Future scenarios and projections for fisheries on the high seas under a changing climate

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Marine biodiversity and ecosystems provide important benefits to human societies through fisheries. But the benefits are not shared equally among countries – and climate change will only exacerbate inequalities. Improving high seas fisheries governance would help redistribute benefits and reduce climate risks, especially in developing countries where many people depend on fish for their food and nutrition security, livelihoods and well-being. Developing countries are also among the most vulnerable to climate change impacts. Here, the authors explore different scenarios of future fisheries governance and evaluate the benefits and trade-offs of alternative policy frameworks for governing fisheries under a changing climate.

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High seas fisheries

Areas beyond national jurisdiction (ABNJ) – the 'high seas' – cover 43 per cent of the Earth's surface or 61 per cent of the world's oceans. High seas capture fisheries production grew from about 450,000 tonnes in 1950 to almost 5.2 million tonnes by 1989. Between 2009 and 2014, it averaged 4.3 million tonnes annually (slightly over 4 per cent of total annual marine catch) (SeaAroundUs).

Recent studies suggest that high seas fisheries play a minor role in global food security (Schiller *et al.* 2018, Teh *et al.* 2016). However, in some Pacific Island nations, food commodities such as canned tuna from fish caught in exclusive economic zones (EEZs) and on the high seas are becoming increasingly important in closing food nutrition gaps (Bell *et al.* 2019).

Unsustainable fishing is a key threat to biodiversity (Norse *et al.* 2012; White and Costello 2014) and fish stocks (Pauly and Zeller 2016) on the high seas. This threat is compounded by climate change (Cheung *et al.* 2017) and stark inequalities between countries in sharing the benefits of exploiting the high seas (Sala *et al.* 2018). Climate-induced shifts in species distribution affecting fish and fisheries add to the problems (Cheung *et al.* 2017).

Exploring three contrasting futures for high seas fisheries

This working paper examines how different plausible future scenarios of social, economic and environmental development impact on the benefits derived from fisheries in ABNJ, particularly for developing countries, under climate change. To this end we developed and applied a set of scenarios and models:

- Firstly, we developed storylines of alternative tenable futures of fisheries governance – including different combinations of area and fishing effort-based interventions on the high seas – given a world with sharply contrasting political, socioeconomic, technological and environmental priorities. Scenarios were developed from contributions provided by key experts during a two-day workshop in Vancouver in November 2018 using the shared socioeconomic pathways (SSP) framework (O'Neill *et al.* 2017).
- Secondly, we translated the qualitative scenarios into key representative quantitative metrics and applied biological and economic simulation models to global fish stocks and fisheries in ABNJ. Our aim was to project the future of fisheries' ecological (mean species abundance or MSA) and economic (revenues, profits and catches) performance based on the scenarios. We also introduced two climate-change scenarios (Representative Concentration Pathway or RCP8.5 and RCP2.6) to examine alternative futures of high seas fisheries under climate change.[1]

Out of a possible five SSP futures, we developed three contrasting scenarios of high seas fisheries determined by a range of interconnected biophysical, social and economic factors:

- The first future (SSP1) – 'charting the blue course' – is an ocean with relatively higher fish abundance and lower levels of impact from fishing and climate change than the other two scenarios, made possible by global cooperation centred on sustainable development. Across the three futures, in SSP1 the high seas contribute the least to income and livelihoods.
- In the second future (SSP3) – 'rough seas ahead' – national interests, particularly those of high-income countries, drive the intense exploitation of marine resources on the high seas. Impacts on marine biodiversity through fishing and climate change are high, while subsidies are responsible for maintaining the viability of high seas fisheries.
- The third future (SSP5) – 'fossil-fuelled development' – is characterised by intense exploitation of high seas fisheries resources to support rapid and broad-based economic development, particularly for lower-income countries. Fishing intensity and its impacts are the highest across the three futures, exacerbated by high fossil-fuel use and few environmental concerns.

[1] A Representative Concentration Pathway (RCP) is a greenhouse gas concentration trajectory adopted by the Intergovernmental Panel on Climate Change (IPCC) for its fifth assessment report in 2014.

The results

Our analysis suggests that high seas fisheries are not economically viable across the three ocean futures. Under SSP1, societies support ocean sustainability leading to the elimination of subsidies. While the change in fisheries revenues is positive, the difference in fishing profits – net benefits from fishing minus the fishing cost inclusive of fisheries subsidies – is still negative. The rate of change in fishing costs is greater than that of fishing revenues.

In SSP3, although future high seas catches are projected to increase, revenues are projected to be relatively stable. Fish prices are expected to decline due to increases in seafood supply. Moreover, the unit cost of fishing on the high seas is expected to decrease. As the scenario storyline suggests, finding forced or underpaid workers on fishing vessels and at processing plants is common. However, higher seafood demand and less-regulated fisheries lead to increases in fishing effort beyond economically optimal level, and hence greater total fishing costs. Although subsidies are expected to increase to satisfy higher seafood demand, fishing profits for all country income groups are still projected to decline.

Under SSP5, rising demand for seafood and lack of environmental concern increases fishing subsidies. However, this also leads to economically suboptimal increases in fishing effort resulting in increases in total fishing costs. Together, these factors decrease profits from high seas fisheries across all countries. Higher greenhouse gas emissions in both SSP3 and SSP5 further reduce the productivity and profitability of high seas fisheries.

The relative importance of the main direct drivers depends on whether findings are examined from an ecological, social or economic perspective and on the timeframe considered. Fishing effort under different SSPs on the high seas is consistently one of the most important drivers of future biodiversity, catches and economic benefits throughout the 21st century. Besides fishing effort, protected areas are important in determining fisheries catches and benefits over the near term (2030). But climate change plays an increasingly dominant role towards the end of the 21st century.

Developing future pathways that work

Our results highlight the potential for economic-based interventions in developing future pathways to support biodiversity conservation and sustainable fisheries on the high seas. Fishing effort is strongly influenced by a range of economic factors, including fish price, fishing costs and subsidies (Sala *et al.* 2018). The discourse around ABNJ conservation action (eg large marine pelagic protected areas) is mostly separate from the need for economic fisheries reform (but see Sumaila *et al.* 2015). Our findings underscore the importance of economic drivers (Cisneros-Montemayor *et al.* 2016) and fisheries management reforms in making high seas fishing more sustainable (WTO 2019).

We also explored hypothetical marine protected areas (MPAs) on the high seas for fish stocks and fisheries production in EEZs. Across the three ocean futures, high seas MPAs played a relatively small role in affecting future fish stocks and fisheries in EEZs compared to the influence of climate change, particularly in the mid (2050s) to long term (2090s). The reasons may be twofold:

- Unlike previous studies, which predict more extreme fishing mortality rates, we placed constraints on future changes in fishing. These constraints were calibrated to quantitatively represent the qualitative storylines and to adhere to expectations from bioeconomic theories through quantitative modelling.
- The boundary of the hypothetical high seas MPA scenarios did not account for the biogeography of fish stocks and fisheries, and thus may be suboptimal in their effects on fisheries resources in EEZs.

Our findings highlight important questions. None of the ocean futures we explored supported economically viable high seas fisheries. And fishing effort is projected to increase, particularly under SSP3 and SSP5, affecting species abundance and biodiversity and increasing conservation risks.

If our future resembles SSP3 or SSP5, what high seas governance and management approach(es) would be most effective in conserving high seas biodiversity and sustaining equitable fisheries? Or if the future is more likely to resemble SSP1, what approaches, as well as climate mitigation and adaptation measures, would be most effective in ensuring sustainable development?

Projecting long-term changes in complex coupled human-natural systems such as the global ocean and high seas is unavoidably uncertain. However, integrating qualitative information obtained through a participatory process with quantitative modelling creates rich contrasting plausible ocean futures. These scenarios are not predictions, but highlight perhaps unexpected patterns and may inform decision making to support equitable and sustainable ocean stewardship.

1

High seas fisheries and future ocean changes

There are significant challenges facing the future sustainability of high seas fisheries. These include declining fish stocks, threats to biodiversity and cultural heritage from human activities, climate change, and stark inequalities in the distribution of benefits. This chapter examines the current status of high seas fisheries while unpacking key issues related to their governance.

1.1 Current status of high seas fisheries and governance issues

The high seas cover 47 per cent of the Earth's surface or 64 per cent of the world's oceans (Costello and Chaudhary 2017). The high seas encompass areas beyond national jurisdictions (ABNJ), defined by the United Nations Convention on the Law of the Sea (UNCLOS) as including the water column beyond the exclusive economic zones (EEZs) of coastal nations and the 'area', which is the seabed beyond the limits of the continental shelf (Biodiversity A-Z). Biodiversity in the high seas provides significant benefits to society, from oxygen production and climate regulation to global fisheries. Meanwhile, the high seas are also of increasing interest owing to the commercial potential of marine genetic resources (MGR) and mineral deposits (Glover and Smith 2003; Vierros *et al.* 2016).

High seas fisheries started to develop after World War II, spurred by improvements in navigation technology and fishing gear. They expanded rapidly in the 1960s to 1980s as coastal fisheries declined. High seas capture fisheries production – including mostly highly migratory pelagic and deep-sea fish – grew from about 450,000 tonnes in 1950 to almost 5.2 million tonnes by 1989 (Dunn *et al.* 2018). Between 2009 and 2014, production averaged at 4.3 million tonnes annually, or slightly over 4 per cent of total annual marine catch (Schiller *et al.* 2018). China, Taiwan and Japan are among the largest fishing nations in terms of revenue, accounting for about 45 per cent of the US$7.6 billion in high seas catch-landed value in 2014 (Sala *et al.* 2018).

Some studies suggest that high seas fisheries play a minor role in global food security (Schiller *et al.* 2018, Teh *et al.* 2016). But a more recent study draws a link between human health and high seas fisheries. In countries such as some Pacific Island nations, food commodities such as canned tuna (Bell *et al.* 2019) from fish caught in exclusive economic zones (EEZs) and on the high seas are becoming increasingly important in closing food nutrition gaps.

Unsustainable fishing remains one of the main threats to biodiversity on the high seas. Bottom trawling in particular has led to considerable declines in species diversity in ABNJ (Norse *et al.* 2012, Wright *et al.* 2015), especially around seamounts and deep-coral ecosystems, as these are composed of extremely slow-growing and long-lived organisms. This makes them particularly vulnerable to fishing impacts (Roberts 2002; Clark *et al.* 2015). Pelagic fisheries on the high seas have also substantially contributed to the overexploitation of a number of targeted highly migratory stocks (eg tuna and billfishes) (Cullis-Suzuki and Pauly 2010; White and Costello 2014). And there are declines in a number of bycatch species, including marine turtles, seabirds, sharks and marine mammals (McKinnel and Seki 1998; Oliver *et al.* 2015; Lewison *et al.* 2014). Weak regulation and perverse economic incentives, such as fishing subsidies that promote fisheries stock depletion, are likely to further exacerbate existing challenges (Norse *et al.* 2012).

Management of the high seas is particularly challenging. They have long been thought of as being open access and 'free', as well as vast and remote. Today, almost all of the high seas are covered by legally mandated regional fisheries management organisations (RFMOs), and a number of international conventions and institutions address shipping and environmental protection on the high seas. RFMOs are established through international treaties between states to cooperatively manage international transboundary fisheries resources consistent with the principles and legal framework provided by UNCLOS and the UN Fish Stocks Agreement (Ásmundsson 2016). Although established for international governance of high seas fisheries (Rochette and Billé 2008), findings that two-thirds of fish stocks managed under RFMOs were either depleted or overexploited (Cullis-Suzuki and Pauly 2010) put the performance of RFMOs in conserving fish stocks in doubt (Gilman *et al.* 2014). This is despite the fact that conservation is part of the mandate of most RFMOs (Cullis-Suzuki and Pauly 2010; Wright *et al.* 2015). A review of the governance performance of RFMOs also suggests that they tend to lack adequate provisions for developing states (Cullis-Suzuki and Pauly 2010), with developing or least developed countries (LDCs) underrepresented on RFMOs (Telesetsky 2012).

Governance of ABNJ is arguably the responsibility of all nations. Yet, to date, there is decidedly no global cohesion in addressing protection or the sustainable use of the high seas. UNCLOS is the global legal framework governing rational use of the ocean. While UNCLOS contains general provisions for marine environmental protection, it does not offer sufficient protection for the emerging uses of high seas biodiversity that have developed since its adoption in 1982 (Rochette and Billé 2008). A number of governing bodies and legal instruments have been established to manage issues relevant to ABNJ, but they tend to be unevenly and narrowly focused on specific sectors and geographical areas. The lack of an international mechanism to coordinate decisions and account for their cumulative impacts across sectors and geographic regions has precluded effective environmental protection on the high seas. Indifference towards equitable benefit sharing also contributes to weak cooperation in managing transboundary resources (Campbell and Hanich 2015).

1.2 The future of high seas fisheries and their governance

1.2.1 Changing fisheries management and governance

If current fisheries management regimes persist, most deep-sea and open-ocean fisheries will not be sustainable in the long term (Glover and Smith 2003; Ortuño-Crespo and Dunn 2017). The threat to deep-sea species from fisheries and other industries (including oil and gas extraction and mining) is exacerbated by our limited understanding of the biogeography and basic life history of most deep-sea animals (Thurber *et al.* 2014). This prevents accurate projections of the future state of deep-sea systems or any physical and ecological feedbacks that will occur (Levin and Le Bris 2015), or impact assessments of the risk presented by different extraction sectors (Collins *et al.* 2013; Watling and Auster 2017; Auster *et al.* 2010). In open-ocean environments, fisheries have contributed to declines in biodiversity and species abundance, with impacts on community structure, dynamics and resilience (Ortuño-Crespo and Dunn 2017). Increasing fishing expansion on the high seas as a result of declining catches per unit effort in many EEZs are likely to contribute to the overexploited stock status of many high seas fisheries, including for some pelagic species such as tuna and sharks (Ortuño-Crespo and Dunn 2017). Illegal, unreported and unregulated (IUU) fishing only compound this issue (Flothmann *et al.* 2010).

