log-transformed. The solid line and the shaded area represent the regression line and 95% level of the confidence interval. The dotted lines represent 1:1 between predicted and reported production.

Assuming a constant farm gate price (last five-year average 2011-2015), the Gilthead bream MPP was projected to increase by 52.35% and 41.7% by the mid-21st century relative to the present-day (1995-2015) under strong mitigation (RCP 2.6) and business-as-usual (RCP 8.5) respectively (Figure 4.3).

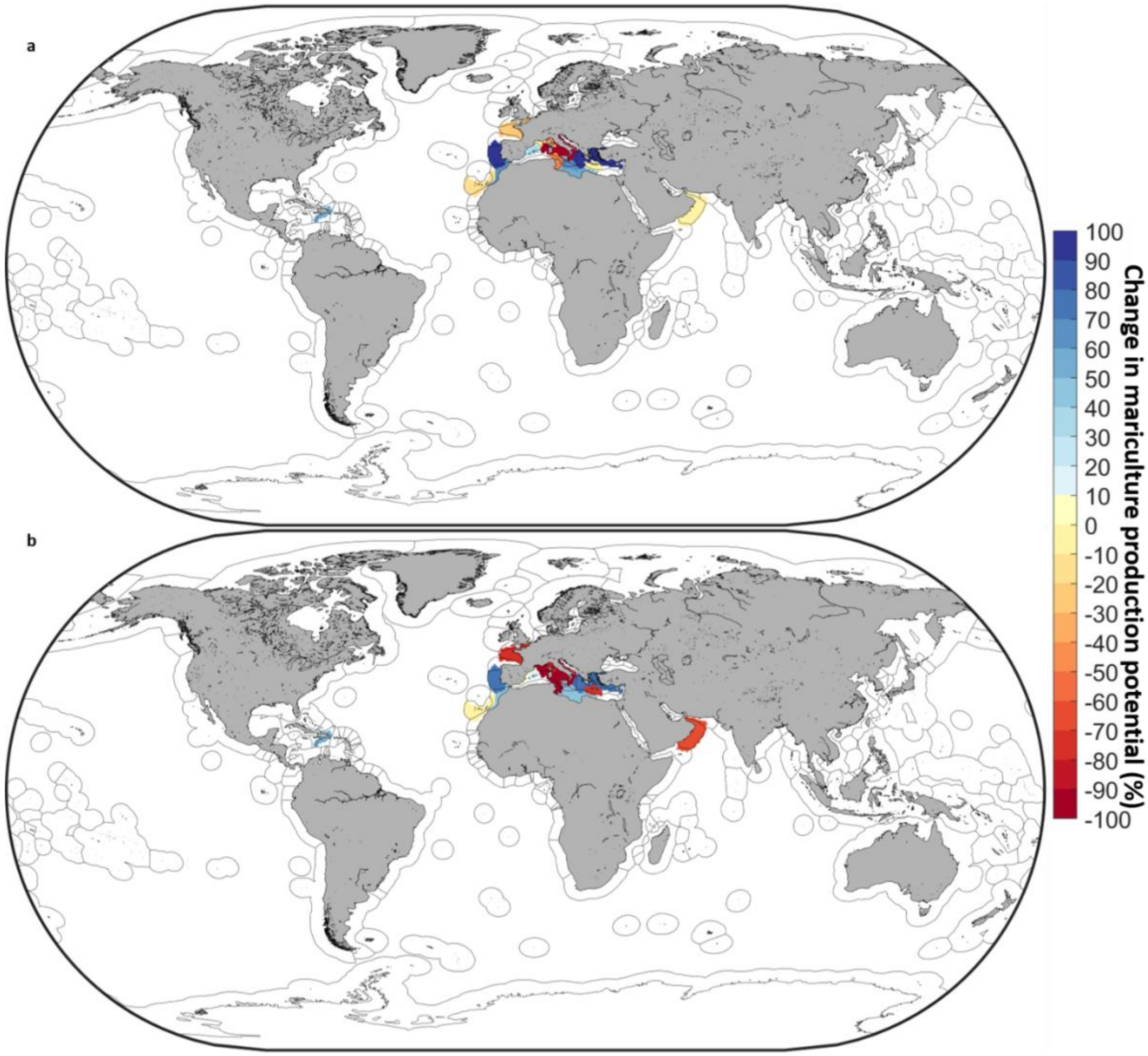

Figure 4.3: Percentage change in mariculture production potential for Gilthead bream by the 2050s (average between 2040-2060) relative to the 2010s (average between 1995-2015) under (a) RCP2.6 and (b) RCP8.5 scenarios.

Discussion

In this chapter, we described an approach to project future mariculture production potential under climate change. The model projections were driven by biophysical and socio-economic drivers that are linked to other components of DIVERSE. Particularly, model accounts from changes in ocean conditions under greenhouse gas scenarios as projected by the ESMs. Fishmeal and fish oil production, which is a variable used in projection of MPP, was linked to outputs from the dynamic bioclimate envelope model and effort dynamic model described in earlier chapters of this report. Price of mariculture commodities were projected by the global seafood market model described by Chen (this volume). Scenarios of marine protected areas were specified under the Shared Socioeconomic pathways (SSP) described by Wabnitz et al. (this volume).

Various uncertainties are associated with this projection:

1) A significant percentage of aquafeed ingredients is from terrestrial-based food production (Gatlin et al., 2007; Pahlow et al., 2015). Climate change is projected to alter agriculture production (Fischer et al., 2002; Easterling W. et al., 2007) and potentially, the supply of plant-based aqua-feed ingredients. This may consequently affect MPP in similar ways as the changing supply of FMFO;
2) Other environmental hazards such as harmful algae bloom (Gobler et al., 2017), disease prevalence (Leung et al., 2013), and hypoxia zones (Breitburg et al., 2018) could be limiting factors to mariculture production (Froehlich et al., 2018). There is a possibility that these factors will be exacerbated under climate change (Cochrane et al., 2009). However, these factors are not explicitly considered in this study;
3) There are limitations to the use of species distribution model. SDMs may not adequately quantify the species environmental preference (Pearson and Dawson, 2003) because these ranges are determined only by climate variable; equilibrium exists between the realised species range and its potential range by the climate. Mariculture practices such as selective breeding or technological use that could ensure species and the adaptive industry capacity are not considered; and
4) Socioeconomic factors which are not considered in this present study such as trade, market, consumer preferences, and governance could limit mariculture production.

These model uncertainties and assumptions can be incrementally addressed through further refinement of different sub-component of the mariculture production model. For example, potential linkages with models of land-based food production and the use of plant-based aqua-feed for mariculture production could be developed. New model sub-components that projected climate-induced threats to mariculture production such as harmful algal bloom or disease of farmed species and how these threats would affect mariculture production could be further developed. The incorporation of additional predictors that are related to technology could be included into the existing mariculture production model.

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Chapter 5: Seafood market model

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Abstract
This chapter describes a newly developed global seafood market model (GFish) that aims to simulate the effects of changing market and non-market forces on global seafood supply, demand and trade. The GFish is a partial equilibrium economic model. It is built from the country (smallest unit) level to global level. In GFish, fish products are essentially sourced from domestic (marine capture, inland capture, and aquaculture sectors) and foreign (import agents) sources, and then distributed to local (consumers) and foreign (exports agents) markets. Hence, the model comprises three core components namely, producer, consumer, and trader. The behavioral assumptions of aquaculture producer, consumer, and trader are normalized under a quadratic profit function approach, linear approximation almost ideal demand system (LA-AIDS), and Armington, respectively. Both inland and capture sector are treated as exogenous components in the model. Illustrative examples are provided to project the supply and demand of four key commodity group namely, shrimp, salmon, tilapia, and tuna, in 2030, under different potential impact of changes derived from exogenous forces such as seafood production (from the dynamic effort model) and changes in demographics, income level and seafood consumption (from the Shared Socioeconomic Pathways). The model can further be improved through data, estimations of supply, demand and trade elasticities, model structure, and specifications. It is flexible enough to incorporate different types of producer groups (i.e., by production scale) consumers groups (i.e., by income level and demographic group), different domestic market channels (i.e., food service channels, tourism), and different trade relationships or flows (i.e., bilateral/multilateral trade relationships between/among countries).

Introduction
As fish has become an important animal-protein element of the human dietary across the globe, it is not surprising that there is an increasing effort to incorporate fish in food sector analysis. The aim of fish supply and demand simulation models (Chen, 2016; World Bank, 2013; Charlebois, 2013; Dey et al., 2005) is to facilitate the analysis of the supply, demand and trade consequences, associated to different scenarios subject to changing market forces, policy, demographic, environments, to name a few. The objective of this modeling exercise was to develop a model that would allow exploration of the importance of interactions between global fish supply, demand and trade. More specifically, the main focus is to assess the impacts that market and non-market forces have on the marine resources and the effects of changing seafood supply from capture fisheries and mariculture on global seafood market. Hence, this model focuses more on the marine sectors. The remainder of this chapter is organized into five sections. It begins with discussions on the model structure, assumptions and datasets. This is followed by a brief

illustrative example given in the subsequent section. Last, is a discussion of the strengths and limitations of the model.

Model structure

The general structure of the global fish supply and demand model (GFish model) is illustrated in Figure 5.1 and Figure 5.2. Note that the term "fish" denotes finfish and shellfish in the subsequent discussions, unless otherwise stated. The GFish model is intended for simulating results for supply, demand, prices, and international trade of fish, at the species level. It is a partial equilibrium model as only the quantities and prices of fish commodities are determined within the system. Notwithstanding this, it is sufficiently adaptable to assess the potential impact of changes derived from the exogenous variables/factors, such as environment and socio-economic factors, on the seafood industry. The GFish model is capable of generating dynamic equilibrium on an annual basis. Dynamic equilibrium, in the sense that quantities and prices are constantly changing, depend on the previous year market clearing equilibrium and the current exogenous shocks imposed. Hence, it is flexible enough for formulating and investigating the movement of a simulation over the projecting period.

The global geographical disaggregation of the model is illustrated in Figure 5.1. It is built from the smallest unit (country) level to global level. A country-unit represents an individual country or a group of countries. Each country-unit is a standalone model where the fish supply, demand and trade of an individual country-unit are comprised. The global model is formed by integrating all the country-unit models through international trade activities. At the global platform, each country-unit trades internationally in a single global market. In other words, bilateral trade that flows between countries is not included in the model and all international trade flows are cleared at one global platform.

The disaggregation of the GFish model, in terms of actors or stages along a respective country-unit fish value chain, is essentially based on the information available. In general, fish products are essentially sourced from domestic (marine capture, inland capture, and aquaculture sectors) and foreign (import agents) sources, and then distributed to local (consumers) and foreign (exports agents) markets. These stages are divided into producer, consumer and trade cores in the model. The producer core covers the domestic marine capture, inland capture and aquaculture sectors. The consumer core represents the end-consumers in the local markets. Lastly, the trade core includes both the import and export agents. Since the model is intended for generating simulations at the species level not product form level, only the live weight unit is applied throughout the model.

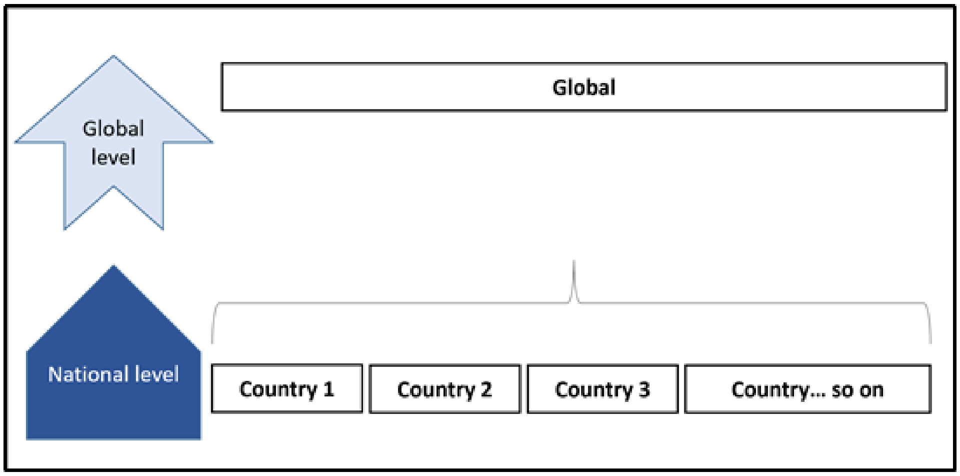

Figure 5.1: The GFish model framework

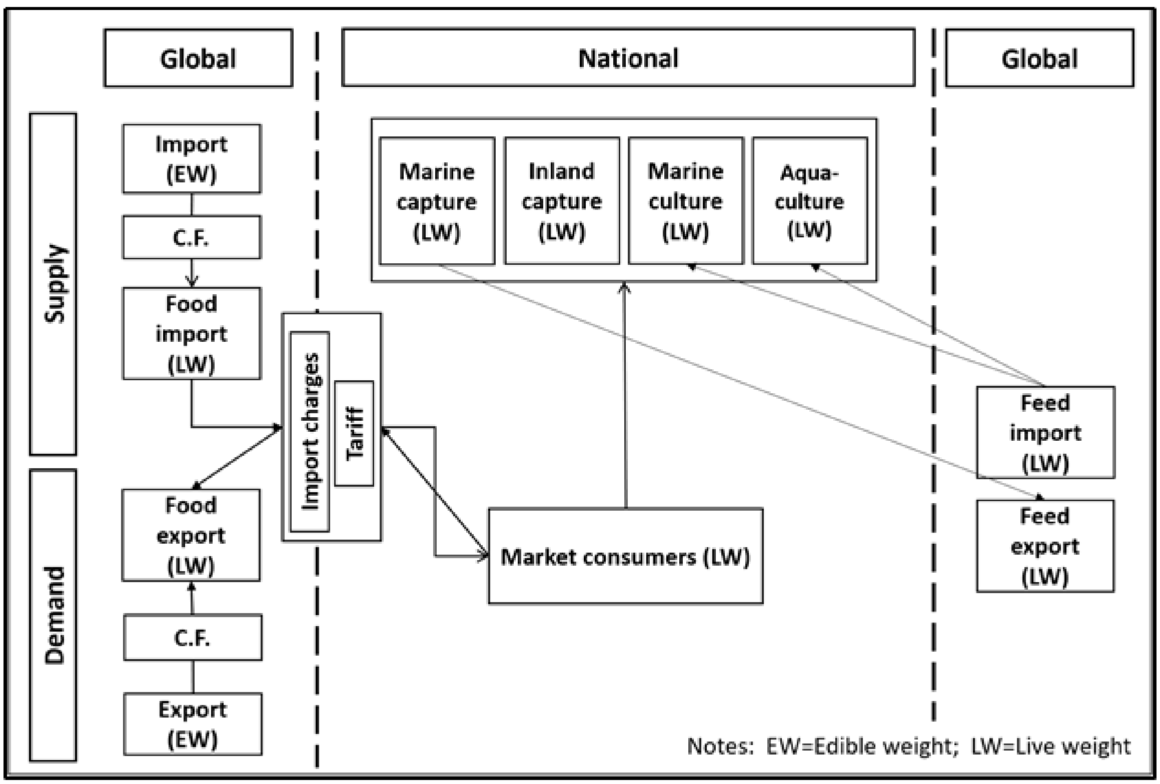

Figure 5.2: Structure of the core national model

Model assumptions and specifications

This section discusses the behavioral assumptions of the three main actors namely, producers, consumers, traders, and the markets (country-unit and global) clearing conditions.

Raw fish supply

In the GFish model, domestic fish outputs are supplied by both the capture (inland and marine) and aquaculture (inland and marine) sectors. The marine capture producer's core is treated as an endogenous component in the model, where prices and quantity supplied are determined within the model. The raw fish catch by the marine capture sector relies on both the non-market and market factors and these interactions are modeled in the dynamic bioclimate envelope model (Chapter 2) and effort dynamic model (Chapter 4), while the inland capture producer's core is an exogenous component, where the raw fish quantity harvested is based on deterministic assumption, i.e., assumed to be constant in the model.

Similar to the capture sectors, the production of aquaculture sectors also relies on the market and non-market factors. However, given the nature of aquaculture where producers have more control over their production activities, aquaculture supply is more market oriented than capture sectors. The aquaculture sectors represented in the GFish model can be treated as either an exogenous or endogenous component. In the case of exogenous component, the raw fish quantity supplied is based on deterministic assumption, i.e., assumed to follow the projected supply trends of existing studies.

In the case of endogenous component, the behavior of producers towards fish and input prices change is assumed to follow the normalized quadratic profit function approach. Given that our focus is on marine resources, the model further includes the non-market factors to project production areas that are suitable for a conduct of marine culture (mariculture) initiative, and both market factor (farm-gate price) and non-market factors (suitable area for mariculture, supply of fishmeal and fish oil) on the potential mariculture production. The modelling and projection of seafood production from mariculture are described in Chapter 4. The equilibrium quantity of a respective marine farmed species (or species group) entails a restriction on the potential production in weight for the farming of the respective species (or species group).

The normalized quadratic profit function approach is employed to derive fish supply and inputs demand equations. This approach is widely used in cases of joint agricultural production (Shumway et al., 1987; Ball et al., 1997; Dey et al, 2008; Chen, 2016). In other words, it is assumed that output supplies and input demands are determined jointly within each domestic production source. The model further assumes that technology and policy can be modeled as a proportional and factor-neutral shift in quantity (Alston et al., 1995; Dey et al., 2005; Chen, 2016). This results in a series of equations in which the quantity of fish outputs and inputs are a function of fish prices, input prices, and technology.