In September 2018, the UN General Assembly launched the first of four planned negotiations to draw up an international legally binding instrument (ILBI) to protect and address threats to marine biodiversity in

ABNJ. These negotiations centre around a 'package'[2] of four priority issues that addresses international concerns on biodiversity protection and fair and equitable benefit sharing.

A series of parallel discussions relevant to the 'package' are also taking place in different policy forums. The World Trade Organization (WTO) is working towards binding principles on fisheries subsidies that contribute to IUU fishing, overcapacity and overfishing (WTO 2019). Global obligations to meet the Sustainable Development Goal (SDG) of achieving healthy oceans (Goal 14: Life below water) and tackling poverty and food security are pushing national governments to incorporate equity into decision making. It is now an opportune time for less-developed countries to assert a stronger position in international governance of ABNJ. Yet the low representation of Small Island Developing States and LDCs and low commitment to capacity building and technology transfer at global and regional meetings focused on biodiversity issues in ABNJ are an unfortunate reality (Blasiak *et al.* 2016). Mapping out innovative ways so that outcomes from ongoing negotiations can complement each other to meet the needs of less-developed countries can set the stage for it to become a plausible future (Mohammed 2018).

Development of policies and actions have been suggested as important components for sustainable and responsible fisheries on the high seas. These include ways to curb harmful subsidies (Sala *et al.* 2018; Norse *et al.* 2012; Sumaila 2012), expand area-based management measures (Sumaila *et al.* 2007; O'Leary *et al.* 2012; Ban *et al.* 2014), and apply new technology (Miller 2010; de Souza *et al.* 2016; McCauley *et al.* 2016). The case has even been made to close the high seas to fishing entirely (Sumaila *et al.* 2015; White and Costello 2014). Proponents of high seas fishing closures suggest that such initiatives can contribute towards meeting the Convention on Biological Diversity's Aichi Target 11 of protecting 10 per cent of marine areas by 2020 (Rochette *et al.* 2014), reducing inequality in the distribution of fisheries benefits among fishing nations (Sumaila *et al.* 2015) and increasing resilience of fish stocks to climate change (Cheung *et al.* 2017). The use of automatic identification system (AIS) satellite data to track fishing activities can potentially improve compliance and reduce IUU fishing on the high seas (Dunn *et al.* 2018).

1.2.2 Changing oceans and fisheries on the high seas

Over the course of the 20th century, fish stocks have been responding to ocean warming and associated changes in the physical, biological and chemical properties of the marine environment (Figure 1). Specifically, warming, acidification, deoxygenation and climate-mediated changes in primary production stand to significantly impact production of targeted straddling and highly migratory stocks (Yasuhara *et al.* 2008; Lehodey *et al.* 2011).[3] Generally, marine species worldwide have been observed to shift their geographic distributions towards the poles (Poloczanska *et al.* 2013), to deeper waters (Dulvy *et al.* 2008), or following the temperature gradient of their surrounding environment (Pinsky *et al.* 2013).

Such observed distribution shifts are consistent with expectations informed by the biology of the organisms. Over the course of their evolution, marine species have developed characteristic preferences to environmental temperature and other habitat conditions. As temperatures rise above optimal conditions for different species, their growth and reproduction are impacted and survival rates decline. Such changes may also result in organisms thriving in geographical locations or environments not considered suitable for them before.

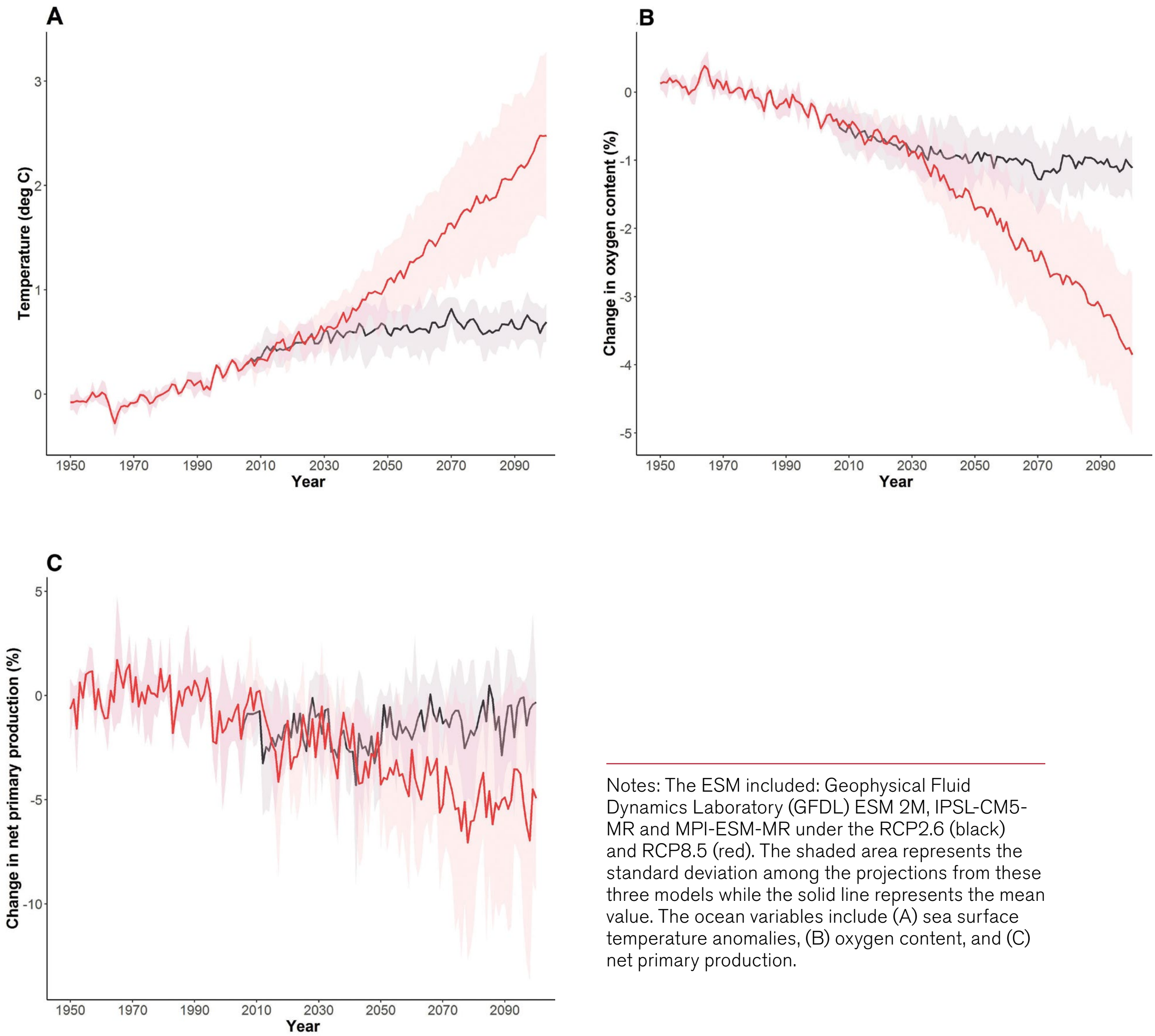
Overall, these shifts in species distribution are leading to the redistribution of fisheries resources, resulting in substantial reduction in potential catches in tropical oceans (Cheung *et al.* 2010), but increased catches – particularly of warmer-water species – in high-latitude regions (Jones and Cheung 2015). Ocean acidification is also increasingly affecting marine fisheries resources (Branch *et al.* 2013; Marshall *et al.* 2017), with projected impacts on catches and dependent communities in the Arctic for instance (Lam *et al.* 2016).

Climate-induced shifts in species distribution affect fish, fisheries and their management across the ocean, including those on the high seas. Particularly for stocks whose distribution straddles the high seas and countries' EEZs, changes in high seas governance under climate change will also impact the productivity of these fish stocks within EEZ boundaries (Popova *et al.* 2019).

Simulation modelling suggests that species abundance and potential fisheries catches of 30 major straddling fish stocks on the high seas are projected to decline by the middle of the 21st century relative to the 2000s

[2] The 'package' of four priority issues encompasses strengthening area-based management tools to protect species and vulnerable ecosystems; integrating cumulative environmental impact assessments to decision-making; defining access and benefits sharing for the management of marine genetic resources; and closing the science and technology divide between developed and developing countries.
[3] Straddling fish stocks are 'the same stock or stocks of associated species [which] occur both within the exclusive economic zone and in an area beyond and adjacent to the zone'. Highly migratory stocks are 'highly migratory species as listed in Annex 1 of UNCLOS [...] and include species that occur both within EEZs and on the high seas' (Maguire *et al.* 2006).

Figure 1. Changes in main ocean variables affecting marine fish stocks on the high seas as projected by three Earth system models (ESM)



Notes: The ESM included: Geophysical Fluid Dynamics Laboratory (GFDL) ESM 2M, IPSL-CM5-MR and MPI-ESM-MR under the RCP2.6 (black) and RCP8.5 (red). The shaded area represents the standard deviation among the projections from these three models while the solid line represents the mean value. The ocean variables include (A) sea surface temperature anomalies, (B) oxygen content, and (C) net primary production.

under the 'business as usual' (RCP8.5) greenhouse gas emission scenario (Cheung *et al.* 2017). Closing the high seas to fishing, or cooperatively managing their fisheries, led to catch projections in EEZs to increase, which may overall compensate for the decline in catches expected under a 'business as usual' scenario (Cheung *et al.* 2017). However, closed areas are one tool in a complex suite of socioecological considerations for the conservation and sustainable management of fisheries. Consequently, more detailed scenarios of the future of fishing on the high seas, including management of fishing effort and changes in the economic incentives of fishing fleets, may alter the implications of closing areas of the high seas for straddling and highly migratory stocks and their fisheries.

1.3 Shared socioeconomic pathways: using scenarios and models to assess ecosystem services

Cumulative human impacts ranging from overexploitation to pollution, habitat degradation and climate change have dramatically altered the marine environment, threatening the survival of numerous species and the oceans' ability to deliver ecosystem services essential to society (Godfray *et al.* 2010; Doney *et al.* 2012; Bell *et al.* 2019). Therefore, there is a critical need to develop effective and informed approaches to achieve the long-term ecological, economic and social sustainability of marine resources utilisation globally.

However, such development is challenged by the uncertainties associated with global environmental and socioeconomic changes, by the policy mechanisms underlying such change, and by the complex interplay across sectors. By investigating possible 'alternative worlds' and the decisions leading to such outcomes, scenario analysis addresses this uncertainty (IPCC 2014). Such an approach allows for the exploration of possible futures for drivers of change, and their expected consequences for biodiversity and associated ecosystem services. It also provides decision makers with a useful framework to elucidate and prepare for the consequences of contrasting political, economic, social, institutional, technological, lifestyle and environmental choices.

Typically, these alternative worlds are described in detail by means of qualitative narratives (also referred to as storylines) that describe in detail what the future might hold with regards to broad societal trends, including the strength of management institutions, political stability or the degree to which citizens are engaged in sustainability initiatives. As a next step, the main ideas conveyed by the qualitative scenario storylines are summarised into key indicators that can be used in models to project the quantitative implications of alternative futures for marine environments and associated ecosystem services. To be most useful in a policymaking context, models typically focus on how management and governance decisions impact on direct drivers. They then project how these impact specific metrics in nature (eg biodiversity, abundance or biomass of certain indicator species). Finally, they project the impacts of such ecosystem changes on the benefits humans derive from these systems, such as fish catches.

Scenarios and models are important tools for prospective analysis that can facilitate the proactive formulation and implementation of science-based policies in support of attaining sustainable social, economic and environmental development (Box 1).

BOX 1. DEFINITIONS OF SCENARIOS AND MODELS

'Scenarios' are representations of possible futures for one or more components of a system, especially for drivers of change in nature and nature's benefits, including alternative policy or management options.

'Models' are qualitative or quantitative descriptions of key components of a system and of relationships between those components. This assessment focuses mainly on models describing relationships between: (i) indirect and direct drivers, (ii) direct drivers and nature, and (iii) nature and nature's benefits to people.

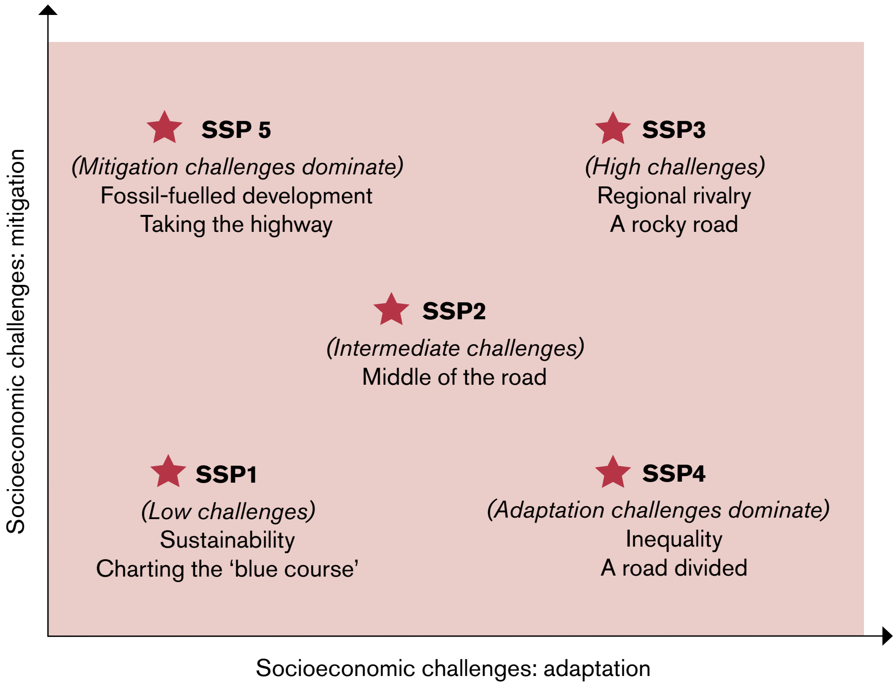
Source: IPBES (2016).

A set of five so-called shared socioeconomic pathways (SSPs) were developed by the modelling community to represent a standardised, internationally recognised framework that provides a description of how global society, demographics and economics might evolve in the absence of climate policy over the next century (O'Neill *et al.* 2017; Riahi *et al.* 2017). The five scenarios span dramatically contrasting worlds.[4] These worlds are shaped by vastly different underlying political, economic, social, environmental, technological and legislative decisions:

- SSP1 depicts a world focused on sustainable growth and equality
- SSP2 depicts a world where historic and current patterns continue to shape the future
- SSP3 depicts a world dominated by 'resurgent nationalism' and regional conflicts
- SSP4 depicts a world characterised by ever-increasing disparities and inequality, and
- SSP5 depicts a world focused on rapid fossil fuel-based and unconstrained economic growth supported by rapid technological developments.

[4] A detailed description of each scenario can be found in Riahi *et al.* (2017).

Figure 2. Mitigation and adaptation challenges for the five SSPs



Source: adapted from O'Neill *et al.* (2017)

Each SSP reflects a world in which mitigation and adaptation challenges vary from low to very high (Figure 2). For instance, SSP1 represents a future world characterised by low challenges to mitigation and adaptation due to relative global equality of income and focused efforts targeted at environmental sustainability, supported by rapid technological advances. Meanwhile, SSP4 features similarly low challenges to mitigation because of rapid technological innovation. However, challenges to climate adaptation are high because of highly unequal investments in human capital and persistent inequality and poverty.

2

Study methodology and objectives

This chapter describes the goal of the research described in this working paper. Our aim was to examine how different plausible future scenarios of social, economic and environmental development – based on the SSP framework – impact the management and governance of biodiversity and living marine resources in ABNJ, particularly in developing countries and the global South under climate change.[5]

Informed by the SSPs, three sets of scenario narratives were developed to represent alternative futures of fisheries on the high seas. Essential elements in the narrative storylines were then translated into contrasting quantitative indicators of fishing effort informed by bioeconomic theories. These three high seas SSPs were projected using simulation models to examine the effects of alternative policy frameworks, as a result of plausible future societal choices, on high seas fish stocks and fisheries. In addition, we included two climate-change scenarios: Representative Concentration Pathway RCP8.5 'business as usual' and RCP2.6 'strong mitigation', to examine how these three high seas governance scenarios performed under climate change. Contrasting area-based management interventions were also explored to examine how they may contribute to the conservation and moderation of the effects of fishing and climate change on straddling and highly migratory fish stocks. The implications of changes in high seas fish stocks included the evaluation of fisheries resources in different countries' EEZs. Outputs used to compare across scenarios included the ecological performance of each scenario (represented by mean species abundance or MSA) and the economic performance of fisheries (depicted by fishery revenue), with a particular focus on developing countries and the global South.

2.1 Developing scenario storylines

Scenarios were developed through contributions from key experts convened at a workshop held in Vancouver, Canada, 19–20 November 2018. Participants were selected based on their disciplinary background, previous exposure to issues on the high seas, and familiarity with the current UN-led intergovernmental

[5] The research was undertaken by the Changing Ocean Research Unit at the Institute for the Oceans and Fisheries, University of British Columbia (UBC) in collaboration with and supported by the International Institute for Environment and Development (IIED).

conference to negotiate an international legally binding instrument. We were able to draw on the expertise of 18 professionals, including fisheries managers, marine ecologists, fisheries scientists, socioecological researchers, economists, marine geospatial scientists and high seas policy advisors, as well as marine policy and fisheries governance specialists.

Participant presentations were used to contextualise the overarching objective of developing alternative plausible narratives for fisheries on the high seas. Topics included the current status of high seas ecosystems and fisheries as well as associated management and governance frameworks. They also explored drivers of change in areas beyond national jurisdiction, social justice as an orienting principle in achieving sustainability and equity, and opportunities and challenges presented by a new high seas treaty. Background on the SSPs and a vision of how they may provide a framework to help inform current research and negotiations on the high seas were also shared.

Participants were then asked to use their background and experience as well as the provided context to draft storylines for fisheries on the high seas under three separate and contrasting SSPs: SSP1, SSP3 and SSP5. Attendees were split into three separate groups – ensuring that each group consisted of experts covering a range of disciplines – and given a specific SSP to start with. At distinct time junctures, SSPs and group assignments were rotated so that each group got the opportunity to discuss qualitative projections of environmental, management, economic, governance and social conditions under each scenario.

At the end of the workshop, the study researchers summarised bullet points and key characteristics provided by each group under each SSP to create storyline drafts. These were posted online and the link circulated to all participants as well as three additional experts (who had been invited to the workshop but were unable to attend) for feedback before being finalised by the study researchers into the storylines presented here.

2.2 Modelling future scenarios of high seas fisheries

Computer simulation models were used to project future changes in fish stock and fisheries on the high seas and in EEZs under different SSPs. A bioeconomic modelling approach was then used to link the results from a biological model and an economic model (Figure 3).

- The biological model employed (a dynamic bioclimate envelope model or DBEM) projects distributional shifts, changes in abundance and catches of exploited marine species in the world's ocean (see Cheung *et al.* 2016 for a detailed description of DBEM).
- The economic model is an effort dynamic model (EDM) that simulates changes in fishing effort in each fishing year based on the expected catch and expected profit of given fisheries.
- A bioeconomic model was also used to quantify changes in fishing intensity.

2.2.1 Biological model

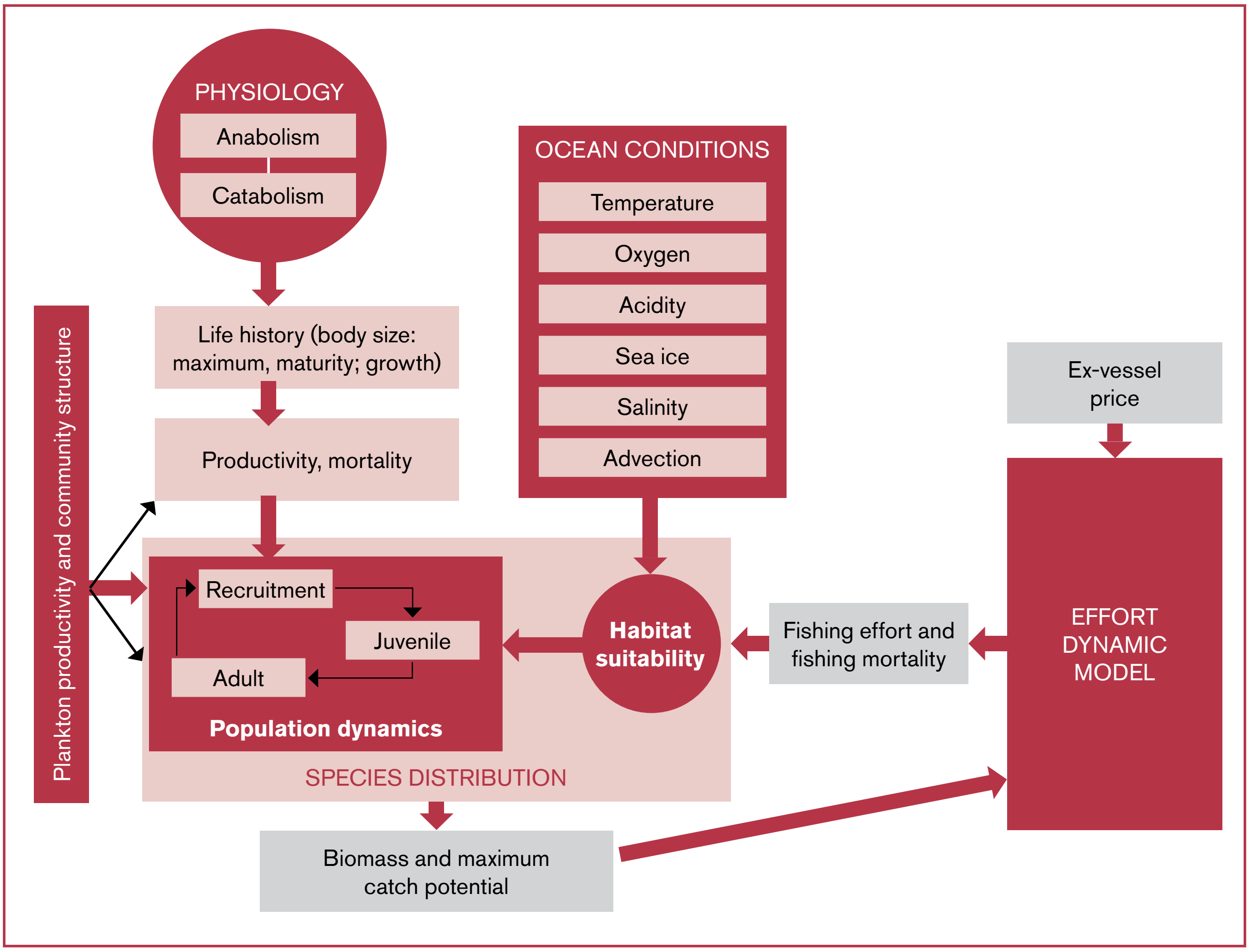
The study first determined the distribution of highly migratory and straddling exploited demersal and pelagic marine fish as well as invertebrate species on the high seas. It focused on high seas catches from 2005–2014, with data available at a resolution of 0.5° latitude x 0.5° longitude. This process was undertaken using an algorithm based on species' depth range, latitudinal range, habitat preferences and broadly known occurrence regions. Values for each of these parameters were obtained from online databases (such as FishBase and SeaLifeBase).

Based on the current distribution of the top 30 exploited marine species (Table 1), accounting for 99 per cent of total catch on the high seas, the DBEM then simulates changes in distribution of abundance and maximum catch potential[6] of fishes and invertebrates over time and space (also on a 0.5° latitude x 0.5° longitude grid) driven by projected changes in ocean conditions. Oceanographic variables were projected using two Earth system models (EDMs) that are part of the fifth phase of the Coupled Model Intercomparison Project: Geophysical Fluid Dynamics Laboratory Earth System Model 2M (GFDL-ESM-2M) and the Institut Pierre-Simon Laplace Coupled Model 5 (IPSL-CM5-MR).

The DBEM also considers physiological and ecological effects of changes in ocean properties on the species themselves as well as density-dependent population growth and movement. The carrying capacity of each species in each grid cell varies according to its habitat suitability, which is predicted by sea surface temperature, salinity, oxygen content, sea ice extent (for polar species), and bathymetry. The DBEM simulates changes in relative abundance and biomass of a species based on changes in population carrying capacity, intrinsic population growth, and the advection-diffusion of adults and larvae in the population driven by ocean conditions projected from Earth system models. Temperature and oxygen concentration are also utilised to simulate changes in individual growth (Table 2).

[6] Understood to represent the maximum potential production from fisheries as described in Cheung *et al.* (2010).

Figure 3. Structure of the DBEM and its linkages to the EDM



Based on projections of the future distribution of selected marine species and projected changes in primary production from the outputs of the Earth system models, the study then estimated the annual maximum catch potential (MCP) using the published empirical model of Cheung *et al.* (2010). MCP is a proxy for maximum sustainable yield (MSY), calculated as:

$$MCP = F_{MSY} \times B$$

where F_{MSY} is the fishing mortality required to achieve MSY (approximated from F_{MSY} = natural mortality rate of the stock) and B is the projected biomass in each year and spatial cell.

Next, the study estimated the projected catch potential based on the fishing mortality (F_{Mort}) derived from projections in fishing effort from the effort dynamic model (EDM) (see also Section 2.2.2). In each grid cell, the projected catch for a given species was allocated to each fishing country based on cell-based data from the reconstructed catch database of the Sea Around Us. Total MCP and catch potential for the top 30 species exploited on the high seas were calculated as the sum of catch in cells identified as areas beyond national jurisdiction.

2.2.2 Effort dynamic model (EDM)

The effort dynamic model assumes that each year, commercial fishers decide to go out fishing or stay at the dock, based on profits accrued over the course of the last fishing year. Over time, total fleet size will change depending on the profitability of the fishery, as equilibrium is reached between investment in new fishing capacity, and the loss of existing capacity to depreciation.

Given this framework, fishing effort (in terms of the number of fishing boats) was projected using contrasting sets of economic and fishery parameters under different environmental and economic conditions. Some economic variables such as unit cost of effort, cost of each fishing boat, inflation rate, reinvestment ratio and depreciation rate are exogenous. Details of variables and parameters used in the EDM are shown in Table 2. Parameters for which data were not available (such as catchability, operating cost, capital cost of a fishing vessel, investment ratio, vessel depreciation rate, and the rate of change of catchability and subsidy etc) were estimated based on historical catch and fishing effort data using the sum-of-squares optimisation approach prior to running the EDM.

Table 1. Top 30 species with the highest catch on the high seas (2005–2014)[7]

TAXON NAME	COMMON NAME	FAMILY	% CATCH TO TOTAL CATCH FOR TOP 30 SPECIES ON THE HIGH SEAS
Katsuwonus pelamis	Skipjack tuna	Scombridae	29.2
Euphausia superba	Antarctic krill	Euphausiidae	19.2
Thunnus albacares	Yellowfin tuna	Scombridae	16.1
Thunnus obesus	Bigeye tuna	Scombridae	9.3
Micromesistius poutassou	Blue whiting	Gadidae	6.1
Prionace glauca	Blue shark	Carcharhinidae	4.7
Thunnus alalunga	Albacore tuna	Scombridae	3.6
Xiphias gladius	Swordfish	Xiphiidae	2.4
Pandalus borealis	Northern prawn	Pandalidae	2.2
Dissostichus mawsoni	Antarctic toothfish	Nototheniidae	0.9
Thunnus maccoyii	Southern bluefin tuna	Scombridae	0.8
Gadus morhua	Atlantic cod	Gadidae	0.7
Reinhardtius hippoglossoides	Greenland halibut	Pleuronectidae	0.7
Coryphaena hippurus	Common dolphinfish	Coryphaenidae	0.4
Carcharhinus longimanus	Oceanic whitetip shark	Carcharhinidae	0.4
Kajikia audax	Striped marlin	Istiophoridae	0.4
Hippoglossoides platessoides	American plaice	Pleuronectidae	0.4
Carcharhinus falciformis	Silky shark	Carcharhinidae	0.4
Auxis thazard	Frigate tuna	Scombridae	0.3
Istiompax indica	Black marlin	Istiophoridae	0.3
Isurus oxyrinchus	Shortfin mako	Lamnidae	0.2
Thunnus orientalis	Pacific bluefin tuna	Scombridae	0.2
Maurolicus muelleri	Silvery lightfish	Sternoptychidae	0.2
Istiophorus platypterus	Indo-Pacific sailfish	Istiophoridae	0.2
Limanda ferruginea	Yellowtail flounder	Pleuronectidae	0.2
Alepocephalus bairdii	Baird’s slickhead	Alepocephalidae	0.1
Melanogrammus aeglefinus	Haddock	Gadidae	0.1
Tetrapturus angustirostris	Shortbill spearfish	Istiophoridae	0.1
Sebastes mentella	Beaked redfish	Sebastidae	0.1
Acanthocybium solandri	Wahoo	Scombridae	0.1

[7] Together, the top 30 species account for over 99 per cent of total catch.