The stochastic specification of the normalized quadratic profit function is represented as:

$$\pi^* = \alpha_0 + \sum_i \alpha_i P_i^* + \sum_k \gamma_{0k} v_k + \frac{1}{2}\sum_i \sum_j \alpha_{ij} P_i^* P_j^* + \sum_i \sum_k \gamma_{ik} P_i^* v_k + \frac{1}{2}\sum_k \sum_l \gamma_{kl} v_k v_l + \sum_i \varepsilon_i P_i^* + \varepsilon \quad \text{.................(5.1)}$$

where π^* is normalized profit, the α's and γ's are parameters of the model, $P_{i^*} = P_i/Pnum$ is the normalized price of the i_{th} netput with P_i as the producer price, Pnum is the price of the numeraire good, V_k is the k_{th} conditioning variable (fixed input which is treated as exogenous element in the model), and ε is the error term. Applying the envelope theorem, the netput supply QA_i are the fish and input price derivatives of the profit function as follows:

$$QA_i = \alpha_{0i} + \sum_j \alpha_{ij} P_j^* + \sum_k \gamma_{ik} v_k + \varepsilon_i \qquad \text{.................(5.2)}$$

Note that if $QA_i < 0$ then netput i is an input. Supply response to price changes, expressed in terms of own- and cross price elasticities, can be readily computed from (SC2).

To derive the supply function of the numeraire good (Qnum), multiply the expression in (SC1) by Pnum to obtain nominal profit, then differentiate with respect to Pnum to yield:

$$Qnum = \alpha_0 + \sum_k \alpha_{0k} v_k + \frac{1}{2} \sum_i \sum_j \alpha_{ij} P_i^* P_j^* + \frac{1}{2} \sum_k \sum_l \gamma_{kl} v_k v_l + \varepsilon \qquad \text{.................(5.3)}$$

The derivation of the supply functions from a profit function entails certain restrictions on the former. A profit function is homogenous of degree one in prices and should have equal cross-price derivatives. Therefore, the supply parameters must comply with the homogeneity and symmetry restrictions. In the present specification, the homogeneity restriction has been incorporated by normalization while the symmetry restriction can be implemented by imposing $\alpha_{ij} = \alpha_{ji}$.

It is assumed that technology and policy can be modeled as a proportional and factor-neutral shift in quantity. For a given supply function, this may be represented as a distinction between actual and effective prices (Alston et al., 1995; Dey et al., 2005). When a changing supply condition takes place, for example, a productivity improvement of a fish type, ceteris paribus, will essentially shift its supply curve rightward, subsequently, the output rises and its price falls. The normalized price, in effective form, is computed as:

$$PE_i = \frac{P_i * \lambda_i}{pnum * \lambda num} \qquad \text{..........................(5.4)}$$

Where λ_i is the proportional change of output of supply fish type i due to technological progress or policy shift, and λnum is the expansion for the numeraire fish type.

Marine capture and feed interactions

This component attempts to model the feed linkages between the marine capture and aquaculture sectors. Given the lack of information to model the feed sector explicitly, the behaviors of feed supply and demand are treated as an exogenous component, where it depends on a set of deterministic assumptions. The model calibrates only the quantity flows of feed supply and demand through a global platform. The global platform is essentially the platform for sourcing all the feed products coming from all the producing countries (export flow of producing countries), and then distributing to the buying countries (import flow of buying countries). The effects of exogenous factors on the availability of marine capture fish to supply fishmeal and fish oil in aqua-feed is modelled through the DBEM and effort dynamic model (Chapters 2 and 3). Such effect is also accounted for in modelling the potential production from mariculture (Chapter 4).

The following are the discussions on the interactions between the feed supply and demand flows in the model, and these are calibrated to an individual species (or species group) level.

The national feed demand is formulated as follows:

$$QDFeed = \sum_{i}^{n} QS_i \times FCR_i \quad \text{.....................(5.5)}$$

Where, *QDFeed* represents total feed demand of a country; QS_i is the national supply of *i* commodity (i.e., farmed salmon), FCR_i is the feed conversion rate to farm *i* commodity.

The total global feed demand is the sum of feed demand from all countries. The model assumes fully utilization of feed supplied (zero surplus). This denotes equating the total supply and demand of feed, as follows.

$$GQSFeed = \sum_{k}^{n} QDFeed_k \quad \text{.....................(5.6)}$$

Where, *GQSFeed* represents global feed supply; $QDFeed_k$ is total feed demand of country *k*.

To calibrate the species origins of the feed, a species-weighted-ratio is applied. In other word, the model assigns an average species share in the production of feed. This ratio is calculated based on the recent available information.

$$GQSFeed_i = GSHFeed_i \times GQSFeed \quad \text{.....................(5.7)}$$

Where, $GQXFeed_i$ represents the global feed supply of *i* commodity; $GSHFeed_i$ is the supply share of *i* commodity in the global feed supply.

Lastly, the feed is supplied from a number of producing countries and the national feed supply is formulated as follows:

$$QSFeed_i = NSHFeed_i \times GQSFeed_i \quad \text{.....................(5.8)}$$

Where, $QSFeed_i$ represents the national feed supply of *i* commodity; $NSHFeed_i$ is the national (country) supply share of *i* commodity in the global feed supply of *i* commodity.

Import charges and tariff

In the case of imported fish commodities, import charges and tariff linkages are calibrated within the system to enable flexibility in imposing import charges (insurance, freight and other costs) and tariff on the dutiable imported fish commodities. All the import charges and tariff variables are treated as exogenous elements in the model and calibrated to individual fish species. Hence, when necessary, it is fairly easy to reformulate the baseline assumptions to incorporate the changing import charges and/or tariff conditions.

Seafood demand

Seafood market demand

The consumer core represents the behavior of the end-consumers. The decision process of each end-consumer is specified as the Linear Approximation Almost Ideal Demand System (LA-AIDS), in which the expenditure shares of the different fish types are expressed as a function of fish prices and real fish expenditure (Deaton and Muellbauer, 1980).

The LA-AIDS (Deaton and Muellbauer, 1980) is formulated as follows:

$$SH_i = \alpha_i \times \sum_j \gamma_{ij} \ln PC_j + \beta_i \ln (FEX/P) + v_i \qquad \text{......................(5.9)}$$

where, *ij* represents the fish commodities; *γ*, *β*, and *α*, are the parameters of the model; SH_i is the expenditure share of fish *i* among the fish commodities; PC_j is the price of fish j; *FEX* is the total fish expenditure of all fish commodities included in the model; v_i is the error term of the model and P is the price level which is approximated using Stone price index as:

$$STONE = \sum_i SH_i \ln(PC_i) \qquad \text{......................(5.10)}$$

The theoretical demand restrictions in terms of adding-up, homogeneity in prices and income and the symmetry of cross effects of demand function are imposed in the model. All of these restrictions are imposed at the parameter level.

The theoretical restrictions are defined as follows:

Adding up: $\sum_{i=1}^{n} \alpha_i = 1; \quad \sum_{i=1}^{n} \gamma_{ij} = 0; \quad \sum_{i=1}^{n} \beta_i = 0$ ....(5.11)

Homogeneity: $\sum_j \gamma_{ij} = 0$; and ....(5.12)

Symmetry: $\gamma_{ij} = \gamma_{ji}$. ....(5.13)

The average quantity demanded for fish type *i* derived from the share equation is given below.

$$QD_i = \frac{SHi * FEX}{PC_i} \qquad \text{.....................(5.14)}$$

Where, QD_i represents the quantity demanded for fish type *i*; PC_i is the consumer price for fish type *i*.; SH_i is the expenditure share of fish *i* among the fish commodities and *FEX* is the total fish expenditure of all fish commodities included in the model.

Trade

Seafood trade

The model assumes that prices, product availability/demanded, and substitutability between foreign and domestic products are the key factors affecting the fish trade flows. However, it is recognized that income (GDP), population, geographical distance, and bilateral trade related factors (i.e., bilateral trade barrier and resistance to trade) are some of the important factors (Anderson and Wincoop, 2003) in defining the trade flows among fish trading partners. It is assumed that income, population, and geographical distance (essentially the transportation cost) are ubiquitous factors for all countries, and it requires a significant time and effort to build and grow any bilateral relationship (Ramanarayanan, 2011). Hence, these are treated as exogenous elements in the model.

Substitutability and price effects

The model follows the tradition of market equilibrium models that impose the Armington assumption (Armington, 1969). The key assumption of Armington is that the products traded internationally are primarily not homogenous. Factors contributing to the export flow are (i) the price in foreign markets relative to domestic markets and (ii) domestic output. On the other hand, factors contributing to the import flow are (i) the price of imports relative to domestic products, and (ii) domestic demand.

In the following discussion, the QSF_i and QDF_i are market supply and demand aggregates, respectively. Consider the case of imports: the combination of total demand for the domestic component (QHM_i) and the total demand for imports (QM_i) into the import-domestic aggregate is described by:

$$QDF_i = \left(\delta 1m * QHM_i^{-\rho mi} + \delta 2m * QM^{-\rho mi}\right)^{\frac{-1}{\rho mi}} \quad \text{......................(5.15)}$$

The parameter ρmi is a transformation of the elasticity of substitution σmi, i.e., (ρmi = (σmi -1)/ σmi.

The expenditure constraint is:

$$PARM_i = \frac{PS_i * QHM_i + (IFC_i + (Pm_i * (1 + TA_i))) * QM_i}{QDF_i} \quad \text{............ (5.16)}$$

Where $PARM_i$ is the price of the import-domestic aggregate; PS_i is the producer price of fish type i, IFC_i is the import charges including freight, insurance and other costs of fish type i, TA_i is the tariff imposed on fish type i, and pmi is the import price of fish type i. Minimizing the right-hand side of (16), subject to fixed QDF_i in (5.16), implies the following conditional demands:

$$QHM_i = \delta 1m^{\sigma mi} * (\frac{PARM_i}{PS_i})^{\sigma mi} * QDF_i \quad \text{............. (5.17)}$$

$$QM_i = \delta 2m^{\sigma mi} * (\frac{PARM_i}{IFC_i + (pm_i * (1 + TA_i))})^{\sigma mi} * QDF_i \quad \text{............. (5.18)}$$

Consider the case of exports: for fish type i, let QHXi represents the domestic component (for domestic consumption), and QHi the foreign component of export. The export-domestic aggregate equation is given by

$$QSF_i = (\delta 1x * QHX_i^{\rho xi} + \delta 2x * QX^{\rho xi})^{\frac{1}{\rho xi}} \quad \text{..................(5.19)}$$

The parameter ρxi is a transformation of the elasticity of transformation σxi. By a similar derivation, the trade core equations for exports are given by:

$$PARX_i = \frac{PS_i * QHX_i + px_i * QX_i}{QSF_i} \quad \text{............. (5.20)}$$

$$QHX_i = \delta 1x^{\sigma xi} * (\frac{PS_i}{PARX_i})^{\sigma xi} * QSF_i \quad \text{............. (5.21)}$$

$$QX_i = \delta 2x^{\sigma xi} * (\frac{px_i}{PARX_i})^{\sigma xi} * QSF_i \quad \text{............. (5.22)}$$

Where, $PARX_i$ is the price of the export-domestic aggregate and px_i is the export price of fish type i.

Price effect

In the case where price is the only key element in defining the trade flows among trading partners. The decision to or not to trade can be framed as follows:

Country A decides to import species *I* when import price (PM_i) offered is lower than domestic price (PS_i) and marketing cost (M_i):
$PMi < PS_i + M_i$

Country A decides to export species *I* when export price (*PMi)* offered is higher than domestic price (*PSi*) and marketing cost (*Mi*):
$PX_i > PS_i + M_i$

Market clearing

Equilibrium prices and quantities of fish types are derived by a series of interactions of supply and demand. In the case of equilibrium quantity, the model assumes that all the fish supplied will be fully utilized. Hence, the equilibrium quantity conditions require the equality of domestic demand to domestic supply for each fish type at the global level. In other words, this is equivalent to equating the sum of domestic production to the sum of domestic consumption, and net exports (exports minus imports). Note that at the national level, one can either be a net importer or net exporter. At the global level, the market clearing is equivalent to equating the total seafood supplied to total seafood demanded. In other words, the world export is equivalent to the world import.

The national market clearing condition, at fish type level:

$QSF_i + QM_i = QDF_i + QDFeedX_i + QX_i$ ....(5.23)

The global market clearing condition, at fish type level:

$$\sum_k^n QM_{ik} = \sum_k^n QX_{ik} \quad \text{................(5.24)}$$

Where, QM_{ik} and QX_{ik} represent commodity *i* imports and exports of country *k*, respectively.

The model generates values for the endogenous variables based on the model structures and values of model parameters and exogenous variables. The exogenous and endogenous variables are listed in Table 5.1.

Table 5.1: The endogenous and exogenous variables of the GFish Model.

a) Endogenous variables
1. Aquaculture output and price, by species, by country
2. Marine capture output and price, by species, by country
3. International trade (import, export) quantity and price, by species, by country
4. Consumption, quantity and prices, by species, by country
b) Exogenous variables
1. Inland capture outputs, by species
2. Technology or productivity change, by species
3. Input, quantity and prices, by sector
4. Fish spending, by species, by country
5. Population, by country
6. Tariff, by species, by country
7. Import charges (i.e., transportation, insurance, other charges), by species
8. Feed conversion factor, by species, by country
9. Price demand and spending elasticities, by species, by country
10. Price supply elasticities (fish and inputs), by species, by country
11. Elasticity of substitution between domestic and imported fish, by species
12. Elasticity of transformation between domestic and exported fish, by species

Model data and behavioral equations parameters

This section discusses the data used in modeling the producer, consumer and trade cores. Not included in the discussion is data used in modeling the DBEM, effort dynamic model, and mariculture production potential model, as each is discussed in Chapter 2, Chapter 3, and Chapter 4, respectively.

The GFish model requires a baseline year to initialize (average of 2008-2010), which consists of, for each country-unit (consisting of an individual country or a group countries), a fish sector profile, parameters for the behavioral equations of producers, consumers, and traders, and other exogenous variables. There is no single source of information accessible for the data requirements of the model. Also, information for some variables is not directly accessible. The succeeding paragraphs describe the assumptions used to generate the complete and consistent data sets for the application of the model.

The country-unit fish sector profile contains information on the quantities and prices of domestic supply (S), imports (M) and exports (X). The model assumes that the total fish supplied will be fully utilized (C), that is, C = S + M - X. The profile contains two key components: fish for human consumption and fish for feed utilization. The following are the key sources of information used in constructing the country fish sector profile: in terms of volume of fish production or catch, the model relies on *Sea Around Us* (Pauly and Zeller, 2016) for the marine catch information, while FishStatj (FAO, 2016) was used for the catch from inland capture and aquaculture. The quantity of feed supplied and demanded was analyzed using the data from Tai et al. (2017). Data on exports and imports was obtained from the FishStatJ (FAO, 2016). As the fish live weight unit is used throughout the stages in the model, this approach was adopted to convert the fish processed weight into fish live weight (landed). The conversion factors applied in this exercise were drawn from published information such as FAO (1990-2015), EUMOFA (2013).

The subsequent discussion on prices information were mainly for seafood products (for human consumption), as only feed quantity is represented in the model. The ex-vessel (marine capture) and farm-gate (aquaculture) live-weight prices are obtained from Tai et al. 2017, Oyinlola (in prep., as described in Chapter 4), and FishStatj (FAO, 2016). Note that price information was not available for inland capture, hence, it is assumed to follow the relevant ex-vessel (marine capture) and farm-gate (aquaculture) live-weight prices used in the model. Data on exports and imports live-weight prices were obtained from the FishStatJ (FAO, 2016). The consumer live-weight prices were weighted domestic farm-gate, ex-vessel, and import prices.

The model required parameters for the behavioral equations of its producer (aquaculture), consumer and trade cores. In the case of aquaculture producer core, estimates of elasticities from the existing literature were used. In the case of consumer and trade cores, the objectives were twofold: first, to estimate elasticities using our constructed-consumption-and-trade-datasets (consisting of country-unit profiles); and second, to use elasticities from the existing literatures. Note that in some cases, some of the raw estimates of elasticities compiled had to be transformed based on certain assumptions. Once elasticities were finalized, they were transformed to parameters to suit the specification of the model equations. The intercept terms of all the relevant equations were then computed to ensure that the model replicates the base dataset.

Other information includes tariffs, import charges, population, and per capita income/GDP. These were obtained from existing statistical databases and literatures. The details of these datasets are further discussed in Chapter 8 of this document.

Illustrative example

This section provides illustrative examples on partial equilibrium analysis under different scenarios. The discussion focuses on the application of the method rather than the absolute results. In other words, given that all the behavioral parameters used in this exercise are hypothetical, interpretation of results shall focus at how the pathway (direction) changes when a change in assumption takes place rather than the absolute change in value.

Following the method discussed in the previous sections, a global model was developed to project the supply and demand of four key commodity group namely, shrimp, salmon, tilapia, and tuna, in 2030. The base period of the model is an average of years 2008 to 2010. The geographical aggregation consists of 11 country-units (individual or region), namely, Africa, China, East and Southeast Asia, Europe, Latin America, North America, North, West and Central Asia, Pacific, SIDS-Caribbean, SIDS-Pacific, and South Asia.

The model was used to project the species trends under 2 scenarios consist of scenarios of Shared Socioeconomic Pathway (SSP) and greenhouse gas emissions. Specifically, two scenario combinations: SSP1 & RCP2.6 scenario and SSP3 & RCP 8.5 scenario were explored (see Chapter 6 for detailed descriptions of these scenarios). Projected changes in exploited populations of shrimp, salmon, tilapia and tuna (see Table 5.2 for commodity groups and examples of species included in each group) were projected from DBEM and effort dynamic model under the two RCPs and SSPs. Table 5.3 presents the definition of each SSP scenario, with incorporation point (models) of respective assumption.