Table 2. Variables used in the DBEM and EDM models

VARIABLES	DEFINITION	UNIT	SOURCES
Biological			
K	Carrying capacity	Metric tonnes	FishBase and SealifeBase
B	Biomass	Metric tonnes	FishBase and SeaLifeBase
r	Intrinsic population growth rate for each species		FishBase and SeaLifeBase
Habitat association	An index of association to particular habitat		Cheung *et al.* (2009)
Movement rate	Estimated based on species' morphology and life style	Metre per second	Cheung *et al.* (2009)
Economics			
p	Ex-vessel price	US$ per tonne	Sea Around Us
CostRate	Inflation rate		**
Cost	Unit cost of effort	US$ per vessel	Sala *et al.* (2018)
Capcost	Cost of each fishing vessel	US$ per vessel	
rev	Total revenue from fishing	US$	**
Totcost	Total cost of effort	US$	Sala *et al.* (2018)
Inv	Reinvestment ratio – proportion of profit reinvested into fishery		**
deprec	Capital depreciation		**
revfleet	Expected per vessel profit	US$	**
profit	Total profit	US$	**
subsidy	Subsidy (expressed as ratio to revenue)	-	Sala *et al.* 2018
Fisheries			
q	Catchability	Metric tonnes/unit effort	**
qinRate	Catchability increase rate	Metric tonnes/unit effort	**
acteff	Active fishing effort	Vessels	**
obseffvar	Initial fishing effort (fleet size)	Vessels	
cureff	Total fishing effort	Vessels	**
addeff	Additional new vessels	Vessels	**
effrep	Effort response to profit – response of latent effort to expected profit (or, how fast do existing boats 'activate' into the fishery?)		**
totobsc	Total observed catch on the high seas	Metric tonnes	Sea Around Us

** No reference source and/or estimated from the effort dynamic model or DBEM.

The model applied in this study is an integrated approach for projecting future impacts of climate change on fisheries as it links changes in fishing effort – based on the change in catch and profit (and vice versa) – to the biological model that projects changes in catch potential (DBEM). Here, profits refer to the financial gains estimated by the difference between total fishing revenues and operating fishing costs, in addition to subsidies at the end of each fishing season.

Based on the dynamic version of the Gordon-Schaefer model (Schaefer 1957), fishers seek to maximise their profits. Hence, fishing profits from their harvest each year determine active fishing effort (in terms of the number of fishing vessels) for the next year, after considering changes in:

- Biomass of exploited species under changing environmental conditions
- Ex-vessel price of fish
- Operating cost of fishing
- Costs of purchasing new vessels
- Investment ratio, and
- The depreciation cost of existing vessels.

If fishing is considered profitable, fishing effort would be expected to increase over time. Similarly, if profits are negative, fishing effort would be expected to decline (potentially to zero) in the next fishing season.

As a next step, the estimated fishing effort for the next year is converted into fishing mortality and provided as an input parameter to the DBEM, which combined with other biological and environmental variables is used to project annual biomass and catch potential of each marine species on the high seas (Figure 4).

2.2.3 Linking scenario storylines to quantitative projection pathways

All countries known to have fishing vessels operating on the high seas were grouped into three major income groups: low-income countries (LIC), middle-income countries (MIC) and high-income countries (HIC), based on their Human Development Index (HDI) ranking (UNDP) (see Figure 4).

For each income group and each of the three defined SSPs, fishing effort on the high seas 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 storylines developed in this report (Table 3; see also Section 2.1 for the storyline development process and Chapter 3 for the storylines themselves). These indicators included ex-vessel price, operating and capital cost of fishing, fishing subsidies and catchability increase rate.

For example, the study assumed that the SSP1 scenario would be characterised by high fuel prices, leading to increases in future fishing costs. It further assumed that, in accordance with the promotion and implementation of measures to support effective sustainable development, fishing nations with a strong presence on the high seas would support the elimination of harmful subsidies for high seas fisheries. This would result in the complete elimination of subsidies in low and middle-income countries (those with a low capacity on the high seas to start with and which mostly depend on fishing in areas within national jurisdiction for income, employment, food security and livelihoods) and a 75 per cent reduction in subsidies in high-income countries by 2050.

In addition to scenarios of future changes in fishing effort, area-based management options were also considered under each SSP (Table 4). Following consultation with IIED, three scenarios – based on closing different proportions of the high seas to fishing – were considered: 0 per cent, 30 per cent and 50 per cent closure.

Of particular interest were the effects of fishing scenarios in combination with area-based high seas management interventions on fisheries resources in different country EEZs. To increase the potential of ‘spill-over’ effects of increases in fish stocks’ abundance in high seas marine protected areas (MPAs) into surrounding EEZs, the study hypothetically allocated the spatial cells (0.5 degree latitude x 0.5 degree longitude) on the high seas that are closest to EEZ boundaries as protected areas (Figure 5). To ensure that MPAs were spread evenly across different ocean basins, the study used the statistics provided by the Food and Agriculture Organization of the United Nations (FAO) Major Fishing Areas as geographical units and prorated the hypothetical protected areas based on the size of each FAO Area.[8] Note that area and location of a given MPA were assigned mainly for the purposes of exploring how area-based interventions may interact with fishing scenarios to determine future potential catches, particularly for coastal states, rather than according to feasibility or other determinant factors.

[8] Information about the FAO Major Fishing Areas can be found here: www.fao.org/fishery/area/search/en

Figure 4. Map of countries in the three income categories (low, medium and high)[9]

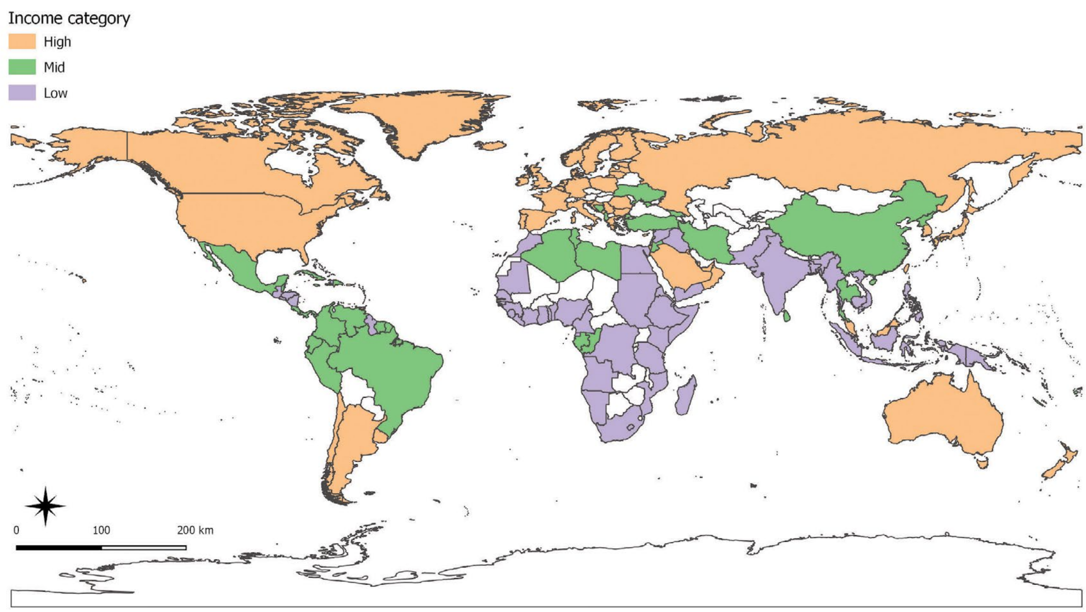


Table 3. Model parameters (indicators) adjusted under different SSPs to reflect quantitatively the broad social considerations captured in the high seas SSP narratives

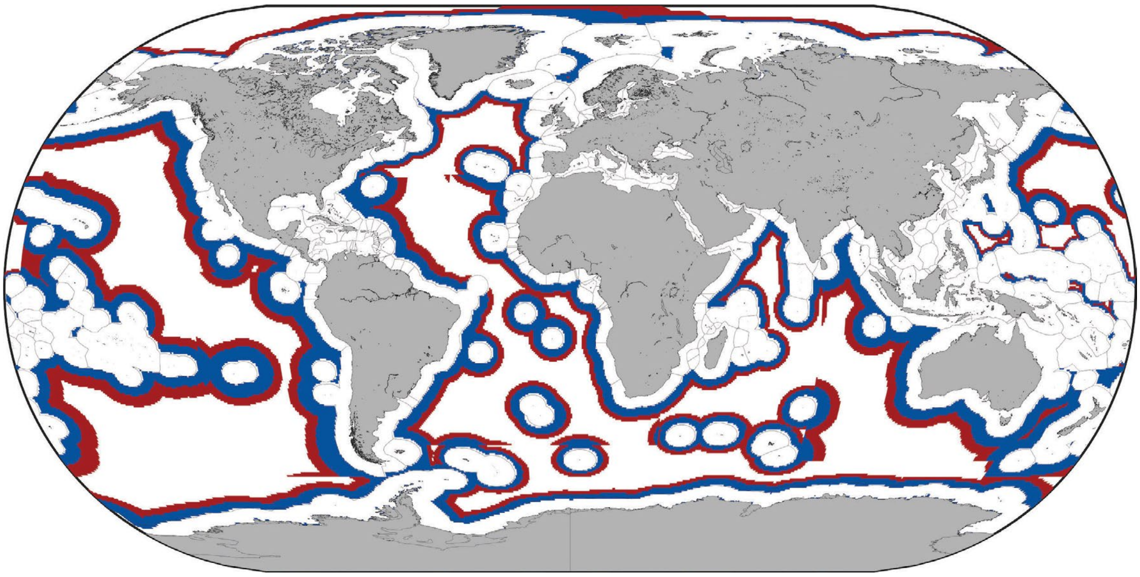
	SSP1	SSP3	SSP5
Ex-vessel price of exploited marine species on the high seas	Unchanged	Low (because of increase in supply): decrease by 25% in 2050	High: increase by 25% in 2050
Operating and capital cost of fishing	Increase by 50% in 2050	Decrease by 25% in 2050	Decrease by 50% in 2050
Fishing subsidies	Reduce: remove for both LIC and MIC; decrease by 75% for HIC	Increase by 25% for LIC; 50% for MIC and HIC	Increase by 25% for all income groups
Catchability increase rate	Unchanged	Unchanged	Increase by 25% for HIC and MIC

Table 4. Future high seas scenarios expressed as plausible combinations of SSPs, climate change scenarios and area-based policy conservation options (as % of marine protected area (MPA) from fishing on the high seas)

CLIMATE CHANGE SCENARIOS UNDER DIFFERENT RCPS	HIGH SEAS FISHERIES UNDER DIFFERENT SSPS			
RCP	SSP (REFERENCE)	SSP1	SSP3	SSP5
2.6	PA: 0%, 30%, 50%	PA: 30%, 50%	N/A	PA: 0%, 30%, 50%
8.5	PA: 0%, 30%, 50%	N/A	0%	PA: 0%, 30%, 50%

[9] The income categories follow the United Nations HDI. Countries in white were not included in the scenario analysis in this study.

Figure 5. Scenarios of high seas fishing closure: 30 per cent (blue) and 50 per cent (blue and red) of high seas area for each FAO statistical area



All modelling work was also undertaken under two contrasting climate change scenarios ('business as usual' RCP8.5 and 'strong mitigation' RCP2.6) to examine how the governance scenarios (SSPs and area-based policy options) performed under climate change.

The study excluded combinations of area-based policy options, climate change RCPs and SSPs that would not be internally consistent with the scenario storylines (ie ones that would be considered not plausible) (Table 4). For example, under SSP3 ('rough seas ahead'), the storyline would not logically be compatible with large high seas MPAs, as it would be unlikely that the world would reach an agreement on such a type of area-based intervention. Similarly, SSP1 ('charting the blue course'), where the world would engage in strong carbon-mitigation measures, would be incompatible with a 'business as usual' (RCP8.5) carbon emission pathway.

The study simulated changes in fish stock abundance and potential fisheries catches using DBEM for each combination listed in Table 4. The model outputs were then used to calculate three quantitative indicators that represented different dimensions of ocean sustainability. These indicators included:

- Changes in total fisheries catches
- Changes in mean species abundance (MSA), and
- Changes in fisheries profits.

Indicator values are reported by EEZs grouped by the three different country income groups (low, medium and high) and for the high seas. The study focused on three future time periods and calculated a 20-year average for each to reduce the effect of interannual variability of ocean conditions on the result:

- Near future (2021–2040)
- Mid-21st century (2041–2050), and
- End of the 21st century (2081–2100).

3

Results: unpacking the scenario storylines

The three future high seas SSP scenarios described in this chapter enable us to explore possible economic and environmental impacts on the high seas as well as issues of governance and management. It also examines modelled projected changes in fish catches, species abundance and economic viability of fisheries across different income-group countries and under different SSPs combined with area-based management measures and climate change.

3.1 Scenario SSP1: charting the 'blue course'

This section looks at the plausible future high seas scenario developed for this study and based on the shared socioeconomic pathway framework of SSP1. This narrative describes a future on the high seas where challenges to adaptation and mitigation are both low:

Sustainability becomes a key leitmotiv, with actions at national and international levels fostering more inclusive development and emphasising environmental stewardship. Consequently, management of the global commons improves, and the current emphasis on economic growth is replaced by a shift towards 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).