Table 5.2. Commodity groups represented in the seafood market model (GFish) and examples of species included each group.

Commodity groups	**Example species**
HERRING, ETC	*Clupea harengus, Sardina pilchardus, Sardinella brasiliensis*
COASTAL	*Lutjanus malabaricus, Dicentrarchus labrax, Epinephelus analogus*
JACK, ETC	*Caranx hippos, Scomber scombrus, Trachurus murphyi*
COD, ETC	*Gadus morhua, Merluccius senegalensis, Merlangius merlangus*
TUNA, ETC	*Katsuwonus pelamis, Thunnus albacares, Thunnus tonggol*
SHARK, RAY, ETC	*Centrophorus lusitanicus, Carcharodon carcharias, Carcharhinus brachyurus*
WHALE	*Huso huso*
SALMON, ETC	*Salmo salar, Oncorhynchus kisutch, Salmo trutta*
FW	*Morone saxatilis, Morone americana,*
SHRIMP	*Penaeus vannamei, Penaeus monodon, Penaeus indicus*
MOLLUSCS	*Crassostrea gigas, Mytilus chilensis, Ruditapes philippinarum*
CRAB, LOBSTER	*Homarus americanus, Scylla serrata, Panulirus homarus*
KRILL	*Euphausia superba, Meganyctiphanes norvegica*
CEPHALOPODS	*Illex argentinus, Octopus vulgaris, Loligo forbesii*
ECHINODERM	*Echinus esculentus, Apostichopus japonicus, Loxechinus albus*

Table 5.3: Broad definition of Shared Socioeconomic Pathway scenarios.

	Assumption incorporation point	
	Effort model	Market model
SSP 3 (business-as-usual) scenario		
High shrimp trawl and aquaculture productivity	X	X
Tilapia aquaculture status quo		X
All tuna catch above maximum sustainable yield (MSY)	X	
Salmon: high aquaculture productivity and wild shrimp catch above MSY	X	X
Strong international trade barriers (i.e., high tariff)		X
Slow per capita income growth		X
High population growth		X
High subsidies	X	

SSP1 - sustainable scenario		
Low shrimp catch and aquaculture productivity	X	X
High productivity of tilapia aquaculture		X
Skipjack and yellowfin catch at MSY, other tunas are caught below MSY	X	
Salmon: low aquaculture productivity and will shrimp catch at MSY	X	X
Free international trade		X
Fast per capita income growth		X
Low population growth		X
Low subsidies	X	

Source: Authors' illustration.

Note that other factors including inputs prices (real) were assumed to be constant in this exercise. Assuming other factors remain constant, the projected results show the following trends: first, the marine capture catch is projected to decline under both scenarios with higher decline observed under SSP3 & RCP 8.5 scenario attributed to lower catch efforts (Figure 5.3). In terms of the sub-country's contribution in the total global catch, no huge change was observed across all the scenarios (Figure 5.4).

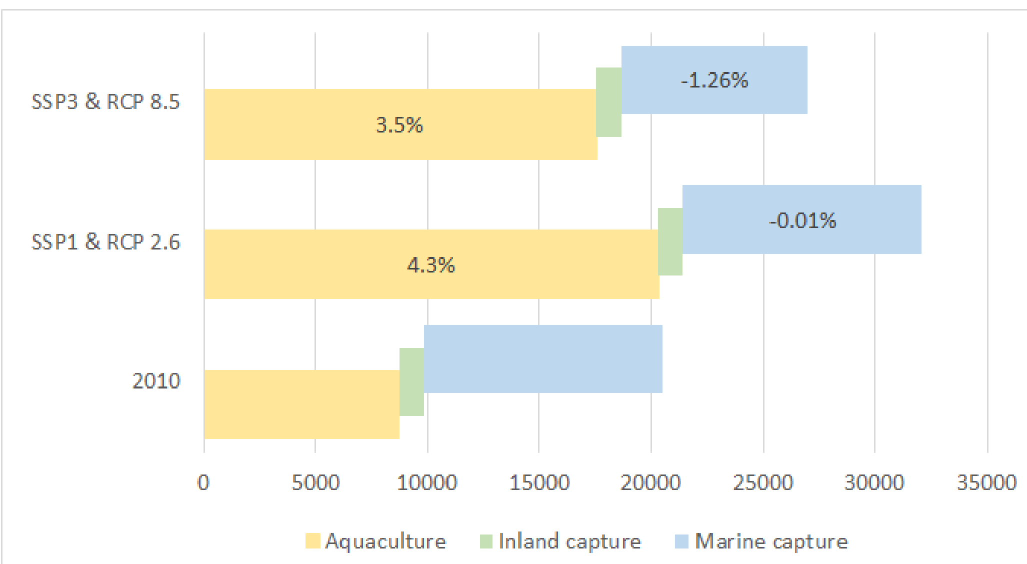

Figure 5.3: Projected global production by sector in 2030, volume in thousand ton (x-axis) and change per annum from base period in percentage (in bar). Value in percentage denotes compound growth rate from base period (% p.a.).

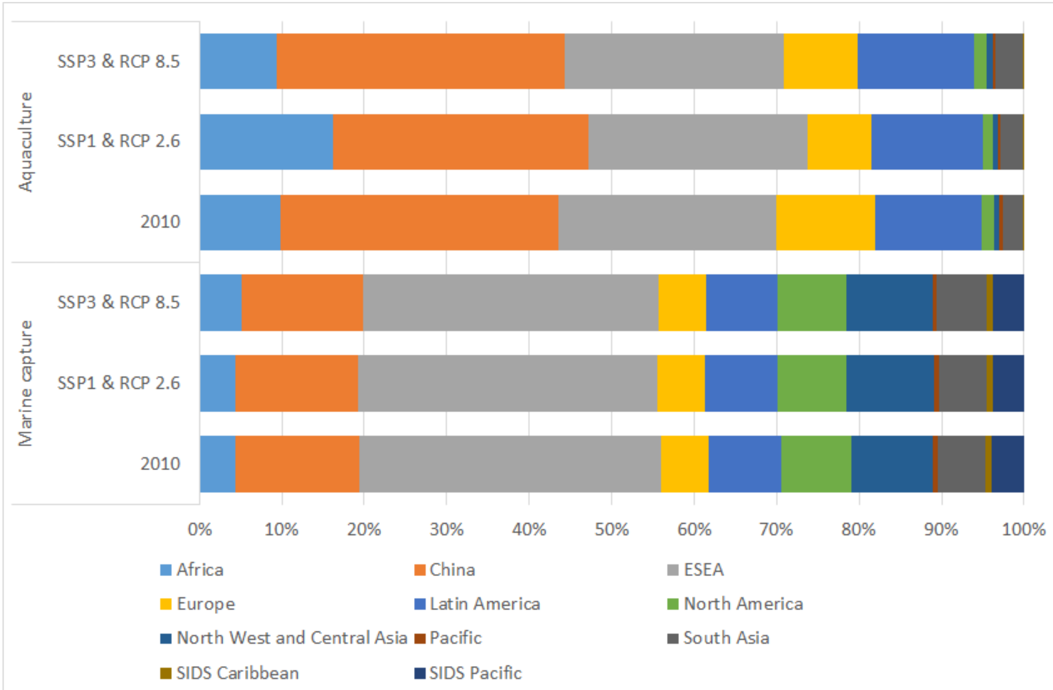

Figure 5.4: Projected percentage of global production by sector and region in 2030.

Second, aquaculture production is projected to grow under both scenarios attributed to lower marine capture catch, higher aquaculture productivity, higher population and higher per capita real income. Despite higher decline in marine capture catch and higher demand (growth in population), the aquaculture production is projected to grow slower under SSP3 & RCP8.5 scenarios, which suggests the effects of lower per capita spending (affordability). The results show a change in the landscape of the producer's composition under SSP1 & RCP2.6, with a higher contribution coming from Africa while lower from Europe. This projected change in Africa and Europe is driven by higher tilapia aquaculture productivity and lower salmon aquaculture productivity, respectively.

Third, international trade is projected to grow at a sluggish trend under SSP3 & RCP8.5 scenarios attributed to barrier to trade, i.e. tariff (Figure 5.5). Higher impact was observed in tuna. Comparing the barrier-to-trade and free trade scenarios, the exclusion of tariff seems to benefit the tilapia sector more than salmon and shrimp sectors. However, this effect is resulted from the underlying assumption of the scenarios, that is, slower salmon and shrimp farming productivity while faster productivity of tilapia farming in SS1 & RCP2.6 scenario. Hence, the bigger trade effect on tilapia under SSP1 & RCP 2.6 was not solely attributed to the relaxation of tariff but coupled with higher productivity. Care needs to be taken when interpreting the results, particularly for scenarios that consists of a combination of features (variables) that have diverse interactions among the variables.

Fourth, results show positive projected trends in per capita consumption (Figure 5.5). However, the diet composition is projected to change with relatively faster growth in tilapia intake under both scenarios attributed to more affordable price compared to other species (SSP3) and higher productivity growth than other farmed species (SSP1).

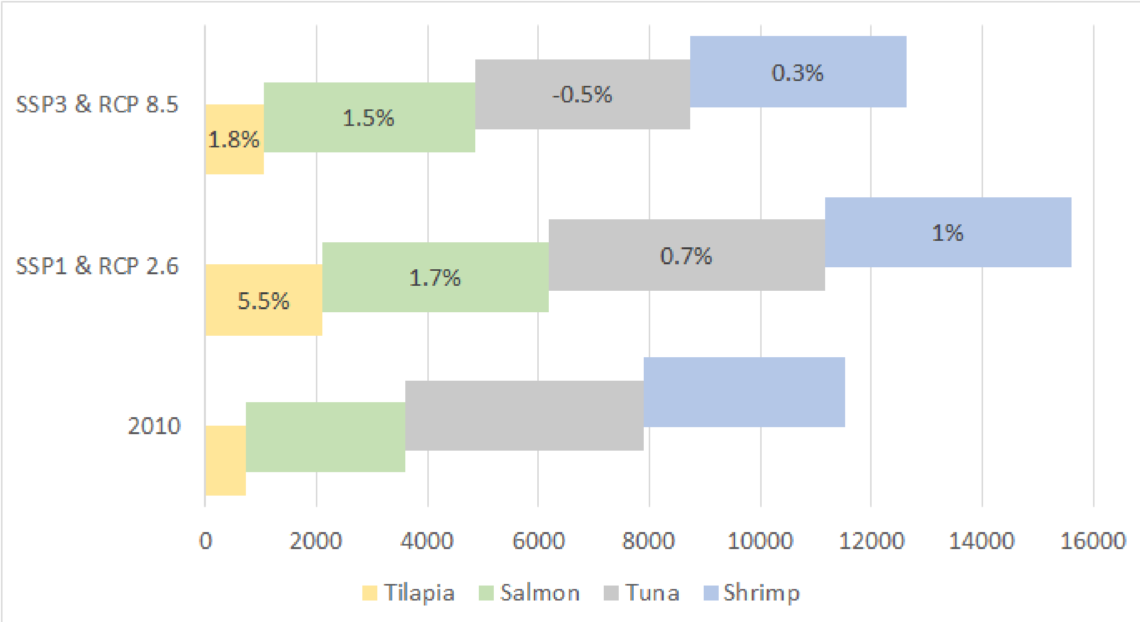

Figure 5.5: Projected global trade of shrimps, salmons, tilapia and tuna in 2030, volume in kg per person (x-axis]) and change per annum from base period in percentage (in bar). Value in percentage denotes compound growth rate from base period (% p.a.).

This section presents a simple example using the method of GFish model and the projected values of endogenous variables under alternative scenarios. The results show that the model is capable of generating logical projections under different scenarios (Figure 5.6). It also shows that both model and scenarios modeling tasks are equally important. Logical scenarios with distinctive features are more easily comparable among alternative scenarios. While, other less-distinctive feature scenarios (i.e., 1% vs 2% growth in income per capita) can be treated as sensitivity analysis.

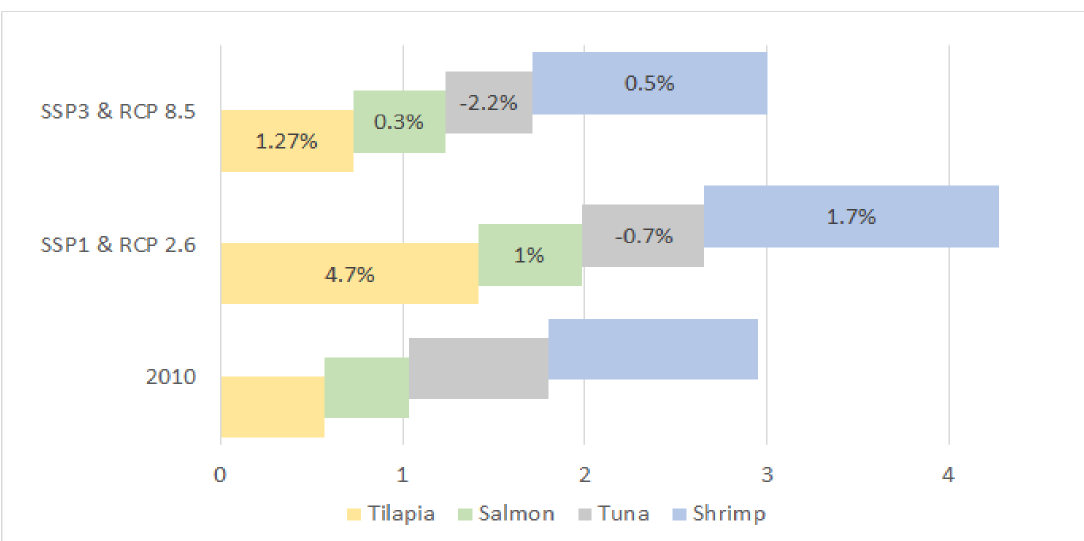

Figure 5.6: Projected global per capita consumption of shrimp, salmon, tilapia and tuna in 2030, volume in kg per person (x-axis) and change per annum from base period in percentage (in bar)

Strengths and limitations

Strengths

Each scenario relies on certain assumptions (deterministic assumption). The exogenous linkages (such as tariff, import charges, to name a few) calibrated within the model allow for more flexibility in incorporating different set of assumptions. Moreover, the behavioral parameters represented in the model are fairly easy to be updated. Hence, this model is not only a conceptual model, but it could serve as a tool to inform decision-making. However, it is also important to note that the results of the analysis may not be directly comparable to the results of other projection studies (other models) because of the differences in assumptions used (i.e., model structure, parameters, data). The results are scenario-dependent and hence, need to be interpreted within the context of the scenario.

The model is flexible enough to incorporate different types of producer groups (i.e., by production scale) consumer's groups (i.e., by income level and demographic group), different domestic market channels (i.e., food service channels, tourism), and different trade relationships or flows (i.e., bilateral/multilateral trade relationships between/among countries). The model structure with stand-alone (independent) country-unit model enables more flexibilities in incorporating different assumptions for the country of interest. For example, one can expand a country-unit model to incorporate more disaggregate consumer groups, without requiring it to expand for all the other country-units included in the GFish model. The expanded (more detailed) respective country-unit is then integrated with other country-units where they interact in the single global market (model default). This results in a more detailed analysis of the respective country-unit with linked domestic and international markets, which is an important element in the seafood market as seafood is the most traded food commodity in the world. In addition, this reduces the resources and time required to conduct a specific study, as data availability is mostly country specific.

Limitations and areas of improvement

The datasets used in the model is *Sea Around Us* data on marine catch, Tai et al. data on ex-vessel prices, FAO data on aquaculture production, inland capture catch and trade, and World Bank data on population and per capita GDP. The methodology used to calculate the apparent consumption data used in the model is heavily reliant on the production and trade data. Some of the data, particularly price data, are estimated data. Hence, timely improvements of data availability and quality of the required data would improve the accuracy of the projections.

The supply, demand and trade elasticities used in this model are borrowed from existing studies. However, most of the existing studies are not meant for projection analysis use. In addition, most of the studies are conducted in isolation (i.e., for a particular country), hence, do not take into account the relative effect across countries. Improvements of estimations of supply, demand and trade elasticities for global projection study would improve the accuracy of the projections.

Due to lack of data and behavioral parameters, the model does not include subsistence farmers/fishers, subsistence consumers and bilateral trade flows. Incorporation of these actors and relationships may improve the model specifications.

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Chapter 6: Scenarios for the future of the ocean and fisheries

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Abstract

The existing Shared Socioeconomic Pathways (SSPs) provide a standardized, internationally recognized, global framework that allows for the exploration of five distinct futures based on contrasting societal choices - including political, economic, social, technological, legal, and environmental. These alternative futures revolve around how human societies might evolve over the coming century and the mitigation and adaptation challenges associated with societal choices and associated developments. The aim of this chapter is to develop broad narratives of different futures for oceans, fisheries and seafood demand using the SSP architecture and applying it to the Dynamic Integrated Marine Climate, Biodiversity, Fisheries and Seafood Market Model (DIVERSE). We focus on three SSPs representing the "Sustainability" (SSP1), "Regional Rivalry" (SSP3), and "Fossil-fuel development" (SSP5) pathways. We expand on existing scenario-based work to identify relevant quantitative drivers of global fisheries and parameterise them to explore the impact of alternative futures in DIVERSE.