3.1.1 Economic impacts

In this narrative, and moving towards a sustainable way of life and development, powerful high seas fishing nations agree to progressively eliminate harmful fishing subsidies, including on the high seas. This decision, together with high fuel prices – due to stringent taxes and regulations for cleaner energy – make fishing on the high seas generally unprofitable and result in a dramatic decline of (and investment in) fishing effort. Consequently, to promote technology transfer as targeted under the SDGs, high seas fishing nations donate – and/or sell at a discounted price – redundant vessels from their high seas fleets to least developed countries in support of their EEZ fishing capacity and more equitable development in line with SDG 14.7 to increase by 2030 'the economic benefits to SIDS and LDCs from the sustainable use of marine resources, including through sustainable management of fisheries, aquaculture and tourism' (Sustainable Development Goals Knowledge Platform). Sustainability principles also guide fishing in different country EEZs.

In this scenario, consumers are aware of the power of their choices and their role in achieving social and environmental sustainability. They demand transparency in seafood sourcing, labour conditions and means of harvest, leading to the growth of comprehensive seafood certification schemes and traceability programmes (with prices reflecting environmental sustainability requirements). As part of this movement, greater transparency in monitoring of financial investments in fisheries, fishing agreements, and associated data is achieved (for example, through enterprises such as the Fisheries Transparency Initiative or FiTI). Customers limit the purchase of fish caught on the high seas and support sustainable fisheries for the same species within EEZs, as these fleets typically support more jobs and have a lower carbon footprint per trip.

SSP1 also sees the promotion of technology transfer, government taxes of private enterprises, and other economic incentives to land and process fish in LDCs into value-added products prior to export. This leads to greater profits that are used to further development – including through investments in welfare, education, infrastructure and health. More stable catches and improved earnings contribute to livelihoods as well as both food and nutritional security.

3.1.2 Management and governance

In the projections for SSP1, the economic and political climate of the day leads to and supports strong, representative and effective institutions and transparent decision-making in most countries.

Civil society engagement is high and constructive. Partnerships between non-governmental organisations (NGOs) 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 upon institutional capacity and, based on scientific evidence, effectively implement adaptive programmes 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. This ILBI strengthens the mandate of RFMOs and their efficacy, leading to the successful implementation of precautionary and integrated ecosystem-based management approaches (including stringent bycatch rules and marine protected areas) on the high seas.

Nations and the private sector put in place measures to document and monitor commitments to social responsibility and environmental sustainability in the seafood sector.

Fisheries that remain profitable on the high seas in the absence of harmful subsidies are managed via an evidence-based, adaptive quota system, such as a vessel day scheme, that is allocated in an equitable manner among fishing nations.

Technological developments allow for the real-time tracking and effective monitoring of all fishing activities. In combination with 100 per cent observer coverage, such initiatives support the rigorous traceability requirements for sustainability and social responsibility of established certification schemes.

3.1.3 Environmental impacts

Also projected by SSP1 is that coordinated efforts undertaken among the above-mentioned institutions will lead to the implementation of conservation areas. These are identified according to scientific criteria that protect unique habitats and ecologically or biologically significant marine areas (EBSA), such as locations known for their high biological productivity or biodiversity (key biodiversity areas or KBAs).

In addition, there will be a decline in high seas fishing effort because of carbon pricing and the elimination of harmful subsidies. This results in the recovery of high seas biodiversity, particularly targeted straddling and highly migratory fish stocks and an increase in their abundance in different country EEZs. This increases social and ecological benefits in systems closer to shore, including greater catches of key pelagic target species, to the benefit of a number of LDCs.

3.2 Scenario SSP3: regional rivalry and rough seas ahead

This section looks at the plausible future high seas scenario developed for this study and based on the shared socioeconomic pathway framework of SSP3. This narrative describes a future on the high seas where challenges to adaptation and mitigation are both high. And as inequalities worsen, volatility, antagonism and conflict increase:

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 *et al.* (2017) and Riahi *et al.* (2017)

3.2.1 Economic impacts

In this scenario, to satisfy an increase in domestic seafood consumption, industrial fishing on the high seas expands. Dependent on setting, fishing levels in country EEZs are either maintained at current levels or increased as more industrialised players gain more access. Exploitation on the high seas is driven by high-income nations, who continue to heavily subsidise their fishing sector, allowing for an increase in fleet size and fishing capacity (but with no notable changes in fishing efficiency due to low investments in technological development). Lowered fishing costs contribute to this tendency, partly due to the use of forced or underpaid labour on vessels and in processing plants.

The increased consolidation of the fishing sector, with few beneficiaries located in developing nations, further ensures that high-income countries continue to assert and expand their influence and dominance. With global governance regimes not accounting for issues of fair distribution and equity or high tariffs imposed by wealthy nations on their products, food security concerns and poverty levels in developing nations rise. This situation is exacerbated by high population growth in LDCs, and the inability of coastal fisheries to support increased seafood demand. Consequently, inequality among (and within) nations grows rapidly.

3.2.2 Management and governance

The SSP3 narrative sees an increasing mistrust among participating members of global management bodies (including RFMOs). Opaque decision making and corruption leads to a strong lack of cooperation within and across organisations, eroding their mandate and effectiveness. Weak international institutions in turn result in a lack of capacity for enforcement of policies in areas beyond national jurisdiction.

The lack of effective global standards as well as monitoring and enforcement mechanisms also leads to the limited success of international treaties and agreements. Levels of IUU fishing increase, particularly through encroachment by powerful nations' high seas fleets on other nations' EEZs – especially those of developing countries that lack the capacity to effectively enforce sovereignty over their stocks.

This trend is associated with a rising loss in research capacity and an overall decline in and support for evidence-based decision making. Poor traceability exacerbates issues of inequity, further concentrating wealth accrued from fisheries development in the hands of a few nations. By focusing on national issues, strengthening management and enforcement of regulations within their own waters, and establishing adaptive governance mechanisms, a number of Small Island Developing States with large EEZs, particularly in the Pacific, are able to close pockets of the high seas to fishing by other nations to further their own benefits.

3.2.3 Environmental impacts

This scenario projects that a high fishing effort will be exerted on stocks by the subsidised fleets of highly industrialised nations. This results in the continued degradation of deep-sea habitats, loss of biodiversity, and the decline of highly migratory and straddling stocks with impacts extending into different country EEZs.[10] These declines disproportionately affect LDCs which depend on fish for food and nutritional security and rely on large exports of pelagic species as an important source of foreign exchange and employment.

Fishing practices are focused on maximising profit, often at the expense of the environment (for example, the extensive use of destructive fishing gears or high rates of bycatch). Increasingly uncontrolled, unmonitored and unselective fishing effort quickly leads to declining catch per unit effort and systematic overfishing of the high seas. Investment in research and related data collection to set quotas, monitor stocks and the environment declines. Consequently, biodiversity on the high seas is increasingly under threat and the number of red listed species increases and/or their status deteriorates (including culturally important species such as tunas, whales, sharks and turtles).[11]

As a result of the decline in or lack of interest in the status of the environment by governments, NGO financing from the private sector increases. Such investment primarily supports the development of technological fixes, resulting in an increase in the reliance of such approaches to deal with environmental concerns. In a few instances, wealthy concerned individuals leverage environmentalism and conservationism on the high seas by locating closed areas to strongly benefit their own interests and/or simply to exclude others.

[10] It is conceivable that other extractive activities on the high seas such as extensive bioprospecting and mining of nodules would contribute to this trend.
[11] Established in 1964, the International Union for Conservation of Nature's (IUCN's) Red List of Threatened Species is the world's most comprehensive information source on the global conservation status of animal, fungi and plant species. See www.iucnredlist.org.

3.3 Scenario SSP5: fossil-fuelled development – the ocean superhighway

This section looks at the plausible future high seas scenario developed for this study and based on the shared socioeconomic pathway framework of SSP5. This narrative describes a future on the high seas where challenges to adaptation are low but challenges to mitigation are high:

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).

3.3.1 Economic impacts

In the SSP5 scenario there is a strong emphasis on rapid economic growth worldwide, so that all countries may enjoy the benefits of industrialisation and capitalism. This leads to a substantial increase in energy demand. Economic incentives support competitive markets and thus high levels of international trade, contributing to a strongly globalised world. Developed countries also invest in management in LDCs, including through technology transfer for example, recognising the benefits that accrue from fostering overall development worldwide. Activities in LDCs seek to enhance social and human capital.

Driven by the success of this rapid fossil-fuelled growth, poverty levels drop. Wealth among developed and developing countries becomes more evenly distributed. Rapid development leads to the convergence among countries and the rise in long-term global average income levels. 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.

Vertical integration leads to the consolidation of the fishing sector with activities being controlled by a few large corporations. As targeted under the SDGs, and supported by rapid economic growth, developed nations promote technology transfer, supporting the expansion of LDC fleets on the high seas. The latter is further facilitated by low labour costs in LDCs. Developed countries deploy remotely controlled fish aggregating devices (FADs) and further invest in highly efficient technology, such as automatic robotic fishing. This results in a further increase of activities on the high seas, including the exploration of marine genetic resources and seabed mining.

3.3.2 Management and governance

In SSP5, the emphasis is on rapid fossil-fuelled economic development. This leads to increased investment, participation and influence in activities on the high seas by emerging economies. Currently developed countries and emerging economies like China and India focus the application of fishing management activities on profit maximisation (in other words, fisheries management prioritises financial gains and production, rather than jobs, livelihoods and human well-being). Monitoring the impact of fishing remains limited and RFMOs and other management organisations focus on single-species stock assessment and provisioning ecosystem services. 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.

Rising demand for and consumption of seafood products by an increasing middle-class further drives the targeting of highly migratory and straddling stocks on the high seas. There is an increase and improvement in short-term adaptation efforts to climate change because of improvements in adaptive capacity. This ensures seafood supply in the short term. However, delays in establishing global action mean effective global cooperation does not occur until around 2030. Despite these efforts, longer-term adaptation is not effective because of the strong impacts from climate change on society.

3.3.3 Environmental impacts

High fossil-fuel use results in elevated CO_2 emissions, leading to a dramatic rise in ocean temperatures and worsening effects of ocean acidification. Geoengineering initiatives are implemented to mitigate impacts on the abundance and distribution of stocks and avoid runaway climate change. However, the effectiveness and wider socioecological ramifications of such technological activities remain highly uncertain.

Low fuel costs and advanced technology make fishing on the high seas accessible and profitable, with countries exploiting available stocks further and deeper. As a consequence of poor monitoring and weak science-based management, the stock abundance of most targeted fish species declines with substantive knock-on effects on stocks in country EEZs and their associated catches. Biodiversity conservation is considered a low priority with the use of highly effective fishing gear contributing to habitat destruction, the dramatic loss of biodiversity, accelerated rates of species extinction and the overall decline in the productivity of high sea ecosystems.

Thus, overall global improvements in well-being are at the expense of the next generation. Intergenerational issues improve, but longer-term environmental problems will remain a huge challenge for future generations.

3.4 Quantitative model projections

3.4.1 Projected changes in fishing effort and fishing mortality on the high seas

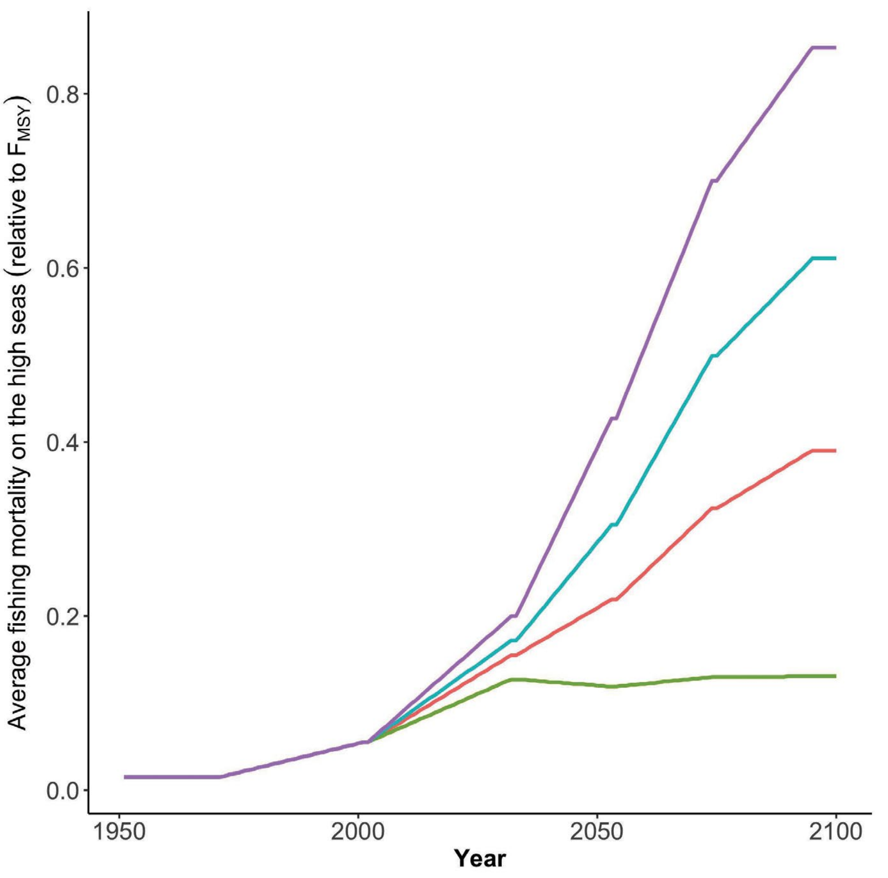
Updated simulation model projections showed that actual fishing mortality relative to fishing mortality at MSY (F_{MSY}) for the top 30 species caught on the high seas increased by 40 per cent and doubled the fishing mortality, when compared to the current status (SSP reference or SRef) by the 2030s and 2050s (Figure 6).

Under SSP1, relative fishing mortality (x F_{MSY}) – without any climate forcing applied – was projected to increase until early 2030 and then level off. By the end of the century, relative fishing mortality (x F_{MSY}) for all 30 species was projected to increase by about 17 per cent relative to the current status under this scenario. Relative fishing mortality (x F_{MSY}) was projected to increase continuously and increase two-fold and three-fold by the 2050s under both SSP3 and SSP5 scenarios respectively – again, without climate-forcing considerations.