Introduction

Marine and coastal ecosystems play a critical role in providing a range of services - such as regulating the climate, stabilising shorelines, protecting land areas from floods and storms, and supplying food – as well as important cultural and other benefits. For the last several decades, multiple and interacting pressures from diverse human activities have been threatening the services and benefits humans accrue from these systems worldwide. While concerns about ocean sustainability traditionally overshadow concerns about social equity (Stanton, 2012; Halpern et al., 2013; Boonstra et al., 2015), access to ocean benefits and resources, as well as exposure to harms is distributed inequitably, and climate change may further exacerbate such inequalities (Burke et al., 2015; Hallegatte et al., 2015; Sovacool et al., 2015; Diffenbaugh and Burke, 2019). Improving ocean and fisheries governance, could help improve the sustainability and sharing of fisheries resources among countries and reduce their climate risks as well as help support long-term ecological, economic, and social sustainability objectives (i.e., support countries in meeting the Sustainable Development Goals). However, the development of policies that would support such action is challenged by the uncertainties associated with global environmental and socioeconomic change, the legislative mechanisms underlying such change and the complex interplay across sectors.

Scenarios are considered a useful tool for planning in the face of such complexity and uncertainty. As part of a new climate scenario framework, climate scientists, economists and energy systems modellers have developed a range of “pathways” that examine how global society, demographics and economics might change over the next century (Moss et al., 2010; Kriegler et al., 2014; O’Neill et al., 2014; van Vuuren et al., 2014; O’Neill et al., 2017). These so-called Shared Socioeconomic Pathways (SSPs) (van Vuuren et al., 2014; O’Neill et al., 2013, 2017; Riahi et al., 2017) provide a standardized, internationally recognized, concept that allows for the exploration of five distinct futures based on contrasting societal choices - including a range of demographic, political, economic, legal, social, environmental and technological drivers. They describe futures that revolve around how human societies might evolve over the coming century, based on two challenge types: challenges that future societal choices may present to adaptation, and challenges they may present to mitigation (Rothman et al., 2014) (Figure 6.1). The SSPs originally were designed to be used alongside the Representative Concentration Pathways (RCPs) to analyse feedbacks between climate change and socioeconomic factors. They were also meant to be used, explored, and extended beyond their original scope to other sectors and geographic scales (O'Neill, 2017). The scenarios are not meant to be or serve as predictions; but by describing optimistic and challenging possible, plausible, and credible futures they can help guide strategy. By investigating possible ‘alternate worlds’ and the decisions leading to representative outcomes, the SSP scenario analysis helps address uncertainty and supports decision-makers explore and prepare for the consequences of contrasting future alternatives. Such scenarios can also assist in learning and assessing how the environment responds to human activities (Zandersen et al., 2019), support our understanding of the extent to which societal developments can influence the nature and severity of climate change risks and response options (Frame et al. 2018), and help adapt to altered environmental conditions. Global population projections (Jones and O’Neill, 2016; Samir and Lutz, 2017) and GDP projections (Dellink et al., 2017), consistent with the Shared Socioeconomic Pathways framework, have been developed to support the exploration of alternate futures.

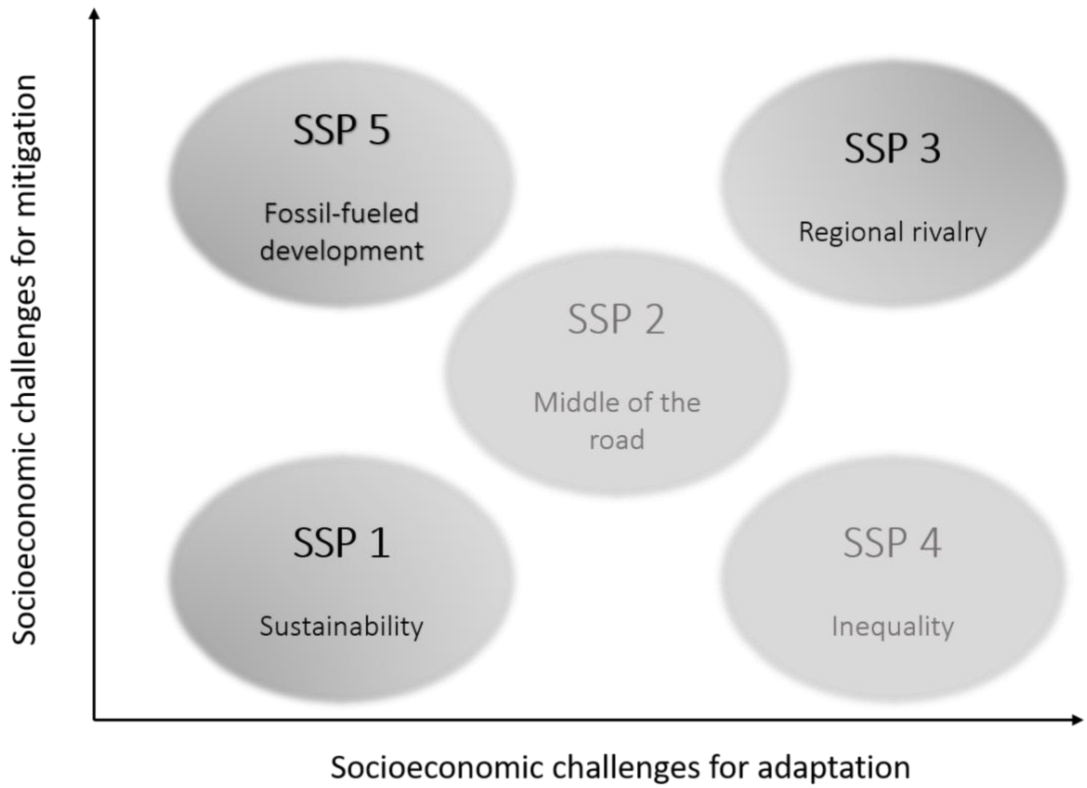

Figure 6.1. The Shared Socioeconomic Pathways (SSP) framework, representing each of the five SSPs within a space of low to high socio-economic challenges for adaptation and mitigation. SSPs that were used in this IAM (SSP1, SSP3 and SSP5) are depicted in the bold dark font.

Detailed narratives of the storylines for each SSP have been published (O'Neill et al., 2017). A number of key defining features are briefly highlighted:

- SSP1 (Sustainability – Taking the Green Road) consists of a world focused on sustainable growth and equality.
- SSP2 (Middle of the Road) imagines a world where trends broadly follow current and historical patterns.
- SSP3 (Regional Rivalry – A Rocky Road) exposes a world fragmented by resurgent nationalism, concerns about competitiveness and security, as well as regional conflicts.
- SSP4 (Inequality - a Road Divided) describes a world of ever-increasing inequality; while
- SSP5 (Fossil-fueled Development – Taking the Highway) portrays a world of rapid technological progress and development of human capital, as well as characterised by unconstrained growth in economic output and energy use.

In terms of adaptation and mitigation challenges, SSP3 and SSP4, for instance, are characterised by high challenges to adaptation due to slow development, low investments in human capital and technology, increased inequality, as well as weak institutions. Low challenges to adaptation due to rapid development, high investments in human capital, and reduced societal inequalities, on the other hand, characterise the world's futures under SSP1 and SSP5.

While global in scope, the SSP framework has found broad scale application across a range of different countries and sectors. Country-relevant scenarios have included initiatives in New Zealand (Frame et al., 2018), the Barents Sea (Nilsson et al., 2017) to understand climate change risks, and spatially-explicit population projections along the Mediterranean coastal zone (Reimann et al., 2017). Examples of sector-specific applications include, for instance, urbanisation (Jiang and O'Neill, 2017), freshwater utilisation (Mouratiadou et al., 2016; Graham et al., 2018), air pollution (Rao et al., 2017), and civil conflict (Hegre et al., 2016). While SSP applications have been wide ranging, most have focused on terrestrial-based considerations, including land-use changes (He et al., 2017; Popp et al., 2017), energy demand (Bauer et al., 2017), agriculture (Palazzo et al., 2017), and livestock production (Lassaletta et al., 2019). Notable exceptions include Maury et al. (2017), who explore five contrasting Oceanic System Pathways (OSPs) Zandersen et al. (2019) who included fisheries in their consideration of future development in the Baltic Sea region, and the underway CERES initiative (Pinnegar et al., 2018) that explores socio-political scenarios for the fishery and aquaculture sectors in Europe.

The aim of this portion of the overall IAM study was to develop broad narratives for the future of oceans and fisheries under each of the three SSPs of interest - SSP1, SSP3 and SSP5 - and expand on existing scenario-based work to identify relevant quantitative drivers of global fisheries and parameterise them for implementation in DIVERSE.

Methods

For each of the three SSPs under consideration, we developed a general scenario narrative to contextualise contrasting futures for oceans and fisheries. Information to develop the framework of the storylines were drawn from the diverse expertise of colleagues that are part of the Nippon Foundation-the University of British Columbia Nereus Program, as well as the literature on topics including, but not limited to, the current status of marine ecosystems and fisheries; fisheries management and governance frameworks; drivers of change and projected impacts; social justice as an orienting principle in achieving sustainability and equity; and, socio-ecological opportunities and challenges presented by different development paths.

In accordance with the globally applicable SSPs (O'Neill et al., 2017) the study assumed for economic growth and the world's population to follow established trends. For each scenario, the International Institute for Applied Systems Analysis (IIASA) and the National Center for Atmospheric Research (NCAR) have developed a set of population growth and urbanisation projections. For GDP, three alternative interpretations of the SSPs by the teams from the Organization for Economic Co-operation and Development (OECD), the International Institute for Applied Systems Analysis (IIASA) and the Potsdam Institute for Climate Impact Research (PIK) exist. The GDP projections are based on harmonized assumptions for the interpretation of the SSP storylines in terms of the main drivers of economic growth, and were developed by Dellink et al. (2017).

All countries, which are known to have operating fishing vessels were grouped into four major income groups: Low Income Countries (LIC), Lower-middle Income Countries (LMIC), Middle Income Countries (MIC), and High Income Countries (HIC), informed by their Human Development Index (UNDP 2019) and the way the World Bank classifies country and lending groups (World Bank 2019) (see Figure 6.2). For each income group and each of the three defined Shared Socioeconomic Pathways (SSP), fishing effort was projected using the effort dynamic model. Model-relevant and representative quantitative indicators were derived for each SSP and each income group based on the drafted narratives. Fishing-relevant indicators included: operating and capital cost of fishing, fishing subsidies, and catchability increase rate. For example, under SSP1, high fuel prices led to increases in the cost of fishing in the future. In addition, in accordance with the promotion and implementation of measures to support effective sustainable development, fishing nations support the elimination of harmful subsidies. This results in the significant reduction of subventions in LIC, LMIC, MIC (countries that strongly depend on fishing in areas within national jurisdiction for income, employment, food security, and livelihoods), and their complete elimination in HIC by 2050.

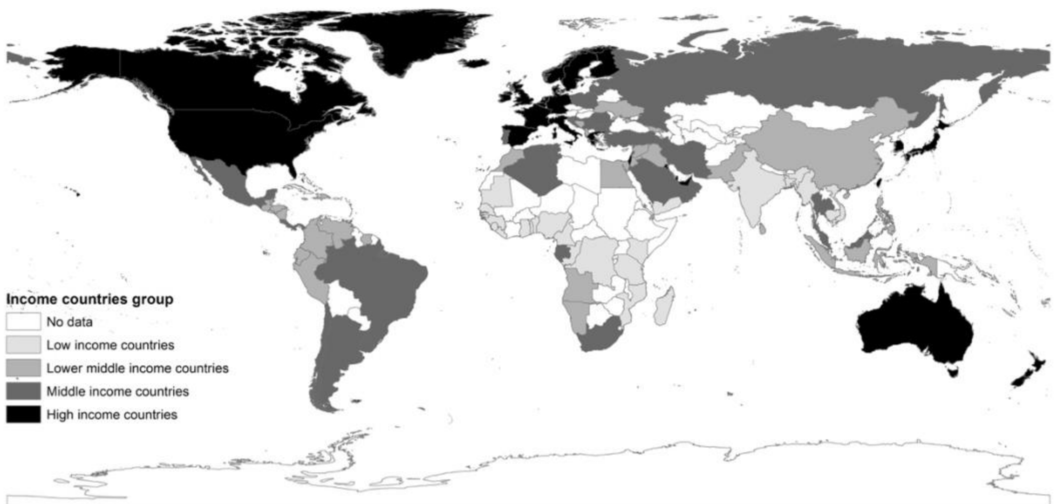

Figure 6.2 - Map of world nations according to four income level categories (Low, Lower-middle, Middle and High) . Countries in white are land-locked and were not included in the scenario analysis in this study.

Scenario storylines

SSP 1 - Sustainability: Charting the blue course

*Under **SSP1**, sustainability becomes a key leitmotiv, with actions at national and international levels fostering more inclusive development and emphasizing environmental stewardship. Consequently, management of the global commons improves, and the current emphasis on economic growth is replaced by a shift towards the achievement of the Sustainable Development Goals and general support for human well-being. Inequalities within and across countries are reduced.* (modified from O'Neill et al. 2017 and Riahi et al. 2017).

Economy

To support sustainable fisheries (Sakai et al., 2019), and in line with international commitments, including the Sustainable Development Goals, fishing nations agree to "prohibit certain forms of fisheries subsidies that contribute to overcapacity and overfishing, eliminate subsidies that contribute to illegal, unreported and unregulated fishing, and refrain from introducing new such subsidies" (Target SDG 14.6). This results in the rapid phasing out of harmful fishing subsidies in all income countries worldwide, with the concurrent development of clear and transparent goals for fishery performance that explicitly incorporate ecological sustainability, economic dynamics as well as principles of social equity (Gutierrez et al., 2011). In line with SDG 14.6 and the Doha mandate that "appropriate and effective special and differential treatment for developing and least-developed members should be an integral part of the fisheries subsidies negotiations, taking into account the importance of this sector to development priorities, poverty reduction and livelihood and food security concerns" (WTO 2005), funding by governments that had thus far been committed to harmful subsidies, is diverted to support sustainable and equitable fishing practices, capacity building for better management and governance, alternative livelihoods, etc., with a particular focus on low income countries and small island developing states (Grynberg, 2003; Cisneros-Montemayor et al., 2016). Bottom-up commitments, where countries voluntarily declare a number of harmful subsidies to be eliminated within a certain period, are encouraged (Ye & Gutierrez, 2017). In addition, given that the EEZ of many developed countries may not be able to support their domestic demand - despite sustainable fishing practices and efforts - access agreements with other countries are negotiated mindful of local food and nutritional security and via the establishment of equitable payments for ecosystem services (PES) mechanisms (Naeem et al., 2015; Salzman et al., 2018). Moreover, trade rules and restrictions are used to incentivize sustainable fisheries where international trade is greatly targeted for economic benefits, including import controls from overfished stocks, as prompted by Article XX of the General Agreement on Tariffs and Trade's 'measures relating to the conservation of exhaustible natural resources' (Ye & Gutierrez, 2017). Together with high fuel prices – due to stringent taxes and regulations for cleaner energy – these decisions limit the profitability of large-scale industrial fishing effort, especially on the high seas (Sumaila et al., 2010a; Sumaila et al., 2010b), which results in a dramatic decline of (and investment in) fishing effort, and improves the economic viability of small-scale fisheries (Schuhbauer and Sumaila, 2016). To promote technology and knowledge transfer as targeted under the Sustainable Development Goals (Target 14.a), developed fishing nations focus on a number of initiatives:

a) Advanced aquaculture practices to improve production and reduce disease as well as enhanced post-harvest processing methods to reduce waste, support market access and obtain better returns;
b) Landing of fish in LDCs to generate local revenue and employment; and
c) Capacity building for improved resource management, conservation and governance including through strengthening of enforcement mechanisms – monitoring, control, and surveillance (Pascoe, 2012; World Bank, 2017).

Realising that establishing social sustainability is critical to ecological sustainability (Raworth, 2017), countries worldwide implement economic and social (in addition to environmental) reforms in support of equality, freedom and a healthy standard of living through investments, for instance, in welfare, education, infrastructure, and health. Consequently, life expectancy rapidly increases, fertility declines, especially in high fertility countries, and education expands in line with the education goals spelled out in the SDGs (Lutz et al., 2018).

Consumers are aware of the power of their choices and their role in achieving social and environmental sustainability (Kittinger et al., 2017; Thomas Travaille et al., 2019). As a result, users demand transparency, accuracy, independence, standardization, and cost-effectiveness in sustainable seafood sourcing and responsible labour conditions, leading to the growth of comprehensive and reliable seafood certification schemes as well as value-chain traceability programmes (with prices reflecting such requirements) (Parkes et al., 2010; Bailey et al., 2016a; Gutierrez et al., 2016; McClenachan et al., 2016; Del Giudice et al., 2018). In support of such initiatives and to promote equitable market access, interoperability among actors, as well as providing a basis for more efficient and consistent regulatory practices along the value chain, industry develop voluntary, pre-competitive standards (Askew, 2019). As part of this movement, greater transparency in monitoring of financial investments in fisheries, fishing agreements, and associated data is also achieved (for example, through enterprises such as the Fisheries Transparency Initiative (FiTI) - http://fisheriestransparency.org/). More stable catches and improved earnings as a result of effective measures to support good economic performance of the fleets, adequate sales infrastructure and support contribute to livelihoods as well as both food and nutritional security (Tolvanen et al., 2019).

Management and Governance

The economic and political climate of the day leads to and supports strong, representative and effective institutions, the abolition of corruption and transparent decision making in most countries. Fishing nations take a strong collective approach to resource management and fisheries development, supporting the effective operation of regional institutions in their provision of technical and policy advice, and establishing initiatives in fisheries cooperation that support sustainability as well as social needs while serving global interests (Hanich et al., 2010). Institutional, management, and governance capacities are further enhanced through the delivery and financing of targeted training, technology transfer and equipment (Ye & Gutierrez, 2017). Fisheries on highly-migratory and straddling stocks are managed collaboratively via an evidence-based, adaptive quota system, such as a vessel day scheme (Havice, 2013; Bernadett, 2014; Clark, 2019) that is allocated in an equitable manner among fishing nations, allowing parties to generate substantial revenue growth from the effective and sustainable management of their marine resources. Policies in place not only support the strong economic performance of fishing fleets, but facilitate the supply of high-quality fish from commercial fleets of all gear types to local markets in low income and small island developing states (Tolvanen et al. 2019).

Civil society engagement is high and constructive. Social cohesion is high. Partnerships between Non-Governmental Organizations (NGOs), intergovernmental agencies and academia to advance development knowledge and inform effective conservation and sustainable use are strong, and supported by direct collaboration with state institutions. Governments and relevant stakeholders successfully negotiate and cooperate to improve institutional capacity, data collection and research programs, to effectively implement - based on scientific evidence - adaptive programs to achieve the SDGs. Such measures include the effective implementation and enforcement of the Port State Measures Agreement (PSMA); and an international legally binding instrument (ILBI) to support conservation and the sustainable use of marine biodiversity beyond national jurisdiction that considers the equitable distribution of ocean benefits (Blasiak and Yagi, 2016). This ILBI strengthens Regional Fisheries Management Organizations' (RFMOs) mandate and their efficacy, leading to the successful implementation of precautionary and integrated ecosystem-based management approaches (Halpern et al., 2010; Worm and Branch, 2012; Pons et al., 2018). Such strategies include stringent bycatch rules; effective mechanisms to control/manage FAD deployments, FAD sets, and FAD designs to reduce pollution and entanglement; as well as marine protected areas. Most importantly, all policies are upheld by strong compliance and enforcement measures, such as a ban on all transshipment activities (Ewell et al., 2017; Miller et al., 2018). International governance structures are strongly regulated and effective. Nations and the private sector put in place measures to document and monitor commitments to social responsibility and environmental sustainability in the seafood sector.

Technological developments allow for strong monitoring, control and surveillance (MCS) (Cabral et al., 2018; Klaudija et al., 2019) with international cooperation facilitating a strong global patrol surveillance capacity (Petrossian, 2015). In practice, MCS is enacted through effectual electronic monitoring and reporting of catches, with additional layers of control provided by remote tracking of all fishing activities (Dunn et al., 2018; Kroodsma et al., 2018; Longepe et al., 2018). In combination with 100% observer coverage, such initiatives support the rigorous transparency and traceability requirements for sustainability as well as the social responsibility of dependable certification schemes.

Environment

Coordinated efforts undertaken among the above-mentioned institutions lead to the implementation of a global network of effective, representative and connected conservation areas identified according to scientific criteria (Burgess et al., 2014; Costello and Connor, 2019). This network is composed of strongly enforced no-take areas that protect unique habitats - including deep sea environments (Metaxas and Snelgrove, 2018) and ecologically or biologically significant areas (EBSAs) (Costello and Ballantine, 2015; Dunstan et al., 2016), such as locations known for their high biological productivity or biodiversity (Key Biodiversity Areas – KBA) - as well as dynamic closures that support economically viable fisheries and meet mandated conservation objectives in the face of changing ocean conditions (Hazen et al., 2018). Such networks are also designated according to clearly and objectively defined ecological, social and economic indicators to meet national and international targets (Spalding et al., 2016); including SDGs. Effective marine resource management and conservation action combined with the elimination of harmful subsidies result in the recovery of biodiversity.

SSP3 – Regional rivalry — Rough Seas ahead

Countries become increasingly nationalistic, primarily concerned with protecting their own economy and interests, with little regard for cumulative or synergistic environmental impacts. Powerful and developing nations both see the rise of authoritarian forms of government, extremism and discriminatory political movements. Support for sustainable development, minority groups, and human rights is low. (Modified from O'Neill 2017 and Riahi et al. 2017).

Economy

To satisfy an increase in domestic seafood consumption, in part due to expanding population growth, especially in developing countries, and additionally motivated by the desire to reduce trade dependency (van Vuuren et al., 2014), fishing expands. Substantial urban and rural growth in coastal areas in Africa, Asia and Latin America in particular (Jones and O'Neill, 2016) are associated with increasing fishing effort for subsistence as well as livelihood purposes, with concomitant pressure on coastal and offshore resources. In high-income nations, policies strongly support national interests and protect the fishing sector (Anon, 2019) through the heavy subsidization of domestic fleets (Smith, 2019; Sumaila et al., 2019). Measures, such as vessel financing, tax breaks and loan guarantees, result in an increase in fleet size and fishing capacity - especially on the high seas as stocks in national EEZs are not able to satisfy domestic demand (Swartz et al., 2010; Thurstan and Roberts, 2014; Guillen et al., 2019; NOAA, 2019), despite low population growth (Samir and Lutz, 2017; Wear and Prestemon, 2019). These developments, however, are not associated with notable changes in fishing efficiency due to low investments in technological development (O'Neill et al., 2017). Lowered fishing costs contribute to this tendency, especially on the high seas, partly due to the use of forced or underpaid labour on vessels and in processing plants (Sala et al., 2018; Tickler et al., 2018a). The emphasis is on security at the expense of international development (Pamment, 2018; Crane and Maguire, 2017).

The increased consolidation of industries including the fishing sector (Haas et al., 2016; Bodwitch, 2017; Edvardsson et al., 2018), with few beneficiaries located in developing nations, further ensures that high-income countries continue to assert and expand their influence and dominance (Anticamara et al., 2011; McCauley et al., 2018; Tickler et al., 2018b). With global governance regimes not accounting for issues of fair distribution and equity, as well as high tariffs imposed by high and middle-income countries on their products (Rosenberg, 2018), many countries struggle to maintain living standards for growing populations and see serious food security concerns and extreme poverty levels rising. Wealthy nations exploit their position of power, and the socio-economic struggles of developing countries, by negotiating agreements for seafood products they cannot source domestically that grossly undervalue social and environmental externalities and for which developing countries gain relatively small shares of economic value in return (Moran, 2014; Yu, 2014; Antonova, 2016). Inequality among (and within) nations grows rapidly. This situation is exacerbated by high population growth in developing nations, and the inability of coastal fisheries to support increased seafood demand. Social cohesion is low. Even within developed nations, governance mechanisms undermine the rights to consultation and access of a number of stakeholders, particularly Indigenous Peoples (Klain et al., 2014; Gerwing and Cox, 2017), widening the gap between rich and poor (Manduca, 2018; Manduca, 2019) and contributing to increases in social insecurity and often conflict.

As a result of nationally focused initiatives as well as policies, and high inequality, developing countries experience a stall in educational expansion as well as continued high fertility and high mortality (Lutz et al., 2018).

Management and governance

The absence of legal frameworks, as well as a dearth in capacity and compliance tools necessary for enforcement severely undermines fisheries management in developing countries. Protection of the marine environment is not a priority and existing environmental policies are ineffective. A significant decline in Official Development Assistance (ODA) allocations destined to support sustainable and equitable resource management, further exacerbate this trend (Blasiak and Wabnitz, 2018). In addition, residual ODA increasingly is used as a political tool and bargaining chip, leveraging the status of wealthy nations to advance their interests on the national and international stage.

In developed nations, to boost domestic seafood production and reduce seafood trade deficits (Kite-Powell et al., 2013), legislation is put in place to abolish annual catch limits on numerous fish species, roll back requirements for recovering overfished stocks (D'Angelo and Kaufman, 2018) and open up marine protected areas to commercial fishing (D'Angelo, 2018).

In a world focused on domestic issues, increasing mistrust among participating members of global management bodies (including Regional Fisheries Management Organisations), corruption, as well as lack of stakeholder participation and political will (Pomeroy et al., 2016) result in strong divisions within and across the organisations, eroding their mandate and effectiveness. The clear lack of separation between politics and science, opaque decision-making, as well as the absence of clear terms of reference, effective global standards, and monitoring and enforcement mechanisms also lead to the limited success of international treaties and agreements (Vidal, 2012; Pew, 2019). Weakened international institutions lead to a lack of and capacity for enforcement of policies in areas beyond national jurisdiction. As both a result of increases in fishing capacity (Smith, 2019) and shortage of effective monitoring, control and surveillance (MCS), levels of illegal, unreported and unregulated (IUU) fishing increase. The latter occurs in part through encroachment by powerful nations' high seas fleets on other nations' EEZ, especially those of developing nations that lack the capacity and financial means to effectively enforce sovereignty over their stocks, resulting in considerable losses in revenue for those countries (Belhabib et al., 2012; Petrossian, 2015; Daniels et al., 2016). However, a number of Small Island Developing States with large EEZ, particularly in the Pacific, strengthen their regional solidarity and by applying the capacity and lessons learned from decades of fisheries operations policy development and implementation, close off high seas pockets to fishing by other nations to further their own benefits (Gilman, 2012; WCPFC, 2016; Gullett and Hanich, 2018).

There is an overall rise in the loss of research capacity, an overall decline in and support for evidence-based decision-making (Smart, 2016; Anon et al, 2017) and strict restrictions concerning communication of findings by scientists to the media (Bailey et al., 2016b; Evans Ogden, 2016). Poor traceability exacerbates issues of inequity, further concentrating wealth accrued from fisheries development in the hands of a few nations. As inequalities worsen, volatility, antagonism and conflict increase (Spijkers et al., 2018; Spijkers et al., 2019).

Environment

With high population growth rates, low urbanization levels, increasing poverty, and seafood representing the cheapest and most frequently consumed animal-source food in low-income countries, fish stocks continue to decline (Jentoft et al., 2010). This is compounded by increased fishing effort exerted on stocks on the high seas by the subsidized fleets of highly industrialized nations (Sala et al., 2018), exacerbating degradation of marine habitats and the decline of highly migratory and straddling stocks, with impacts extending into countries' EEZ (Popova et al., 2019). Consequently, biodiversity is increasingly under threat (O'Hara et al., 2019) and the number of red listed species increase and/or their status deteriorates (including culturally important species). Rising uncontrolled, unmonitored and un-selective fishing effort quickly leads to declining catch per unit effort and systematic overfishing of the high seas (Martini and Innes, 2018). These declines disproportionately affect LDCs, which depend on fish for food and nutritional security (Golden et al., 2016; Pauly, 2019) and, in the case of a number of Small Island Developing States, rely on large exports of pelagic species as an important source of foreign exchange and employment (Gillett, 2010; Bell et al., 2013; Johnson et al., 2017).

Fishing practices are focused on maximizing profit (Sethi et al., 2010), at the expense of the environment (i.e., extensive use of destructive fishing gears, high rates of bycatch) (Smith 2019). Investment in research and related data collection to set quotas, monitor stocks and the environment declines.

SSP 5: Fossil-Fuelled Development – The Ocean Superhighway

The promotion of competitive markets and investment in innovation lead to rapid technological progress and increasingly integrated global markets. Investments in health, education, and institutions reduce inequalities among countries. Progress in economic and social development is mainly achieved via the exploitation of fossil fuel resources and the adoption of resource and energy intensive lifestyles. While local environmental problems are successfully managed, faith is increasingly placed in the ability to address larger ecological challenges through tech fixes, including geo-engineering. (modified from O'Neill et al. 2017 and Riahi et al. 2017).

Economy

Strong emphasis on high economic development worldwide, so that all countries may enjoy the benefits of industrialization and capitalism, leads to a substantial increase in energy demand (Sadorsky, 2010; Wolfram et al., 2012) – rapid technological progress and the development of human and social capital, as well as social infrastructure, are seen as the path to sustainable development (Diaconu & Popescu, 2016; Kriegler et al., 2017; O'Neill et al., 2017). International cooperation is strong, with interventions focused on removing institutional barriers to the participation of disadvantaged population groups (Kok et al., 2019) and economic incentives supporting responsible innovation and competitive markets. Developing countries boost their economic growth through effective trade openness, particularly by productively controlling their import levels in a strongly globalised world (Zahonogo, 2016). Seafood trade is driven by fish obtained from the cheapest sources, resulting in the expansion of aquaculture production and trade for re-processing in countries with cheap labour force (Natale et al., 2015), and facilitating the economic participation of disadvantaged population groups. Trade rules and restrictions are primarily implemented to incentivize growth of developing economies and to ensure that trade does not occur at a disadvantage in seafood quality and nutrition to their communities (Asche et al., 2014). Economic incentives are directed at innovative public-private partnerships that develop cost-effective and high production aquaculture systems - often including the culture of genetically improved stocks (Gjedrem et al., 2012; Luo et al., 2014) and radical engineering to farm in offshore environments (Shainee et al., 2012; Holm et al., 2017). Recognizing the benefits that accrue from fostering overall development worldwide, high-income countries invest in fisheries management in LDCs, including through targeted international aid allocations and technology transfer, for example (Morgera & Ntona, 2018). Specific activities include service contracts, turnkey operations, co-production agreements, and notably, transfer of skills and capacity building that can be facilitated through the creation of accountable and well-regulated joint ventures (Munro, 1989; Rasheed et al., 2011). Under such agreements, joint venture vessels may enjoy preferential access to the domestic fishing zone, and receive certain tax concessions.

Conventional access agreements with other countries are negotiated mindful of local food and nutritional security and via the establishment of equitable payments for ecosystem services (PES) mechanisms (Naeem et al., 2015; Salzman et al., 2018). Activities in LDCs seek to improve living conditions - by, for instance, alleviating poverty and promoting education - and substantially enhance social and human capital. Technological development and innovation feature prominently and are actively supported, as they are seen as a crucial mechanism to achieve these goals. Governments and businesses both invest in the development and implementation of new products and processes, that do good and avoid harm (Voegtlin & Scherer 2017). Driven by the successes of this rapid fossil fuel-based growth, poverty levels drop, and wealth among developed and developing countries becomes more evenly distributed. Rapid development leads to the convergence of long-term global average income levels among countries (Rodrik, 2016; Dellink et al., 2017) - a number of middle-income countries achieve developed status by 2030 further strengthening the global economy. As a consequence, consumption and demand for seafood also increases (World Bank, 2013; FAO, 2014).

Vertical integration leads to the consolidation of the fishing sector and activities being controlled by a few large corporations. As targeted under the Sustainable Development Goals, and supported by rapid economic growth, developed nations promote technology transfer supporting LDCs' fleet expansion on the high seas. The latter promotes employment in the fishing sector and also allows developing countries to meet their rising seafood demand.

Management and governance

Emphasis on rapid fossil-fuelled based economic development and short-term gains leads to increased investment, participation and influence in fisheries activities by emerging economies, including on the high seas. High quality of governance is thought to be attained through a strong focus on businesses (Kok et al., 2019). The targeting of highly migratory and straddling stocks in areas beyond national jurisdiction is seen as a means to meet rising demand for and consumption of seafood products by an increasing middle-class.

The monitoring of fishing impacts on ecosystem health remains limited and environmental regulations are relaxed. Apart from at local scales, overall, little attention is paid to impacts of fishing or other human activities on biodiversity, or species not associated with direct benefits, causing increased ecological, social and economic risks. Currently, developed countries and emerging economies like China and India focus the application of fishing management activities on profit maximisation. RFMOs and other management organisations focus on single species stock assessments, or indicator-based management plans with a similar emphasis, and provisioning ecosystem services. Mechanisms to enhance developing countries' institutional and governance capacities are implemented by developed nations through the delivery and financing of training, as well as technology and equipment transfer (Ye & Gutierrez 2017). This strategy is mainly targeted at improving countries' general and governance-specific capacity as well as production ability rather than the sustainable management of their fisheries. Advances in technology, such as deployment of vessel monitoring systems, access to and cost of satellite data as well as electronic monitoring, however, provide robust fisheries data that dramatically enhance monitoring, control and surveillance capabilities, reduce Illegal, Unreported and Unregulated fishing, and improve accountability (Bartholomew et al., 2018; Emery et al., 2018; Jablonicky et al., 2018; Longépé et al., 2018). These systems are complemented by the use of unmanned public drones for marine surveillance (Kopaska, 2014). These advances demand the development of partnerships between fishing companies, other private actors, NGOs, and states to collect and exchange information pertinent to monitoring, control and surveillance of fishing activities (Bush et al., 2017; Toonen & Bush, 2018).

Environment

High fossil fuel use results in elevated CO2 emissions, leading to a dramatic rise in ocean temperatures and worsening effects of ocean acidification and deoxygenation, particularly in coastal areas. Geo-engineering solutions are implemented reactively to attempt to mitigate local impacts through large-scale ventilation and oxygenation of the water column, for instance. However, the effectiveness and wider social-ecological ramifications of such technological activities remain highly uncertain.

Technical efforts and investments target the development of large, autonomous, roaming, robotic aquaculture cages capable of high production levels and of withstanding the environmental loads due to waves, wind and current of offshore environments (Shainee et al., 2012; Holm et al., 2017). Weight is placed on the development of innovations to maximise productivity and profits. In the aquaculture industry this includes the use of genetically modified organisms characterised by high feed-conversion efficiencies and resistant to parasites and disease (Abdelrahman et al., 2017; Elaswad & Dunham, 2018); control-engineering principles to fish production (Føre et al., 2018); robots capable of examining and repairing offshore cages; and robotic cargo ships transporting fish from offshore facilities to market. In fisheries, satellite and cellular modems transmit data from fishing vessels to seafood buyers wirelessly in close to real time. Little emphasis is given to regulations regarding the deployment of such technologies and associated risks. Large proportions of wild fish catches are converted to fishmeal and fish oil to support a growing aquaculture sector, with algae oils, genetically modified omega-3 enriched crops and other advances playing an increasing role (Napier et al., 2019; Sprague et al., 2017). Low fuel costs and advanced technology make fishing on the high seas accessible and profitable, with countries exploiting available stocks further and deeper. Larger, technologically advanced and highly efficient vessels controlled by a strong industrial fishing lobby allow for a dramatic increase in fishing effort. Drifting oceanic FADs - which increase the efficiency of purse seine fishing - equipped with GPS, advanced acoustic technology (Dagorn et al., 2014) and which can be remotely operated are common. Deployment of such technology is responsible for a dramatic increase in tuna fishing (Tidd et al., 2016) and revenue for Small Island Developing States. Such advances also generally result in a further increase of activities on the high seas, including the exploration of marine genetic resources and seabed mining. As a consequence of poor monitoring and weak science-based management, the abundance of most targeted fish species declines with substantive knock-on effects on stocks in countries' EEZ and associated catches (Popova et al., 2019). Reactive temporal and spatial management measures are implemented after severe stock declines, but exploitation resumes quickly after the first signs of stock recovery (Zandersen et al., 2019). Biodiversity conservation is considered a low priority with the use of highly effective fishing gear contributing to habitat destruction, accelerated rates of species loss, and the overall decline in the productivity of marine ecosystems.