3.4.2 Projected changes in fish stocks and fisheries catches on the high seas

Catches on the high seas were projected to increase under a reference (ie extrapolation based on current trend) or 'business as usual' fishing scenario in the 21st century relative to present day conditions (Table 5). Under the reference scenario, catches were projected to increase in the near-term (2030) under both RCPs (RCP2.6 and RCP8.5) by 141–148 per cent (based on the two Earth system models) without any high seas closure.

Figure 6. Projected fishing mortality from 1950 to 2100



Notes: the fishing mortality rates are relative to the level required to achieve maximum sustainable yield projected under the current status (SSP reference or SRef, red line) and the projected scenarios SSP1 (green line), SSP3 (blue line) and SSP5 (violet line). SSP scenario projections as displayed here do not consider any climate forcing.

In high seas protected-area scenarios (30 per cent and 50 per cent), increases in total catches were projected to be between 60 and 65 per cent and between 10 and 16 per cent respectively. By the 2050s (average of 2041–2060), catches on the high seas were projected to increase to around 240 per cent without protected areas, and between 123 and 131 per cent and between 58 and 61 per cent with 30 per cent and 50 per cent protected areas respectively. Variations in projected high seas catches between climate change scenarios (RCPs) were smaller relative to the differences in projected catches between SSPs and protected areas scenarios. Specifically, high seas catches were projected to be lower than the reference (no protected area) with the 30 per cent and 50 per cent protected area scenarios and under SSP1.

Mean species abundance (MSA) on the high seas was projected to increase in the 21st century under the reference scenario (Table 6). Average decrease in MSA was projected to be between -1 and -9 per cent and between -1 and -20 per cent by the 2030s and the 2050s respectively (relative to the 2000s) across RCPs and protected-area scenarios. However, projected decrease in MSA was substantially larger under RCP8.5 than RCP2.6 by 2050 and 2090. The projected differences in MSA were biggest between SSPs than between RCPs.

Table 5. Change in marine catch potential on the high seas under different high seas SSPs, hypothetical protected area scenarios and RCPs[12]

YEAR	SHARED SOCIO-ECONOMIC PATHWAYS (SSPS)	% CHANGE IN CATCH RELATIVE TO THE CURRENT STATUS					
		0% OF MARINE PROTECTED AREA		30% OF MARINE PROTECTED AREA		50% OF MARINE PROTECTED AREA	
		CLIMATE CHANGE SCENARIOS					
		RCP2.6	RCP8.5	RCP2.6	RCP8.5	RCP2.6	RCP8.5
2030	Reference	141 to 147	143 to 148	60 to 63	64 to 65	10 to 12	11 to 16
	SSP1	101 to 104	-	34 to 36	-	-9 to -7	-
	SSP3	-	167 to 172	-	79 to 80	-	-
	SSP5	-	203 to 209	-	102 to 104	-	39 to 46
2050	Reference	237 to 248	234 to 247	123 to 130	123 to 131	54 to 58	58 to 61
	SSP1	108 to 115	-	38 to 42	-	-6 to -3	-
	SSP3	-	315 to 345	-	178 to 195	-	-
	SSP5	-	420 to 458	-	250 to 272	-	155 to 161
2090	Reference	447 to 453	328 to 458	265 to 266	209 to 273	150 to 151	130 to 163
	SSP1	129 to 131	-	52 to 53	-	4 to 5	-
	SSP3	-	473 to 648	-	306 to 403	-	-
	SSP5	-	562 to 762	-	373 to 485	-	267 to 315

[12] The range was based on projections using outputs from the two ESMs.

Table 6. Change in mean species abundance under different high seas SSPs, hypothetical protected area scenarios and RCPs[13]

YEAR	SHARED SOCIO-ECONOMIC PATHWAYS (SSPS)	% CHANGE IN MSA RELATIVE TO THE CURRENT STATUS					
		0% OF MARINE PROTECTED AREA		30% OF MARINE PROTECTED AREA		50% OF MARINE PROTECTED AREA	
		CLIMATE CHANGE SCENARIOS					
		RCP2.6	RCP8.5	RCP2.6	RCP8.5	RCP2.6	RCP8.5
2030	Reference	-9 to -7	-8 to -5	- 7 to -4	-5 to -2	-5 to -4	-3 to -1
	SSP1	-7 to -5	-	-6 to -3	-	-4 to -2	-
	SSP3	-	-9 to -6	-	-7 to -3	-	-
	SSP5	-	-11 to -7	-	-8 to -4	-	-6 to -2
2050	Reference	-13 to -9	-20 to -7	-9 to -5	-21 to -3	-7 to -3	-18 to -1
	SSP1	-9 to -4	-	-6 to -2	-	-5 to -1	-
	SSP3	-	-24 to -11	-	-20 to -6	-	-
	SSP5	-	-28 to -16	-	-23 to -9	-	-20 to -5
2090	Reference	-20 to -15	-55 to -19	-14 to -8	-51 to -13	-10 to -5	-47 to -9
	SSP1	-8 to -3	-	-6 to -1	-	-6 to 1	-
	SSP3	-	-61 to -29	-	-57 to -20	-	-
	SSP5	-	-67 to -39	-	-61 to -27	-	-58 to -19

3.4.3 Projected changes in fish stocks and fisheries catches in EEZs

Across EEZs, under the reference 'business as usual' scenario and without any high seas protected area, total maximum catch potential was projected to decrease throughout the 21st century (Tables 7 and 8). Maximum catch potential is an indicator of the theoretical productivity of fish stocks – a proxy for maximum sustainable yield. Without any protected area, maximum catch potential in all the EEZs was projected to decline by 1 per cent and 4 per cent relative to the 2000s under RCP2.6 and RCP8.5 respectively. Maximum catch potential in EEZs of the middle-income country group was projected to decrease by 2050 (1 per cent and 6 per cent under RCP2.6 and RCP8.5 respectively). Projected maximum catch potential was slightly higher under the 30 per cent and 50 per cent protected-area scenario by 2050 relative to no protected area.

MSA in EEZs was projected to decrease by the 2050s relative to the 2000s under the reference scenario, although protecting 30 per cent and 50 per cent of the high seas reduced the projected decline by about 25 per cent.

In the EEZs, SSPs and RCPs were the main factors affecting changes in maximum catch potential and MSA. Changes in maximum catch potential was projected to be relatively small under SSP1 and RCP2.6 by 2050 relative to 2000, but decreased much more substantially under SSP5 and RCP8.5. This pattern is similar across countries in different income groups. MSA, specifically in low-income countries, remained relatively constant on average under SSP1 and RCP2.6 by 2050. However, MSA was projected to decrease by around 7 per cent by 2050 under SSP3 and SSP5 under RCP8.5.

[13] The range was based on projections using outputs from the two ESMs.

Table 7. Change in mean species abundance (MSA) in the EEZs of (a) LICs (b) MICs, (c) HICs and (d) High seas under different high seas SSPs, hypothetical protected area scenarios and RCPs[14]

(a) Low-income countries – change in MSA in EEZ

YEAR	SHARED SOCIO-ECONOMIC PATHWAYS (SSPS)	% CHANGE IN MSA RELATIVE TO THE CURRENT STATUS IN EEZ					
		0% OF MARINE PROTECTED AREA		30% OF MARINE PROTECTED AREA		50% OF MARINE PROTECTED AREA	
		CLIMATE CHANGE SCENARIOS					
		RCP2.6	RCP8.5	RCP2.6	RCP8.5	RCP2.6	RCP8.5
2030	Reference	-4 to -3	-5 to -2	-4 to -3	-5 to -1	-4 to -3	-5 to -1
	SSP1	-4 to -3	-	-4 to -3	-	-4 to -3	-
	SSP3	-	-	-	-5 to -1	-	-
	SSP5	-	-6 to -2	-	-5 to -1	-	-6 to -1
2050	Reference	-6 to -1	-13 to -1	-5 to 0	-13 to 0	-5 to -0	-13 to 0
	SSP1	-6 to -1	-	-5 to 0	-	-5 to 0	-
	SSP3	-	-	-	-12 to 0	-	-
	SSP5	-	-14 to -2	-	-12 to 0	-	-14 to 0
2090	Reference	-6 to -2	-46 to -9	-4 to 0	-46 to -7	-4 to 0	-46 to -7
	SSP1	-5 to -1	-	-4 to -0	-	-4 to 0	-
	SSP3	-	-	-	-	-	-
	SSP5	-	-48 to -11	-	-45 to -7	-	-48 to -7

(b) Middle-income countries – change in MSA in EEZ

YEAR	SHARED SOCIO-ECONOMIC PATHWAYS (SSPS)	% CHANGE IN MSA RELATIVE TO THE CURRENT STATUS IN EEZ					
		0% OF MARINE PROTECTED AREA		30% OF MARINE PROTECTED AREA		50% OF MARINE PROTECTED AREA	
		CLIMATE CHANGE SCENARIOS					
		RCP2.6	RCP8.5	RCP2.6	RCP8.5	RCP2.6	RCP8.5
2030	Reference	-20 to -6	-22 to 1	-20 to -5	-22 to 1	-20 to -5	-22 to 2
	SSP1	-20 to -6	-	-20 to -5	-	-20 to -5	-
	SSP3	-	-22 to 1	-	-	-	-
	SSP5	-	-22 to 0	-	-21 to 1	-	-21 to 2
2050	Reference	-26 to -12	-38 to -20	-26 to -11	-38 to -19	-26 to -11	-38 to -19
	SSP1	-26 to -11	-	-26 to -11	-	-26 to -11	-
	SSP3	-	-39 to -20	-	-	-	-
	SSP5	-	-39 to -21	-	-37 to -19	-	-39 to -19
2090	Reference	-28 to -13	-65 to -48	-27 to -12	-65 to -47	-27 to -12	-65 to -47
	SSP1	-27 to -12	-	-27 to -12	-	-27 to -12	-
	SSP3	-	-66 to -49	-	-	-	-
	SSP5	-	-67 to -50	-	-64 to -47	-	-67 to -47

[14] The range was based on projections using outputs from the two ESMs.

(c) High-income countries – change in MSA in EEZ

YEAR	SHARED SOCIO-ECONOMIC PATHWAYS (SSPS)	% CHANGE IN MSA RELATIVE TO THE CURRENT STATUS IN EEZ					
		0% OF MARINE PROTECTED AREA		30% OF MARINE PROTECTED AREA		50% OF MARINE PROTECTED AREA	
		CLIMATE CHANGE SCENARIOS					
		RCP2.6	RCP8.5	RCP2.6	RCP8.5	RCP2.6	RCP8.5
2030	Reference	-8 to -3	-10 to -4	-7 to -2	-10 to -3	-7 to -2	-10 to -3
	SSP1	-8 to -2	-	-7 to -2	-	-7 to -2	-
	SSP3	-	-10 to -4	-	-	-	-
	SSP5	-	-10 to -4	-	-9 to -3	-	-10 to -3
2050	Reference	-12 to -2	-28 to -3	-11 to 0	-28 to -2	-11 to 0	-28 to -2
	SSP1	-12 to -1	-	-11 to 0	-	-11 to 0	-
	SSP3	-	-29 to -4	-	-	-	-
	SSP5	-	-29 to -4	-	-28 to -2	-	-29 to -2
2090	Reference	-12 to 0	-70 to -14	-11 to 2	-70 to -13	-11 to 2	-70 to -12
	SSP1	-11 to 1	-	-11 to 3	-	-10 to 2	-
	SSP3	-	-71 to -14	-	-	-	-
	SSP5	-	-71 to -15	-	-70 to -13	-	-71 to -13

Table 8. Change in marine catch potential (MCP) in the EEZs of (a) LICs (b) MICs (c) HICs and (d) High seas under different high seas SSPs, hypothetical protected area scenarios and RCPs[15]

(a) Low-income countries – changes in MCP in EEZs

YEAR	SHARED SOCIO-ECONOMIC PATHWAYS (SSPS)	% CHANGE IN MCP RELATIVE TO THE CURRENT STATUS IN EEZ					
		0% OF MARINE PROTECTED AREA		30% OF MARINE PROTECTED AREA		50% OF MARINE PROTECTED AREA	
		CLIMATE CHANGE SCENARIOS					
		RCP2.6	RCP8.5	RCP2.6	RCP8.5	RCP2.6	RCP8.5
2030	Reference	-3 to -2	-5 to -2	-3 to -2	-4 to -1	-3 to -2	-4 to -1
	SSP1	-3 to -2	-	-3 to -2	-	-3 to -2	-
	SSP3	-	-5 to -2	-	-	-	-
	SSP5	-	-1.8	-	-4 to -1	-	-4 to -1
2050	Reference	-5 to 0	-9 to 0	-4 to 1	-8 to 1	-4 to 1	-8 to 1
	SSP1	-4 to 0	-	-4 to 1	-	-4 to 1	-
	SSP3	-	-10 to -1	-	-	-	-
	SSP5	-	-10 to -1	-	-8 to 0	-	-8 to 1
2090	Reference	-5 to -1	-35 to -7	-3 to 1	-34 to -5	-3 to 1	-34 to -5
	SSP1	-4 to 0	-	-3 to 0	-	-3 to 1	-
	SSP3	-	-36 to -8	-	-	-	-
	SSP5	-	-37 to -9	-	-34 to -5	-	-34 to -5

(b) Middle-income countries – changes in MCP in EEZs

[15] The range was based on projections using outputs from the two ESMs.

YEAR	SHARED SOCIO-ECONOMIC PATHWAYS (SSPS)	% CHANGE IN MCP RELATIVE TO THE CURRENT STATUS IN EEZ					
		0% OF MARINE PROTECTED AREA		30% OF MARINE PROTECTED AREA		50% OF MARINE PROTECTED AREA	
		CLIMATE CHANGE SCENARIOS					
		RCP2.6	RCP8.5	RCP2.6	RCP8.5	RCP2.6	RCP8.5
2030	Reference	-11 to 0	-12 to 1	-10 to 1	-11 to 2	-10 to 1	-11 to 2
	SSP1	-10 to 1	-	-10 to 1	-	-10 to 1	-
	SSP3	-	-12 to 1	-	-	-	-
	SSP5	-	-12 to 1	-	-11 to 2	-	-11 to 2
2050	Reference	-13 to -3	-23 to -10	-12 to -2	-21 to -9	-12 to -2	-21 to -9
	SSP1	-13 to -2	-	-12 to -2	-	-12 to -2	-
	SSP3	-	-23 to -11	-	-	-	-
	SSP5	-	-23 to -11	-	-21 to -9	-	-21 to -9
2090	Reference	-15 to -3	-41 to -25	-13 to -1	-39 to -23	-13 to -1	-39 to -23
	SSP1	-13 to -1	-	-13 to 1	-	-0.6	-
	SSP3	-	-42 to -27	-	-	-	-
	SSP5	-	-43 to -28	-	-39 to -23	-	-39 to -23

(c) High-income countries – changes in MCP in EEZs

YEAR	SHARED SOCIO-ECONOMIC PATHWAYS (SSPS)	% CHANGE IN MCP RELATIVE TO THE CURRENT STATUS IN EEZ					
		0% OF MARINE PROTECTED AREA		30% OF MARINE PROTECTED AREA		50% OF MARINE PROTECTED AREA	
		CLIMATE CHANGE SCENARIOS					
		RCP2.6	RCP8.5	RCP2.6	RCP8.5	RCP2.6	RCP8.5
2030	Reference	-5 to -2	-6 to -4	-4 to -2	-6 to -3	-4 to -2	-6 to -3
	SSP1	-5 to -2	-	-4 to -2	-	-4 to -2	-
	SSP3	-	-6 to -4	-	-	-	-
	SSP5	-	-6 to -4	-	-6 to -3	-	-6 to -3
2050	Reference	-7 to -2	-20 to -5	-6 to -1	-20 to -5	-6 to -1	-20 to -5
	SSP1	-7 to -1	-	-6 to -1	-	-6 to -1	-
	SSP3	-	-21 to -6	-	-	-	-
	SSP5	-	-21 to -6	-	-20 to -5	-	-20 to -5
2090	Reference	-7 to 0	-64 to -17	-6 to 1	-64 to -16	-5 to 1	-64 to -16
	SSP1	-6 to 1	-	1	-	1.3	-
	SSP3	-	-64 to -18	-	-	-	-
	SSP5	-	-65 to -18	-	-64 to -16	-	-64 to -16

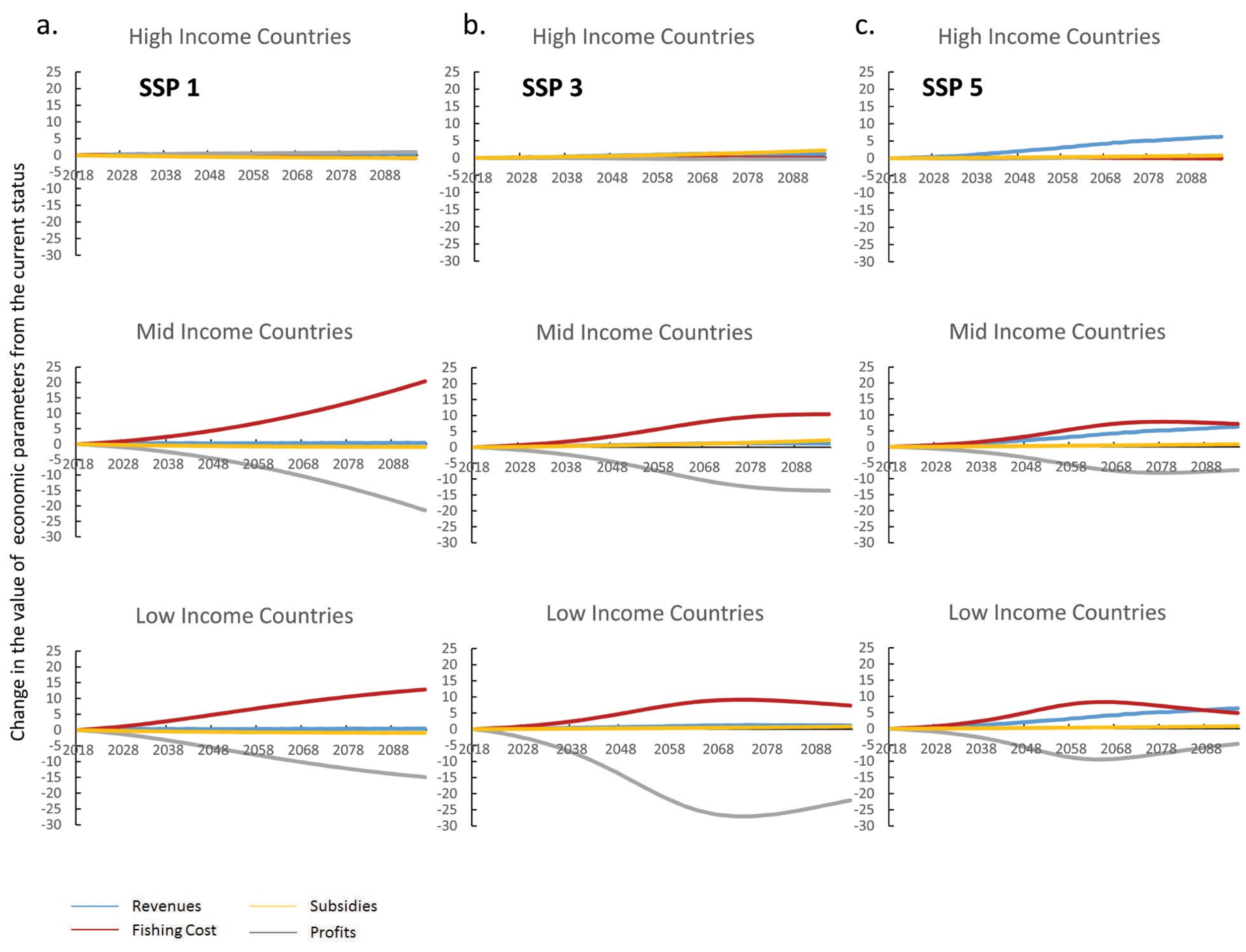
3.4.4 Projected socioeconomic changes

Under SSP1, catches on the high seas are projected to increase through time, with fisheries revenues in all three income groups projected to increase slightly (Figure 7). However, fishing cost on the high seas is expected to increase by 50 per cent for all income groups by the 2050s. Fishing cost is also expected to continue to increase after 2050 under this SSP.

For high-income countries, under SSP1 total fishing cost is projected to decrease slightly even though the unit fishing cost is expected to increase. This is because fishing effort has been adjusted to adapt to lower subsidies and relatively stable revenues. Although the change in fisheries revenue is still positive, the change in fishing profits (the net benefits from fishing after deducting fishing cost and considering fisheries subsidies) is negative. This is because the rate of change in fishing cost is higher than that of fishing revenue for both middle and low-income fishing country groups. Under SSP1 it is assumed that, as societies are more aware of ocean sustainability, subsidies are completely eliminated in both low-income countries (LIC) and middle-income countries (MIC) and reduced by 75 per cent by the 2050s for high-income countries (HIC).

In SSP3, although catches from the high seas are projected to increase in the future, revenue from high seas fishing is projected to be more or less stable. This is because fish prices are expected to decrease due to an increase in seafood supply. Meanwhile, in

Figure 7. Changes in projected revenues, fishing costs, subsidies and profits for different income-group countries under different high seas SSPs



Notes: Figure 7 shows changes in the projected revenues (blue line), fishing costs (red line), fishing subsidies (orange line) and fishing profits (grey line) of each income group of countries throughout the time series under different high seas SSP scenarios: a) SSP 1 – 'Charting the blue course'– under RCP2.6; b) SSP 3 – 'Rough seas ahead' – under RCP8.5; and c) SSP 5 – 'The ocean super highway' – under RCP8.5. Simulations were based on outputs driven by the projected changes in ocean conditions from GFDL ESM-2M only.

accordance with the developed SSP3 storyline, the unit cost of fishing on the high seas is expected to decrease. Specifically, the use of unethical means such as forced or underpaid labour on fishing vessels and in processing plants explains the reduction in fishing cost. However, the higher demand for seafood and less-regulated fisheries on the high seas lead to an increase in fishing effort beyond economically optimal levels – and hence an increase in total fishing cost. Although fishing subsidies are expected to increase to satisfy an increase in seafood demand, fishing profits for all income groups are still projected to decline over time. High seas fisheries across all country income groups are not economically viable under the 'rough seas ahead' scenario.

Revenues from fishing increase over time under SSP5, as both catch and fishing prices are projected to increase substantially under this scenario. However, the unit fishing cost is expected to decrease substantially under this SSP because of assumed low fuel costs and advancement in technologies under this scenario. Here again, an increase in fishing effort leads to an increase in total fishing cost. Rising demand for seafood and lower levels of concern for the environment – because there is faith in the ability to effectively manage systems and address ecological concerns using technology – boost fishing subsidies. This leads to a decline in the profitability of high seas fisheries in all country income groups.

Although model projections show a substantial increase in high seas fisheries' revenues over the mid-term (2050s) under SSP5, high seas fisheries remain economically non-viable because of high total fishing cost. Also, economic benefits may not be transferable to wider society in terms of more job opportunities. High seas fisheries are less labour intensive and labour costs are low to ensure profits (Sala *et al.* 2018). However, without subsidies, high seas fisheries are projected to be non-profitable. Therefore, making profit (with the consideration of subsidies) is not an indication that high seas fisheries are actually economically viable.

3.4.5 Economic viability across different income-group countries

Differences in projected changes in catches and fishing costs between income-group countries resulted in variations in the economic viability of their fisheries on the high seas. Although catch is projected to increase on the high seas under most scenarios, total fishing cost on the high seas is also projected to increase. This is because either the unit fishing cost increases or fishing effort on the high seas increases. High fishing cost led to the negative profitability of high seas fisheries across all SSPs. Increase in total fishing cost also resulted in fisheries profits declining over time in most income-group countries, except for high-income countries.

For high-income countries, profits were projected to increase over time under the high seas SSP1 and SSP5 scenarios. However, profits for this group were projected to decrease in SSP3 without any high seas closure (ie 0 per cent MPA). For middle-income countries, the study found declines in fisheries profits to be largest under SSP1. This is because to align with the drafted narrative, the assumption was that the unit fishing cost would increase by 50 per cent and subsidies would be eliminated by 2050. For low-income countries, projections showed declines in fisheries profits to be the largest under SSP3 as fish prices are expected to decline under this scenario, leading to a lower rate of increase in revenues even though catches are projected to increase. Here again, the higher incentive to fish on the high seas leads to an increase in fishing effort and, consequently, total fishing cost. Figure 7 summarises the changes in profitability under each SSP and for each income-group country.

The analyses do not directly demonstrate whether fishing by one income group undermines the economic viability of fisheries for another income group. However, to date, the most important fishing nations on the high seas have been developed countries (Sala *et al.* 2018). Also, this study did not examine increased exploitation across the board, but rather assumed that exploitation rates would vary in accordance with the storylines crafted under each of the high seas SSP scenario.

4

Discussion

This chapter explores the future sustainability of high seas fisheries. It considers the impacts of change on the high seas as well as different country EEZs as represented and modelled under three separate high seas SSPs. It also outlines key questions and uncertainties about the future of high seas fish stocks and fisheries through the 21st century – including the impacts of climate change.

4.1 The future of global high seas fisheries' sustainability

This working paper has highlighted three contrasting futures of high sea fisheries that are determined by a range of interconnected biophysical, social and economic factors:

- The first future is an ocean characterised by relatively higher fish abundance and a lower level of impacts from fishing and climate change that is made possible through global cooperation and actions on sustainable development. The high seas also contribute the least to income generation and livelihood opportunities in this scenario compared to the other three futures.
- In the second future, powerful national interests, particularly those of high-income countries, drive the intense exploitation of the high seas. Impacts on marine biodiversity through fishing and climate change are high, while the viability of fisheries is mainly maintained by subsidies.
- The third future is one with intensive exploitation of high seas fisheries resources driven by fossil-fuel use and technological innovation to support societal development, particularly for lower-income countries. Fishing intensity and its impacts on diversity and abundance of resources in this scenario is highest amongst the three futures, with high emissions of greenhouse gases resulting in additional impacts.

The analysis suggests that, on average, high seas fisheries are not economically viable across the three ocean futures, although findings highlight variations across the different country income groups considered. Among the three ocean futures investigated, the relative importance of the main direct drivers is dependent on whether the focus is on ecological, social or economic perspectives as well as the timeframes considered. Nevertheless, fishing effort (under different SSPs) on the high seas emerges as one of the most important drivers of future biodiversity, catches and economic benefits across the three ocean futures throughout the 21st century. Protected areas are important in determining fisheries catches and benefits in the near term (2030), while climate change plays an increasingly dominant role (relative to protected areas) towards the end of the 21st century.

Protected areas substantially influenced projections, with gains in future high seas catches increasing over time and expected to be greatest in the absence of MPAs (see Table 5). On the high seas, climate change scenarios did not play much of a role. In fact, taken together, the projections show that climate change will contribute to gains in high seas catches over time. As a note, to ensure proportional distribution of MPAs globally (and avoid results being biased by MPA allocation issues) closed areas were assigned to ABNJ as a continuous polygon along EEZ boundaries. This MPA design may not be the most realistic nor the most effective in terms of implementation or biodiversity conservation targets. In practice, MPAs may be implemented very differently. Identifying and prioritising areas of high biological and ecological importance is critical to the MPA planning process and will bear substantial influence on expected future socioeconomic and ecological outcomes (Wedding *et al.* 2013, Smith *et al.* 2017, O'Leary and Roberts 2018). The impacts of climate change should also be taken into consideration when designing the connectivity and size of MPAs to capture potential shifts in distribution range of marine species (Davies *et al.* 2017, Bruno *et al.* 2018). Next steps for future modelling work may therefore consider different MPA locations and design to determine how this may influence the findings.