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A summary of the key scenario elements that are relevant to DIVERSE are summarized in Table 6.1

Table 6.1 -Broadly applicable and fisheries-specific SSP elements (indicators) that were used in the IAM and quantitatively adjusted in the effort dynamic model, specifically, respectively, under different Shared Socioeconomic Pathways (SSPs). HIC = High income countries; LIC = Low income countries; MIC = Middle income countries.

SSP element	SSP1	SSP3	SSP5
GDP per capita (2100) (see figure 6.3)	Medium	Low	High
Population level (2100) (See figure 6.4)	Low	High	Medium
Urban to rural population (See figure 6.5)	High	Low	Low
Fossil fuel costs (Calvin et al. 2017)	High	Med	Low
Ex-vessel price of exploited marine species	unchanged	Low (because of increase in supply): decrease by 25% in 2050	High: increase by 25% in 2050
Operating and capital cost of fishing	High: increase by 50% in 2050	Low: decrease by 25% in 2050	Low: decrease by 50% in 2050
Fishing subsidies	None: remove for all countries	High: increase by 25% for LIC; 50% for MIC and HIC	High: increase by 25% for all income groups
Catchability increase rate	Unchanged. High fishing selectivity	Unchanged. Low fishing selectivity.	Increase by 50% for HIC and MIC. High fishing selectivity.
Fisheries management target	Harvest control rule that limits fishing to conserve threatened species (avoid species biomass to go below 20% B_0)	Harvest control rule that limits fishing to maximize catches.	Harvest control rule that limits fishing to maximize catches.

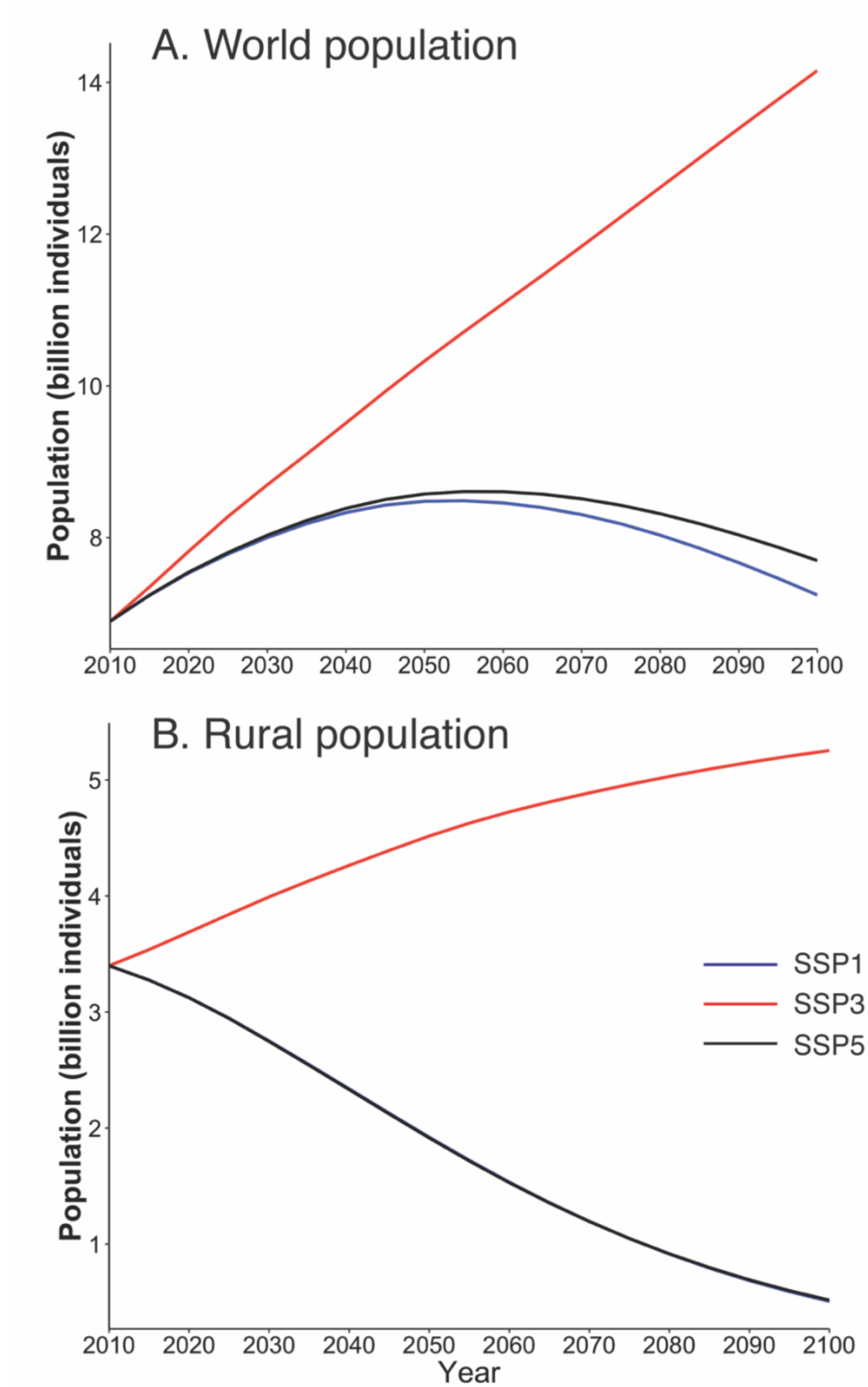

Figure 6.3. Projected world total population (A) and rural population (B) under Shared Socioeconomic Pathway (SSP)1, SSP3 and SSP5. The projected population is based on the NCAR model.

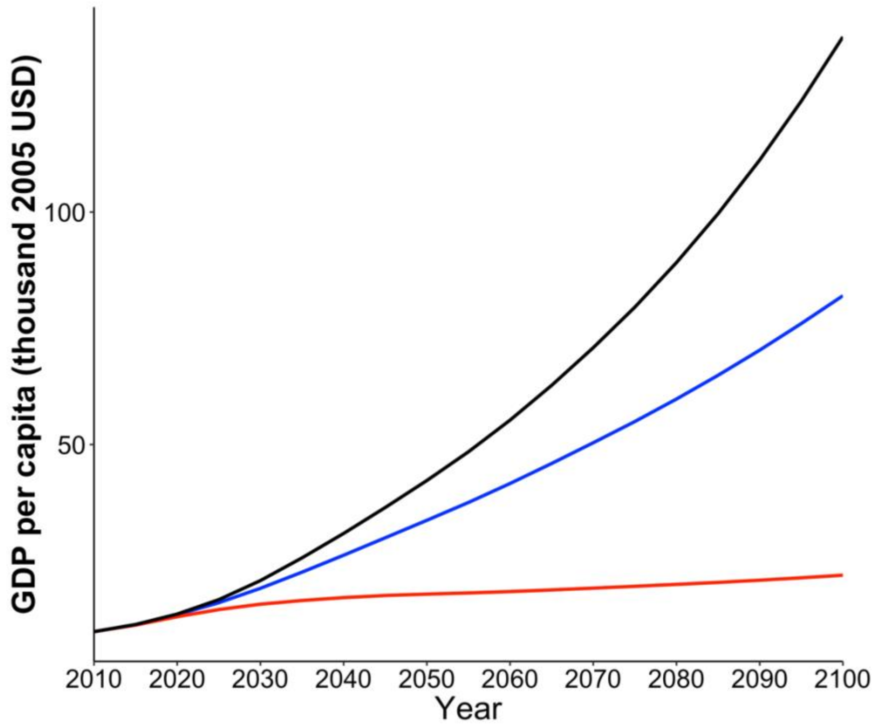

Figure 6.4. Projected Gross Domestic Product (GDP) per capita of the world under three Shared Socioeconomic Pathways (SSP): SSP1 (blue), SSP3 (red) and SSP5 (black).

Scenario projections for subsistence catches

In DIVERSE, subsistence catch is not modelled through the effort dynamic model (Chapter 3). Therefore, we developed an empirical model to project future changes in subsistence catches based on future rural population levels, seafood consumption rates, economic development, and the abundance of fisheries resources. The hypothesis is that as rural population size increases, demand for subsistence catch will also increase. Also, if per capita seafood consumption increases, for instance through behavioural changes, subsistence catch will increase. The relationship between subsistence catches and economic development may be two-fold. On the one hand, as society grows economically, access to fisheries resources by rural communities may increase, for example through improvement in technology and institutional access to resources, resulting in increases in subsistence catches. On the other hand, increases in economic development may reduce the dependence on wild food, resulting in a decrease in subsistence catches. In addition, resource abundance would likely be positively related to subsistence catches.

We applied a generalised least square model (GLS) with estimated subsistence catches by country from 1971 to 2005 as the dependent variable, while rural population size, per capita seafood consumption, world's ranking of GDP per capita and estimated marine resource biomass were the independent variables (Table 6.2). We used a non-parametric representation of economic development by country because of the co-variation between seafood consumption, rural population size and GDP; GDP per capita ranking classes were used to represent economic development relative to world economic growth. Total marine resource biomass by country is estimated from the effort dynamic model (Chapter 3).

Table 6.2. Dependent and independent variables for the generalized least square model to predict subsistence catches.

Variables	Transformation	Unit	Data source
Subsistence catches by country (*SCatch*)	Logarithmic	Tonnes per year	*Sea Around Us* global fisheries catch reconstruction database
Rural population size (*ruralpopulation*)	Logarithmic	Number of individuals	World Bank
Per capita seafood consumption	Logarithmic	kg per individual	Food and Agriculture Organization
Marine resource biomass (*biomass*)	Logarithmic	Tonnes	Effort dynamic model (Chapter 3)
Gross Domestic Product per capita (*gdppc*)	Quantile with 4 classes (i)	Year 2005 USD	Penn World Table

We log-transformed the total subsistence catch, GDP per capita and rural population size so that they follow the normal distribution. Following this step, the structure of the GLS model becomes:

$$\log(SCatch) = a \cdot \log(ruralpopulation) + b \cdot \log(\mathrm{Q}) + \mathrm{c} \cdot \log(\mathrm{biomass}) + \sum_{i=1}^{4} \mathrm{d}_i \cdot \mathrm{factor}(gdppc_i) + corAR(\sim 1|year) + \varepsilon \quad \text{.......(6.1)}$$

We fitted the model using the function *gls* in the package nlme, and we accounted for temporal autocorrelation over consecutive years (Table 6.3).

Table 6.3. Test statistics of the model to predict subsistence catches.

	Estimated	Standard Error	P-value
Intercept	-5.425	0.158	<0.01
Rural population (*ruralpopulation*, log-transformed)	0.863	0.009	<0.01
Per capital seafood consumption (*Q*)	0.809	0.022	<0.01
Resource biomass (*biomass*, log-transformed)	0.168	0.006	<0.01
GDP per capita (25th quartile to median)	1.007	0.057	<0.01
GDP per capita (median to 75th quartile)	1.710	0.056	<0.01
GDP per capita (75th quartile to maximum)	1.999	0.059	<0.01

The model predicted subsistence catches that explained 60% of the variations of the observed catch values (log-transformed) (Figure 6.5). Using the model described above, scenarios of changes in subsistence catches were developed based on projected changes in demography and economic status of each country and fisheries resources abundance in its EEZ under specific SSP and RCP scenarios.

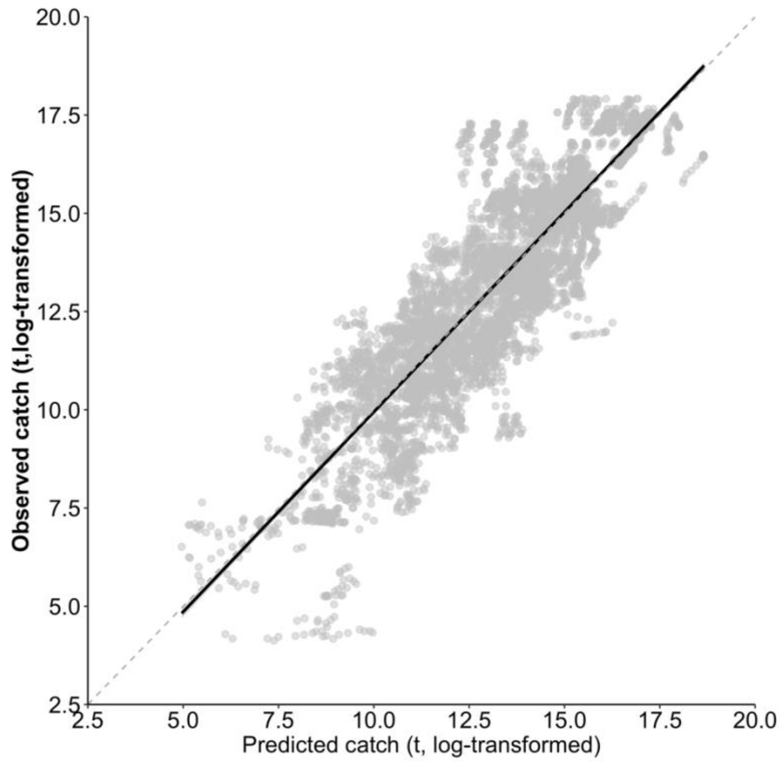

Figure 6.5. Observed and predicted subsistence catches by countries in the world from 1971 to 2005. The black line represents a linear regression between the observed and predicted catches, which is not significantly different ($p>0.05$) than a 1:1 relationship as represented by the dashed line.

Scenario projections for employment

Scenarios of future changes in employment related to fisheries were developed using an empirical statistical model. We assumed that total employment in fisheries-related sectors is related to population size (rural), fisheries catches, and countries' economic development status. The total fisheries-related employment data is based on Teh & Sumaila (2013). Rural population and category of economic development status are as described above.

Here, we applied generalized linear models. Because employment data was only available for a particular time period (standardized for 2003), each country was used as a sample. Fisheries-related jobs, rural population size, and catch were log transformed for use in the model. Each model run was a combination of the three variables, starting with the total set of variables. We tested the hypothesis that higher catches would result in more employment for fisheries-related sectors in particular. Since many fisheries-related jobs occur in rural areas, a greater rural population would, in theory, also be related to higher fisheries-related employment. Available evidence indicates that small-scale labour-intensive fisheries are more dominant in less economically developed countries, while fisheries in developed countries are more technology-intensive, requiring less labour per unit of catches (Teh & Sumaila, 2013). Therefore, it follows that higher income class countries (as indicated by their GDP per capita) would have fewer individuals employed in fisheries-related sectors. There may be interactions between income class and catches in relation to marine-related employment.

$$\log(Employment) = a \cdot \log(ruralpopulation) + b \cdot \log(\mathrm{Y}) + \sum_{i=1}^{4} \mathrm{d}_i \cdot \mathrm{factor}(gdppc_i) + \log(Y) \cdot \sum_{i=1}^{4} \mathrm{d}_i \cdot \mathrm{factor}(gdppc_i) + \varepsilon \quad \text{.......... (6.2)}$$

The model (Model 1) with the lowest Akaike Information Criterion (AIC) predicts that number of fisheries-related jobs is significantly related to rural population size, total fisheries catches and the economic status of the country, with interactions between the latter two factors (Table 6.4, Figure 6.6). Total fish catch was positively related to the number of fishers, indicating that future increases in fish catch will drive additional fisheries jobs. However, for middle- and high- income countries, as indicated by their GDP per capita rankings, the sensitivity of employment numbers to catches is lower than for lower and lower-middle income countries. This supports the hypothesis that fisheries employment in developed countries is likely to be structured differently than in less developed countries. Rural population size was also positively related to fisheries jobs, supporting our assumption that countries with larger rural populations will have proportionally more people engaged in fisheries. For the competing model (Model 2), the conclusion is qualitatively similarly to Model 1, except that it omits the potential interaction between countries' catches and economic status. Since Model 1 aligns with *a priori* expectations of the relationship between fisheries-related jobs and countries' social and economic factors, and performs statistically better based on AIC, we use Model 1 for scenario projections of fisheries-related jobs in DIVERSE.