The results highlight the potential for economic-based interventions in developing pathways for future sustainable fishing on the high seas. High seas fishing effort is strongly influenced by a range of economic factors, including fish price, fishing costs and subsidies (Sala *et al.* 2018). So far, the discourse around conservation action in ABNJ through the implementation of very large marine pelagic protected areas has tended to occur separately from the need for economic fisheries reform (but see Sumaila *et al.* 2015). The results presented here underscore the importance of economic drivers in fisheries (Cisneros-Montemayor *et al.* 2016), the important role economic fisheries management reforms can play in achieving the conservation and sustainable use of high seas resources (WTO 2019), and therefore the attainment of SDG 14.6 (Mohammed *et al.* 2018, Merayo *et al.* 2019).[16]

Trade-offs between socioeconomic and conservation objectives are projected to be more intense under SSP3 and SSP5 than SSP1. For example, high seas fisheries are projected to be economically viable for high-income countries under SSP5 due to an increase in subsidies and ex-vessel prices, as well as lower unit fishing costs. However, as a result of the increase in fishing effort, mean species abundance on the high seas is projected to decline substantially under this scenario. Consequently, the continued intensification of the exploitation of high seas resources by high-income countries under SSP5 could undermine the future sustainability of fish stocks and economic viability of fisheries in low and middle-income countries.

4.2 The effects on fisheries in EEZs

When focusing on findings at the scale of countries' EEZs, climate change emerged as the main factor affecting biodiversity and potential catches across all three ocean futures, followed by fishing dynamics on the high seas. High seas protected areas played much smaller roles. The projected substantially larger declines in maximum catch potential and mean species abundance under the high emission (RCP8.5) scenario relative to the low emission scenario (RCP2.6) towards the end of the 21st century are in agreement with past similar modelling exercises (Cheung *et al.* 2016, 2017).

However, the high seas fishing scenarios explored in all three ocean futures are much more conservative than previous efforts (eg Cheung *et al.* 2017). Particularly, the fishing mortality rate considered in all three SSPs is below the level required to achieve maximum sustainable yield (MSY). In comparison, the fishing mortality rates assumed in Cheung *et al.* (2017) is twice the level required to achieve MSY. The much higher fishing impacts assumed in Cheung *et al.* (2017) result in largely depleted fish stocks straddling the high seas and EEZs, and thus render catch findings much more sensitive to differences in fishing mortality as a result of either fishing capacity reduction or protected-area scenarios. This study did not explore these more extreme fishing mortality rates, as future changes in fishing were constrained by the quantitative expression of the qualitative storylines developed during the workshop and the associated expectations from bioeconomic theories. Thus, this study may provide a more reasonable depiction of the future pathways of changes in fish stocks and fisheries on the high seas.

The hypothetical high seas MPAs contributed minimally to changes in projections for future maximum catch potential across EEZs – with RCPs being the dominant factor(s) affecting differences through time and across income groups (see Table 8). Declines over time and across RCPs are the most important for high-income countries. Mitigating impacts of climate change is important for the future of fisheries in the EEZs.

4.3 Key uncertainties

This study used scenarios and models to develop visions for the uncertain future of high seas fish stocks and fisheries through the 21st century. Projecting long-term changes in complex coupled human-natural systems such as the global ocean and high seas

[16] SGD Target 14.6: 'By 2020, prohibit certain forms of fisheries subsidies which contribute to overcapacity and overfishing, eliminate subsidies that contribute to illegal, unreported and unregulated fishing and refrain from introducing new such subsidies, recognizing that appropriate and effective special and differential treatment for developing and least developed countries should be an integral part of the World Trade Organization fisheries subsidies negotiation' (Sustainable Development Goals Knowledge Platform).

is unavoidably uncertain. By integrating qualitative information, derived from an expert-led participatory process, with quantitative modelling, informed by biophysical and economic theories, the study sought to create contrasting, but plausible, ocean futures. These scenarios are not predictions, but instead serve to highlight perhaps unexpected patterns and focus on answering questions about what plausible futures may look like.

To address these questions with the scenarios created, it is important to consider the levels of confidence associated with each modelling component. For the biological simulation model, this study has outlined some key uncertainties:

- Projections of future ocean conditions, although all biological projections appeared to be robust to outputs from different Earth system models.
- Modelling does not account for behavioural pattern changes or evolutionary adaptations of fish stocks in response to fishing, management and conservation measures (eg protected areas and climate change) (Mee *et al.* 2017).
- Predator-prey interactions are not explicitly considered in the model.
- Protected areas were distributed equally across FAO areas and did not consider realism in implementation or the contrasting characteristics of fish stocks and fisheries.

For the economic analysis, several fisheries and economic variables are not well documented for high seas fisheries. These include catchability, operating fishing costs, effort response, capital cost, investment ratio, depreciation cost of fishing gears and vessels, as well as catchability rates of increase. Hence, the study used an optimisation approach by minimising the sum of squares between historical observed and modelled catch data. Although this approach allows for the efficient estimation of these parameters in a data-deficient world, it adds uncertainty to the projections. In the absence of detailed data, all fleets (eg, purse seine, tuna longliner, pole and line etc) belonging to a given country income group were modelled as operating on the high seas in an aggregated fashion. However, in reality, the behaviour and associated economic variables for each fleet will differ across individual fishing countries. Future research would benefit from obtaining more resolved data for different countries and gear categories.

The effort dynamic model (EDM) required observed values of current fishing costs, subsidies and fishing effort to initialise the model. However, these data are lacking for the high seas. Consequently, the model drew from disparate published data sources to derive proxies for these variables. Informed assumptions had to be made regarding the direction and magnitude of change of these variables through time. For each SSP, these assumptions had to be further modulated to reflect the individual storylines and differentiated according to country income groups. For example, in accordance with SSP1 (a world characterised by a society that seeks a more sustainable way of life) the study assumed that governments would work to eliminate all forms of harmful subsidies by the 2050s for both low and middle-income countries. Given the greater role played by subsidies in high-income countries, it was also assumed that harmful subsidies would decline by 75 per cent under this pathway by the 2050s. While based on discussions held during the expert-led workshop, and where relevant and possible informed by the existing literature, no reference points exist for these assumptions. To address these uncertainties, future studies may want to strengthen the assumption base for the magnitude and direction of change for each variable under each scenario and use a range of change to represent the uncertainty associated with such a modelling exercise.

This work is novel and therefore exploratory by definition. Findings, as indicated earlier, are not meant to be interpreted as predictions, but rather provide a stepping stone for future modelling work and a tangible starting point to inform discussions in the ABNJ negotiation process to support equitable and sustainable fisheries and better ocean stewardship.

4.4 Ways forward: join the debate

The findings from this scenario and modelling exercise brought up important questions about the future of high seas fisheries and their management. Under all three ocean scenarios explored in this study, future high seas fisheries are unlikely to be economically viable. Fishing effort on the high seas is projected to continue to increase, particularly under two of the three high seas futures (SSP3 and SSP5), contributing to a substantial decline in the diversity and abundance of species considered (and hence an increase in conservation risk).

A future as imagined under the high seas SSP1 is characterised by strong political will for international cooperation and a low contribution of the high seas to food provision and income generation. Consequently, what role would marine protected areas play in safeguarding sustainable ocean development on the high seas in such an ocean future?

If instead the world is heading towards a future more similar to those described under the high seas SSP3 or SSP5, what high seas governance and management approach(es) would be most effective in conserving high seas biodiversity and supporting sustainable fisheries?

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Abbreviations and acronyms

ABNJ	Areas beyond national jurisdiction (the high seas)
DBEM	Dynamic bioclimate envelope model
EDM	Effort dynamic model
EEZ	Exclusive economic zone
ESM	Earth system model
FAO	Food and Agriculture Organization of the United Nations
F_{MSY}	Fishing mortality at maximum sustainable yield
GFDL	Geophysical Fluid Dynamics Laboratory
GFDL-ESM-2M	Geophysical Fluid Dynamics Laboratory Earth System Model 2M
HDI	UN Human Development Index
HIC	High-income countries
IIED	International Institute for Environment and Development
ILBI	International legally binding instrument
IPSL-CM5-MR	Institut Pierre-Simon Laplace Coupled Model 5
IUU	Illegal, unreported and unregulated fishing
LDCs	Least developed countries
LIC	Low-income countries
MCP	Maximum catch potential
MGR	Marine genetic resources
MIC	Middle-income countries
MPA	Marine protected area
MSA	Mean species abundance
MSY	Maximum sustainable yield
NGO	Non-governmental organisation
PA	Protected area
RCP	Representative concentration pathway
RFMO	Regional fisheries management organisation
SDGs	Sustainable Development Goals
SSP	Shared socioeconomic pathway
UBC	University of British Columbia
UNCLOS	United Nations Convention on the Law of the Sea

Glossary

Adaptation	Activities undertaken to cope with, limit the risks posed by, or maximise opportunities from changing circumstances (such as climate change).
Biodiversity	The variety and variability of living species on earth and in the oceans and their relationships to each other; this includes diversity within species, between species and of ecosystems.
Biomass	Weight of a stock or of one of its components. For example, 'spawning biomass' is the combined weight of all sexually mature animals in a stock. Standing stock is an alternative term for biomass. Also, the mass of living tissues across organisms in a population or ecosystem. Used as a measure of population abundance.
Bycatch	That part of a fish catch that is caught in addition to the target species because the fishing gear (eg a trawl) is not selective. Bycatch may be retained, landed and sold or used, or may be dumped at sea (ie discard).
Capacity (fleet)	In input terms, fleet capacity can be considered as the minimum fleet size and effort required to generate a given catch. In output terms, capacity can be considered as the maximum catch that a fisher or a fleet can produce with given levels of inputs, such as fuel, amount of fishing gear, ice, bait, engine horsepower or vessel size.
Catch	The number or weight of fish or other animals caught or killed by a fishery, including fishes that are landed (landings, whether reported in statistics or not), discarded at sea (discard), or killed by lost gear (ghost fishing).
Climate Change	Change in global climate patterns as a result of anthropogenic increases in the level of carbon dioxide and other greenhouse gases over periods ranging from decades to millions of years. Climate change is also caused by factors such as variations in solar radiation received by Earth, plate tectonics and volcanic eruptions. It may be a change in average weather conditions, or in the distribution of weather around the average conditions (ie more or fewer extreme weather events such as storms or heatwaves).
Climate change mitigation	Efforts to reduce or prevent greenhouse gas emissions.
Ecosystem	A network of organisms representing a biological community, their physical environment and their interrelationships for a given unit of space.
Equitable	Fair and just.
Exclusive economic zone (EEZ)	Generally, all waters within 200 nautical miles (370km) of a country and its outlying islands, unless such areas would overlap because neighbouring countries are less than 400 nautical miles (740km) apart. If an overlap exists, it is up to countries to negotiate a delineation of the actual maritime boundary. Under UNCLOS, a country has special rights regarding the exploration and use of marine resources inside its EEZ, such as the power to control and manage all fishery resources in this zone. Not until 1982, with the adoption of UNCLOS, did 200nm EEZs become formally adopted; a country needs to formally declare its EEZ to have one.
Ex-vessel price/fish price	The price that fishers get for a unit weight of fish landed at the dock or beach, ie at the first point of sale; corresponding to farm-gate prices in agriculture.
Fishery	A set of persons and gear interacting with an aquatic resource (one or several species of fish) for the purpose of generating a catch.

Fishing effort	A measure – typically measured in number of vessels, amount of fuel used by fishing fleet, hours or days spent at sea or number of hooks used for example – of the amount of fishing activity.
Fishing mortality rate	Fraction of a fish population that dies because of exploitation.
Fixed cost	Expenses incurred by a fishery that are not dependent on the level of fishing that takes place, eg the cost of owning a fishing vessel; see also variable cost.
Food security	People have physical, social and economic access to sufficient, safe and nutritious food to meet an individual's dietary needs.
Governance	Patterns and practices of rule.
High seas	Open ocean space that falls outside of a nation's jurisdiction.
High-seas fleets/ Distant-water fleets/ fishery/DWF	The fleet of a country that is fishing in the EEZ of another country (or the EEZs of other countries), or in high sea regions not adjacent to its own EEZ. Under UNCLOS, a distant-water fishery can be conducted in the EEZ of a coastal state only with its explicit access agreement, generally in exchange for compensation.
IUU/illegal, unreported and unregulated fishing	An acronym proposed by FAO to describe a wide variety of fishing activity and catch that break fisheries laws, occur outside the reach of fisheries laws and regulations and are not reported or misreported to the relevant national authority.
Marine conservation	Protection and preservation of resources found in the marine environment.
Marine protected area	An area of maritime space that is recognised, dedicated, and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values.
Maximum sustainable yield (MSY)	The maximum amount that can be taken (caught) over the long term from a fisheries resource. MSY is best considered an upper limit for fishery management, as opposed to a target level.
Overfishing	Applying a level of fishing effort beyond that which generates a desirable, sustainable, or 'safe' population or stock level. The level of effort can be in excess of that required to generate maximum sustainable yield (biological overfishing), maximum economic yield (economic overfishing), maximum yield per recruit (growth overfishing), or maximum recruitment (recruitment overfishing).
Profit	Amount of revenue left over after expenses, costs and taxes have been subtracted.
Revenue	Total amount of income generated by the sale of commodities.
Shared socioeconomic pathway	One of a collection of trajectories describing alternative futures of socioeconomic development in the absence of climate policy intervention.
Subsidies	Financial allocation (eg tax allowance or soft loan) typically provided by a government to assist an industry or business in maintaining employment and/or the competitive price of a given commodity for example.
Sustainable	Activity that causes little or no damage to the environment or the resource base and is able to be maintained over the long term.
Variable cost	Expenses incurred by a fishery that are dependent on the amount of fishing that takes place, eg fuel cost; see also fixed cost.
Yield	Catch in weight during a conventional period, eg a year; see also maximum sustainable yield or MSY.

Marine biodiversity and ecosystems provide important benefits to human societies through fisheries. But the benefits are not shared equally among countries – and climate change will only exacerbate inequalities. Improving high seas fisheries governance would help redistribute benefits and reduce climate risks, especially in developing countries where many people depend on fish for their food and nutrition security, livelihoods and well-being. Developing countries are also among the most vulnerable to climate change impacts. Here, the authors explore different scenarios of future fisheries governance and evaluate the benefits and trade-offs of alternative policy frameworks for governing fisheries under a changing climate.

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