Table 6.4. Test statistics of the model to project fisheries-related employment

	Estimated (Model 1)	Estimated (Model 2)
Intercept	1.825	4.436
Rural population (*rural population*, log-transformed)	0.321	3.358
Total catches (*Y*)	0.677	3.354
GDP per capita (25th quartile to median) ($gdppc_2$)	-0.635	-0.986
GDP per capita (median to 75th quartile) ($gdppc_2$)	2.256	-2.026
GDP per capita (75th quartile to maximum) ($gdppc_3$)	2.067	-2.606
GDP per capita (25th quartile to median) *log(Y)	-0.035	NA
GDP per capita (median to 75th quartile) *log(Y)	-0.436	NA
GDP per capita (75th quartile to maximum) *log(Y)	-0.471	NA
AIC	455	464

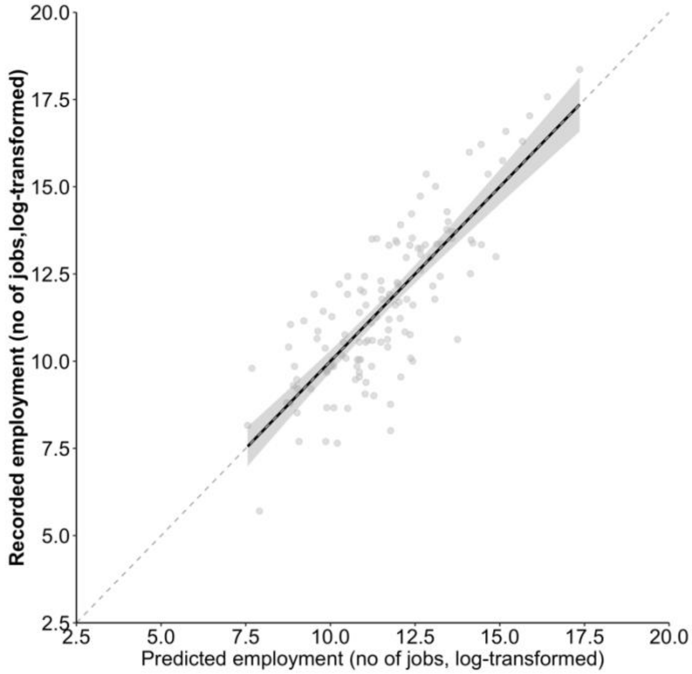

Figure 6.6. Recorded and predicted total marine employment by countries in the world. The black line represents a linear regression between the observed and predicted catches, which is not significantly different (p>0.05) than a 1:1 relationship as represented by the dashed line.

Conclusions

In this chapter, we develop three fisheries-specific scenarios that are coherent with the global Shared Socioeconomic Pathways (SSP) framework and derive quantitative indicators of these scenarios (SSP1, SSP3 and SSP5) to simulate future changes in the ocean and fisheries and evaluate their sustainability under climate change using the model DIVERSE. These scenarios are not meant as predictions nor forecasts. They are projections of consistent sets of assumptions from today into the future and are meant to illustrate a range of possible alternate futures given current trends and ongoing developments in the fisheries sector across countries, as well as highlight perhaps unexpected patterns. The future is likely to consist of a combination of suggested outcomes. The purpose of scenarios, therefore, is to explore uncertainty by developing logical and coherent stories about what the future may look like given a range of socio-economic choices. Doing so is important to highlight possible challenges, likely adaptation and mitigation options and the range of policy measures that may be available to society to support a sustainable and equitable path forward.

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Chapter 7: Scenarios for the future of mariculture

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Abstract

The basic narrative storylines of the global scale Shared Socioeconomic Pathways (SSPs) is not sector specific. In this chapter, we describe the approach of extending the basic SSPs to account for mariculture and its importance to seafood security. We define the future of the mariculture food sector according to three basic SSP storylines: SSP 1, SSP 3, and SSP 5. We employed an expert workshop to develop a set of qualitative socio-economic storylines and identify relevant drivers – and to assist in avoiding cognitive bias while identifying possible future outcomes. The study defined four domains considered as essential to consider in any future mariculture expansion and development worldwide: science and technology, society, governance and economics and trade. These domains and the elements considered thereunder are also vital to future mitigation and adaptation strategies under climate change.

Introduction

The Shared Socioeconomic Pathways (SSPs) (Wabnitz et al. this vol; O'Neill et al., 2013; O'Neill et al., 2015) have been developed to evaluate and understand complex interactions between natural resources use and human activities (Capitani, 2016). The dynamics of such impacts are not only affected by the biophysical factors within the earth systems in which these natural resources are embedded, but also on the socio-economics development surrounding their usage. Accessing the drivers of socio-economic development is fundamental for the sustainable utilisation of the resources. Currently, the existing narratives and projections of SSPs do not capture differences in socioeconomic development between economic sectors, and there is a call for sector-specific and regional extension (Absar and Preston, 2015; Bauer et al., 2016). This chapter described our approach to extend the basic SSPs for the marine aquaculture sector.

Aquaculture is an important component in discussing the challenges to human nutrition and general well-being posed by the fish[1] supply decline from fisheries due to mismanagement (Pauly and Zeller, 2016) and climate change (Cheung et al., 2010). World aquaculture production has grown tremendously over the last few decades, contributing significant quantities of total fish-food supply to the human population and also to the economics of production countries. In 2016, total farmed fish production from both fresh and marine water (with brackish) accounted for 47% (80 million tonnes) consumed by humans with a value of US$ 232 billion, with about 29 million

1 "Fish" here includes finfish and aquatic invertebrates, but exclude aquatic plants

tonnes (36%) of this production from mariculture (both marine and brackish aquaculture) of fish (FAO, 2018).

Mariculture has been widely promoted as a way to contribute to poverty reduction, foreign exchange and food security (Toufique and Belton, 2014). The food sector is an important socio-economic activity contributing to the livelihoods and poverty alleviation, especially for low-income communities (Bondad-Reantaso et al., 2005). Mariculture production and expansion are shaped by social and economic drivers, particularly consumer demand and preferences that may drive technology to increase productivity (Bostock et al., 2010). While biological traits such as fast growth, high fecundity, disease resistance, and ability to breed in captivity are considered to be an important criterion in the selection of species for farming, social-economic factors ultimately shape the development of mariculture (Gempesaw et al., 1995; Gjedrem and Baranski, 2010). For example, the number of farmed marine species have been increasing rapidly in recent decades, which has been attributed to the growing demand for seafood (marine and brackish waters) in developed countries (Campbell and Pauly, 2013). Also, the beliefs and attitudes towards mariculture production are caused by changes in demographic characteristics, education, market locality, and generic advertising (Fernández-Polanco and Luna, 2012).,

In this chapter, we describe a method for developing sector specific SSPs storylines for marine aquaculture. We apply the existing framework of basic SSP by defining the challenges for mitigation and adaption related to marine aquaculture. We aim to; 1) identify the major marine aquaculture development drivers; 2) describe the importance of these drivers to marine aquaculture components efficiencies related to its sustainability; and 3) explore how such drivers would identify potential challenges associated with the SSPs storyline development.

Methodology

An aquaculture expert workshop was held at the University of British Columbia, Canada, from December 2nd to 4th, 2018. The workshop brought together nine participants with diverse professional background, including environmental law and policy researchers, aquaculture management researchers, aquaculture economists, industry experts, and scenario development researchers. The workshop focused on developing future outlooks for mariculture using SSPs as a scenario development framework. At the start of the workshop, two presentations were given to provide participants with a general overview of SSPs and expectations in their application to the mariculture sector. Participants were then split into two groups, ensuring a mix of discipline and expertise in each, and asked to discuss factors affecting mariculture development and possible future trends; and finally, to draft basic storylines for each mariculture SSP (i.e., SSP1, SSP3 and SSP5).

In summary, the workshop followed four key steps:

1) Discuss the main opportunities and concerns about mariculture development based on findings from the literature review, the expert surveys and global mariculture production trends;
2) Group the concerns into wider categories (i.e. domains) and identify key drivers;
3) Discuss critical uncertainties;
4) Develop three separate storylines (SSP1, SSP3 and SSP5) by taking into account projected trends for each identified key driver based on the SSP framework.

Storyline description for mariculture Shared Socioeconomic Pathways (SSPMs)

At the end of workshop day 1, the study researchers summarised the information provided by each group that described each SSP and developed draft scenario narrative (storylines). On the second day of the workshop, the group discussed the draft storylines and developed a set of second SSP storyline drafts. These drafts were then circulated to all participants for feedback before being finalised by the study researchers into each SSP storylines.

Key findings

Review of main opportunities and concerns for mariculture development based on participant discussion

Based on the current status and trends for mariculture production, workshop participants' experience, and information gathered from published literature, the exponential growth of the sector, socioeconomic benefits and the impact of unsustainable practices were identified as the main opportunities and concerns for the future of the sector.

In 1990, more than 5.6 million tonnes of seafood (excluding aquatic plants) were farmed in marine and brackish water environments. However, by 2015 this figure had increased to about 27 million tonnes. Substantial production operations occur in Asia, with China accounting for 61% of total volume production, while other Asian countries contributed about 20% (FAO, 2018). Oceania and Africa, on the other hand, only contributed around 0.6% each. Mariculture growth has been ascribed to the growing demand for seafood from developed countries (Campbell and Pauly, 2013) in particular and the increasing global population along with their consumption of seafood more generally (Troell et al., 2014). The mariculture industry earns valuable foreign exchange for production countries and generates jobs across the sector. The farm gate value for mariculture seafood products was estimated at USD 24 billion in 1990, which increased to about USD 85 billion by 2015 (FAO, 2018). Also, mariculture expansion and growth are viewed as a way to attract foreign investment, enhance export earnings, and improve countries' balance of trade (Stonich et al., 1997). Notably, current mariculture endeavours tended to focus on high value, high trophic levels species such as salmon, tuna and rainbow trout, although there are regional differences. For instance, China and Africa mainly farm species with a mean trophic level that is lower than the global mean trophic level (Campbell and Pauly, 2013). The increasing mean trophic level of farmed species in many regions has raised a concern about the amount of fishmeal and fish oil (FMFO) used in feeds (Cashion et al., 2017).

Other major concerns include the uneven distribution of mariculture production; export-oriented mariculture production with less emphasis on local consumption; and the environmental implications of increasing mariculture production.

Organising opportunities and concerns into domains and identifying drivers

Workshop participants identified four domains that could contribute to mariculture growth, development, and expansion. These domains include; science and technology, society, governance, and economic and trade. They later discussed and organised possible mariculture expansion drivers associated with opportunities and concerns around mariculture development within each domain. The main ideas under these domains are summarised below.

1. Science and technology

Workshop participants identified technology as the only driver within the science and technology domain.

The mariculture sector currently faces many challenges, including combating diseases and parasites; bloodstock improvement and the closing of the life cycle of farmed species; efficient aquafeed development with reduced impact on fisheries; efficient hatchery and grow-out management; and effective methods to reduce environmental impacts (Subasinghe et al., 2003; Klinger and Naylor, 2012). These issues are likely to continue to represent challenges to the sector for the next decades.

However, technological innovations (including biotechnology[2]) have shown a positive impact on the growth, development and diversification of aquatic species farming (Subasinghe et al., 2003). These innovations are the response to increasing societal demand to see the mariculture industry reduce its environmental and ecological impacts (Bostock et al., 2003). Within the sector, technology is perceived as providing solutions to environmental problems such as the escape of farm species, eutrophication and nutrient enrichment of the ecosystem, poor water quality management, reliant on animal protein for aquafeeds, disease prevalence, poor breeding and propagation procedure. For example, recirculating mariculture systems and integrated multi-trophic mariculture (IMTA) systems - that recycle waste nutrients from higher trophic level species into the production of lower trophic level marine species – were both developed to reduce the environmental footprint of mariculture (Troell et al., 2009).

2. Society

Societal consumption behaviour influences the world food systems, production, operations, marketing, and distribution. These behaviours are complicated to understand as they are nested within interactive societal indicators such as population growth, income, and education (Verbeke and Vackier, 2005). Therefore, under the societal domain, we focused on the indirect drivers of societal consumption behaviour that included population, education, and consumer preference.

The world population is expected to reach 9.7 billion by 2050 (UN, 2019). This population growth is expected to increase global food fish demand. Rapid population growth, increasing wealth and urbanisation will drive the increase in the need for fish products in lower and middle-income countries (Msangi et al., 2013). In high-income countries, a population with higher educational levels could have higher fish consumption (Myrland et al., 2000; Shimshack et al., 2007) due to their awareness of the health and nutritional benefit of food fish consumption (Verbeke and Vackier, 2005). Thus, increasing population, and access to education and information might further increase the demand. On the other hand, consumers play a prominent role in present-day food systems (Eggersdorfer et al., 2016), the improving knowledge about the nutritional benefit,

2 Biotechnology means any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use. CBD, 2019. Convention on biological diversity. In Convention on biological diversity. https://www.cbd.int/convention/articles/default.shtml?a=cbd-02 Accessed on 1st August, 2019.

and the environmental footprints of mariculture may increase the demand for more sustainable mariculture products and reduce those that have higher environmental impacts.

3. Governance

An essential component of a sustainable mariculture sector is governance (Salayo et al., 2012; Olsen, 2015). However, the major challenge in mariculture governance is to balance the interaction that connects environmental sustainability, entrepreneurial innovations, and social harmony (Hishamunda et al., 2014) without undermining the growth and development of the mariculture food system. Mariculture relies on natural resources such as marine and terrestrial environments, nutrients, and energy as substantial inputs in production. An integral part of governance is to ensure that the exploitation of such natural resources is within the carrying capacity while protecting investors and maximising societal benefits (Subasinghe et al., 2009).

Workshop participants identified two major driving forces that will affect the effectiveness of governance;

1) A holistic mariculture policy is required to establish sustainable mariculture growth and development. The effective policy requires proper, clear and explicitly defined goals for sustainability;
2) Certification has been a useful tool in the aquaculture industry, especially when governance has shifted away from state regulation (Bush et al., 2013). Sustainable seafood certification schemes are viewed as a market-based mechanism and may not have a balanced effect on the different types of mariculture, e.g., small scale *versus* large scale farming (Swartz et al., 2017). Hence, the effectiveness of certification schemes would partly depend on their impacts on different types of producers in terms of sustainable mariculture growth.

4. Economics and trade

As a significant percentage of mariculture production is exported rather than used for domestic consumption (Anderson and Fong, 1997; Belton and Little, 2008; FAO, 2018), participants recognised the efficiency of the marketing system as the main driver under economic and trade domain.

Food production systems have changed from production- to market-oriented (Meulenberg and Viaene, 1998; Kahan, 2013). Producers focus on meeting the market needs, particularly with consumer satisfaction on the front line (Pieniak et al., 2013). As seafood market continues to be highly globalised, future mariculture production may follow these trends, which centred on the marketing environments worldwide such as economic (i.e. forces of demand and supply) and technological advancement (i.e. biotechnology development), rather than meeting specific local or regional social objectives (i.e. food security). The effectiveness of the market system will impact the fairness of mariculture-related seafood trade, the choice of product (high or low- trophic level species), the production cost, and consumer affordability of the products (price).

Shared Socioeconomic Pathways storylines for mariculture (SSPM)

Detailed storylines for each SSP are included below. Domain contribution to the SSPs is summarised in figure 7.1, and key points under each SPP storyline are summarised in Table 7.1

SSPM 1-Sustainability: The blue growth mariculture

Under this scenario the world accounts for the social and economic costs of mariculture environmental degradation through substantial investments in science (including green technology), education, and the development of policies guidelines and charters, which are inclusive and promote sustainability as well as environmental auditing, life-cycle assessment, the measurement of environmental performance, and environmental reporting (Welford, 2016). These positive characteristics contribute to high global mariculture production.

Science and Technology

- Mariculture technology development and application are high, leading to a gradual reduction in mariculture dependence on marine inputs in operations. This is mainly driven by a breakthrough in aquafeed improvement, which leads to the replacement of the use of wild forage fish FMFO in aquafeed with protein from non-genetically modified sustainable plant and sustainable insect-based sources;
- By 2050, reliance on forage fish usage for aquafeed is minimal worldwide, and the availability of wild fish stocks for aquafeed is no longer a barrier to mariculture growth;
- Economic and societal drivers result in a rapid increase in farming of low trophic level species with a focus on increased species diversity and richness. Substantial biotechnology developments support the farming of these farmed species under closed life cycle conditions (i.e., through well-established breeding procedures and to the exclusion of captured-based mariculture);
- Improved management practices and scientific breakthroughs limit the impacts of disease and parasites on farmed (and wild) fish;
- Advancements in technology are applied to addressing environmental issues related to mariculture farm practices.

Society

- The world population is low because of investments in proper education and health;
- Consumers are aware of environmental and social sustainability issues around seafood;
- Food preferences in most societies rapidly change to diets with low trophic level species, driving the mariculture industry to farm such species;
- Development of mariculture technical knowledge in low and lower-middle-income countries is rapid due to substantial technology transfer from upper-middle and high-income countries and support of gradual active international cooperation promoting global mariculture development in all income countries by 2050.

Governance

- There is global support for effective governance mechanisms in mariculture and the development of transparent, reliable ecologically sustainable and socially responsible certification schemes;
- Strong corporate responsibility within the industry due to economic incentives and social pressure;
- Certification schemes meet or exceed the minimum substantive criteria related to animal health and welfare, food safety, environmental integrity as well as social considerations (Kittinger et al., 2017);

- Mariculture operations and their development are underpinned by ecosystem-based scientific understanding and adaptive management. Production intensification follows ecological principles (Henriksson et al., 2018; Aubin et al., 2019) with increased investments channelled towards offshore mariculture to increase overall mariculture carrying capacity;
- There are efforts to develop mariculture operations at the community level to meet local food and nutrition security. Such efforts are encouraged and supported by national policy instruments;
- There is high compliance with mariculture regulatory laws due to adequate and appropriate monitoring that is based on robust evidence-based mechanisms, supported by clear ecological standards and indicators on all aspects of sustainable development, including environmental, economic and social;
- Marine spatial planning includes diverse uses of coastal, land and offshore areas (distance from coast > 2 km) that ensures a reduction in mariculture ecological footprint;
- Active collaboration among ocean users sees a substantial decline in intersectoral conflicts (i.e., between mariculture and other coastal and open oceans users).

Economics and trade

- This scenario sees rapid economic growth in low-income and lower-middle-income countries with an increase in per capita income;
- Informed consumer choices lead to an overall decline in seafood price due to high demand for farmed freshwater species and low trophic level mariculture species;
- Globalised trade market through fairness because of average labour costs and production costs;
- Mariculture industry enjoys policies liberalisation, which makes the industry more market and service-oriented. As well, rapid technological development occurs in harvesting, processing, packaging, transportation, marketing, and distribution.

SSPM 3-Regional rivalry

Under this scenario, the world shifts towards national and regional security issues, especially the mariculture products trades. Mariculture technology benefits high-income countries with low patterns in technology transfer. Mariculture production is low under this scenario due to the increasing impact of mariculture on environment, weak local and global governance, and a lack of cooperation to tackle environmental challenges.

Science and Technology

- The slow growth of mariculture biotechnology brings little change in the diversity of species farmed, the industry dependence fishmeal and fish oil from fisheries, aquafeed and growth efficiency, and the reduction in diseases prevalence;
- There are no breakthroughs in sustainable plant-based or insect-based source replacement for FMFO, causing continuous pressure on fishing for forage fish and the increased reliance on bycatch for aquafeed production;
- There are environmental concerns about the increase of ecological impacts from mariculture, especially as the world turns towards regional development of mariculture with the proliferation of unregulated small-scale mariculture systems;

- Low, lower-middle and upper-middle-income countries focus on local species because of substantial reliance on traditional methods with lower efficiency in farm production. Meanwhile high-income countries continue to farm high trophic level species, with their operations placing low priority on environmental issues;
- Diversity of mariculture farmed species is low in low, lower-middle and upper-middle countries. In contrast, high-income countries continue to diversify the farmed species mostly from seedlings and fingerlings that are obtained through capture-based aquaculture production;
- High disease prevalence and transfer are caused by high stocking density, poor water quality, and environmental degradation. As a result, mariculture contributes to marine biodiversity loss and reduction of recruitment in fisheries.

Society

- The population is low in high and upper-middle-income countries but higher in the lower middle and low-income countries;
- Countries' support for sustainable mariculture development is weak;
- Increasing inequality within and across countries because of racial and nationalistic beliefs, putting self-interests as the priority;
- There is an increase in unsustainable farm practices to meet seafood demand because of material-intensive consumption and diet, especially in the upper-middle and high-income countries;
- Barriers to trade in low and lower-middle-income countries lead to low global mariculture production;
- Small investments in technology transfers and international cooperation lead to high production cost and high environmental impact farming systems especially in low, lower-middle and upper-income countries;
- The risks to human health increase because of the high contamination of farmed species from pollution and environmental degradation. The health risks are further exacerbated from the increased use of antibiotic and other chemical products to boost farmed species growth.

Governance

- Weak regional environmental systems due to lack of management and institutions leads to an increase in conflicts due to reduced space to support mariculture ventures;
- Corporations control most of the mariculture sector, especially in high - and upper middle - income countries, leaving small actors out of the industry;
- There is a low priority for environmental issues with no effective marine spatial planning;
- Regional efforts towards the use of technology to deal with environmental problems or to allow for alternative mariculture development (offshore or otherwise) reduced drastically. Although upper-middle and high-income countries do have some technology and other capacities, there is no global collaboration and technological transfer.

Economics and trade

- Economic growth is slow globally;
- There is de-globalised trade with limited free and fair-trade systems;

- Increase tariffs on mariculture products between regions, especially by high-income countries;
- The market becomes inefficient in ensuring maximum benefits for all market actors. Hence, low - and lower middle - income countries lose the opportunity to secure revenue from export;
- There is low investment in mariculture because of its high risk;
- The rapid increase in the price of seafood from mariculture due to increase in demand and decline in supply.

SSPM 5-Fossil fuel-driven development: Fast line to mariculture development

SSPM 5 scenario describes a world that is driven by the economic success of industrialised and emerging economies. Mariculture development is oriented towards economic growth. Under this pathway, global mariculture is high but not sustainable mainly because mariculture contributes to further destruction of the aquatic ecosystem and climate change.

Science and Technology

- High technological advancement that leads to intensive mariculture development with an emphasis on farming high trophic level species;
- Strong dependence on natural resources and the environment to increase mariculture production;
- Rapid biotechnology development helps to improve plant protein source in aquafeed production, and such technology is largely genetically modified. There are still substantial uses of fisheries forage fish for FMFO production;
- Rapid biotechnology also fosters the application of farmed species breeding practices for some particular species. Capture-based mariculture increased for ocean ranching of high trophic level finfish. Lower species diversity as an intensive monoculture of carnivorous species become economically viable;
- Technology is transferred from high and upper-middle-income countries to low and lower middle-income countries;
- Low energy prices allow the use of high technological advance farming systems globally;
- Technology is used to solve environmental issues in the context of increasingly intensified aquaculture production, especially disease prevalence.

Society

- The population is high in the upper-middle and high-income countries but low in lower and low-income countries;
- Consumer's preferences are more materialistic with status consumption, which leads the mariculture industry to produce high trophic level species to suit this consumption habit;
- This lifestyle is funded by an economy that is highly dependent on fossil fuels;
- There is a strongly globalised mariculture industry with few actors controlling the sector;
- International cooperation is useful in the pursuit of mariculture related development regarding the volume and value of production with limited environmental sustainability goals.

Governance

- Effective global management and environmental regulations;

- Certification schemes are useful in upper-middle and high-income countries. However, the certification schemes only meet the minimum substantive criteria that are related to animal health and welfare and socio-economic aspects, leaving out environmental integrity as a non-essential criterion. This is because global trade requires food safety certificates without consideration of the sustainability of management practices in the exporting country;
- Mariculture related institutions are increasingly effective but more oriented towards a competitive market;
- Less competition among sectors as high mariculture production efficiency and increase offshore mariculture reduces space demand especially in coastal waters;
- Inadequate global environmental standards allow gradual destruction of ocean habitat and increasing damage on ocean biodiversity;
- There is strong advocacy for spatial planning that avoids ecologically sensitive areas. However, site selection/assessment protocols are conducted with inconsistency in both principles and guidelines.

Economics and trade

- There is rapid economic growth in low and lower-middle-income countries that increases mariculture production to foster competitive markets;
- There is a global specialisation in high trophic level species that reduces the diversity of farming;
- Economic policy favours the reliance on free markets to meet increasing demand, especially from mid-income class;
- There is a decline in the prices of seafood from mariculture.

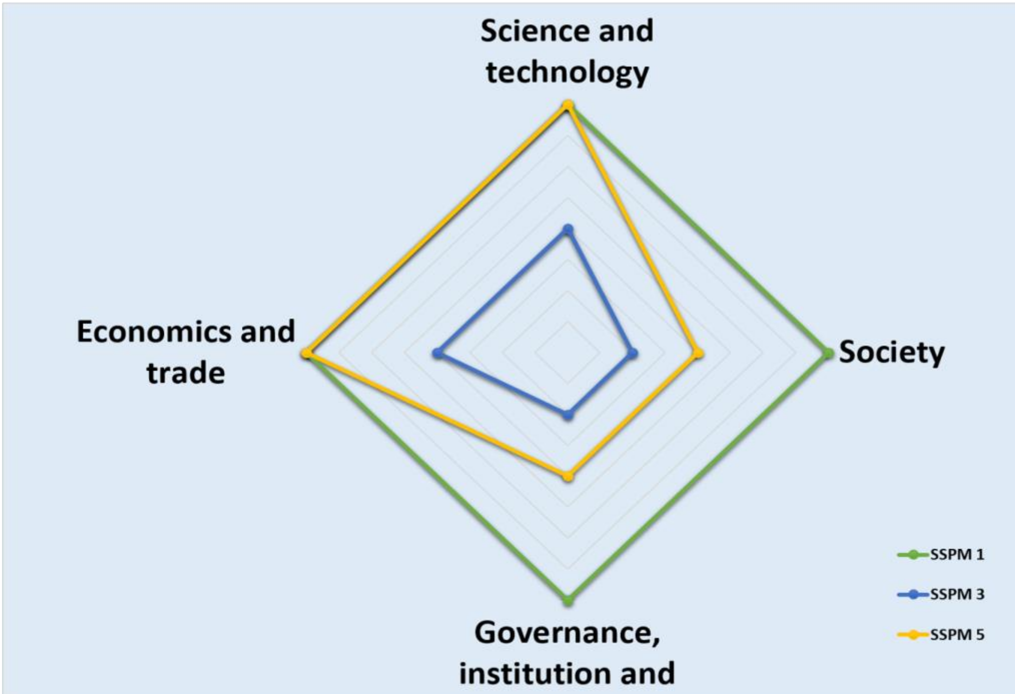

Figure 7.1. A schematic diagram illustrating the relative contributions of each domain to mariculture sustainability within SSPMs. The scale of each domain is hypothetical, and the points were drawn based on the quality description of each SSPM

Table 7.1: Summary of assumptions for each Shared Socioeconomic Pathways for Mariculture

SSPM element	SSPM 1	SSPM 3	SSPM 5
Population growth	Global low population	The population is low in high and upper-middle income countries but high in the lower middle and low-income countries	The population is high in the upper-middle and high-income countries but low in lower and low-income countries
Economic growth	Rapid economic growth in low-income and lower-middle-income countries with an increase in income by a person	De-globalised economic	Rapid economic growth, with low and lower-middle-income countries, increasing exactitude in mariculture production to foster competitive markets
Trade	Globalised trade market through fairness	De-globalised trade with limited free and fair-trade systems	Global specialisation of high trophic level species
Policy	Improved management with effective regulation	Low perseverance	Global focus solution
Technology development	Rapid development	Slow development	High technological advancement
Aqua-feed production	With a breakthrough in a decrease of capture-fisheries forage fish as a protein source (i.e. Fishmeal and fish oil) in Aquafeed with replacement	No new sustainable plant-based or insect-based source replacement breakthroughs	Genetically modified replacement
Farmed species	A rapid increase in farming of low trophic level species but increase species diversity and richness	Low, lower-middle and upper-middle-income countries focus on local species because of substantial reliance on traditional methods with low production output. While high-income countries continue to farm high trophic level species	Capture-based mariculture increased for ocean ranching of high trophic level finfish. Lower species diversity as an intensive monoculture of carnivorous species become economically viable
Farmed species health and welfare	High	Low	Moderate
Consumption & diet	Low trophic level farmed species diet	High trophic level farmed species diet	High carnivorous species diet
Marine spatial planning	Global effective planning	No effective marine spatial planning	Strong advocacy for spatial planning that avoids ecologically sensitive areas with inconsistency in principles and guidelines.

Conclusions

Food systems are dynamic systems that encompass social, economic, and biophysical interactions across multiple dimensions (Garnett et al., 2016). Understanding these dimensions required long term scenario analyses. The present study presents the initiation of extending the basic Shared Socioeconomic Pathway (SSP) (O'Neill et al., 2013; O'Neill et al., 2015) to the mariculture sector.

This sectorial extension is intended as a description of plausible future pathways that can serve as a basis for the impact, adaptation and vulnerability (IAV) assessment analyses. Specifically, we adopted the multiple approaches in cohering the main issues related to sustainable mariculture production. This study highlights that future sustainability of mariculture will depend on the efficiency of four domains; 1) science and technology; 2) society; 3) governance, and 4) economics and trade. Moving forward is to turn the qualitative narratives described in the study into quantitative elements so that it can enable the definition of the future forcing variable necessary for IAV research.

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Appendix. Databases supporting the development of DIVERSE

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Despite significant gaps in information related to marine social-ecological systems (Cisneros-Montemayor et al., 2016; Pauly and Zeller, 2016), there are many large-scale efforts to produce and compile data on such systems, including biodiversity, capture fisheries, mariculture, and seafood markets and trade. At local, national, and global scales, these data are being produced by universities, government and non-government organizations, industry groups, and by many other stakeholders and individuals. This decentralization of data production and maintenance is undoubtedly a good thing because it can produce information for a wide array of themes and for many different contexts that could not be addressed by a single source (Cisneros-Montemayor et al., 2016) . It can, however, make it more difficult to identify or obtain existing data required for highly interdisciplinary applications such as the DIVERSE model described in this report, which are intended to lead to policy advice in the context of complex social-ecological marine systems (Cheung, 2019). Thus, the challenge is to find existing information and connect it in a way that allows for addressing a specific issue though information may not have collected for that purpose--and create research synergies.

Efforts to compile marine systems data have involved a wide array of research groups, and the Nippon Foundation-the University of British Columbia Nereus Program has involved collaborations between many such groups, focusing on aspects from oceanography to economics and human development (Pauly et al., 2019). The Princeton Global Fluid Dynamics Laboratory produces information on oceanographic conditions and primary productivity under given climate conditions. The Changing Oceans Research Unit (CORU) at the University of British Columbia (UBC) has connected such data with information on marine species' physiology, biology. and ecology compiled by the *Sea Around Us* project, producing global maps of projected species abundance and distribution under various climate scenarios. On the human dynamics side, the UBC Fisheries Economics Research Unit has collected information on fishing costs, employment, and prices that adds layers to predictions of system outcomes under a range of climate, economic, and governance scenarios.

The datasets highlighted above are certainly not the only sources of global information on marine systems. The World Bank has extensive (mainly country-level) information on social and economic trends that can be used to draw inferences on local conditions and possible development scenarios (WB databank). For seafood production, The United Nations' Food and Agriculture Organization (FAO) compiles and presents data on behalf of member states, including yearly estimates of fisheries and mariculture production by species, as well as yearly seafood imports and exports by product and country. Overall, there is a wealth of available information to inform integrated assessments such as the one presented in this report, data gaps and caveats notwithstanding.

Perhaps the greatest source of data uncertainty, in the context of this assessment, is the variable scale and specificity of available information. For example, fisheries catch is often presented aggregated by country or into very coarse taxonomic groups. Similarly, information on economic dynamics that drive fisheries is not available for all fisheries in all countries, or throughout time. While these challenges should not preclude the development of models using the best available information with transparent and clear assumptions, input data must always be treated as hypotheses to be tested along with model scenarios.

Description of datasets

Here, brief summaries of datasets that contributed to the various components of DIVERSE are provided. These data include ecological, biodiversity and fisheries socio-economic information that is housed at the University of British Columbia and other member institutes of the Nereus Program, and at other academic, government, and intergovernmental institutions around the world. Each summary includes a brief description of the data contents and unit types, and a reference and/or web address where the data can be accessed or located.

FishStatJ (Capture): Dataset includes wild capture fisheries catch (in metric tonnes), by species (or species group), reporting country, and year, from 1950 to the present (with a lag of approximately 2 years). These data are compiled by the UN FAO on behalf of member states and are intended to represent official catch statistics of these states. Reference: http://www.fao.org/fishery/statistics/software/fishstatj/en.

FishStatJ (Aquaculture- Market model): Dataset includes aquaculture (marine and inland) production (in metric tonnes and dollar value), by species (or species group), reporting country, and year, from 1950 to the present (with a lag of approximately 2 years). These data are compiled by the UN FAO on behalf of member states, and are intended to represent official statistics of these states. Reference: http://www.fao.org/fishery/statistics/software/fishstatj/en.

FishStatJ (Trade): Dataset includes seafood production (wild capture and aquaculture) and trade (export, import, and re-export), by seafood product (or species group), reporting country, and year, from 1976 to the present (with a lag of approximately 2 years). These data are compiled by the UN FAO on behalf of member states, and are intended to represent official catch statistics of these states. Reference: http://www.fao.org/fishery/statistics/software/fishstatj/en.

Ex-vessel Price Database: Dataset includes ex-vessel unit prices (USD/tonne) by species, country, and year, from 1950 to 2016. Prices are compiled from official country statistics and peer-reviewed literature, using meta-analytical methods to estimate missing prices using available data for comparable countries and species Reference: Tai et al. (2018)

Price Elasticities: Dataset includes price elasticities (relationship between unit price and total supply) by marine species and geographic area (or country, when available). Data was compiled from review of peer-reviewed literature. Reference: Sumaila et al. (2019).

Tariff Facility Database: Dataset includes tariffs at the standard codes of Harmonized System (HS) for all WTO members. Reference: http://tariffdata.wto.org/

World Bank World Development Indicators: Datasets include demographic, social, economic, ecological, and development indicators compiled by the World Bank from official sources, available yearly (or quarterly) from 1960 to 2016. Reference: https://data.worldbank.org/data-catalog/world-development-indicators.

FishBase and SeaLifeBase: Global biological databases of marine life including all fishes and invertebrates. FishBase: www.fishbase.org; Sealifebase: www.sealfebase.org

***Sea Around Us* Database:** Datasets include wild capture fisheries and mariculture production (weight and value) by species, country, and year, from 1950 to 2014. Importantly, this dataset includes spatial information and uses a formal method to account for production that is unreported in official (e.g. FAO) statistics. Reference: seaaroundus.org.

Cost of Fishing Database: Dataset includes variable and fixed costs for fishing fleets by country, using available data on unit (vessel and gear type) costs from literature review. Cost components included are fuel, operation, repair, labor, depreciation and interest. Reference: Lam et al. (2011).

Fishing Employment Database: This dataset provides the total number of marine fisheries jobs in 144 maritime countries around the world, including direct and indirect jobs. Direct jobs are those involved in the harvest of fish, while indirect jobs are those in the secondary sector such as manufacturing and processing, as well as typically ancillary activities such as marketing and equipment repair. A special focus was put on estimating the number of small-scale fishers globally, where both reported and unreported fishers were accounted for. All estimates are static and referenced to the year 2003.

Reduction Fisheries Database: The database was derived from the reconstructed fisheries landings (i.e. excluding discarded catch) by taxon for each fishing country/Exclusive Economic Zone (EEZ) for each year from 1950 to 2016 as documented in Pauly and Zeller (2016) and Cashion et al (2017).

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