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The Expected Impacts of Climate Change on the Ocean Economy

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Highlights

- The ocean is critically important to our global economy. Collectively, it is estimated that ocean-based industries and activities contribute hundreds of millions of jobs and approximately US $2.5 trillion to the global economy each year, making it the world's seventh-largest economy when compared with national gross domestic products. In addition, the nonmarket services and benefits provided by the global ocean are significant and may in fact far exceed the value added by market-based goods and services.
- Climate change is altering ocean climate, chemistry, circulation, sea level and ice distribution. Collectively, these system changes have critical impacts on the habitats, biological productivities and species assemblages that underpin many of the economic benefits of the sea.
- Swift efforts to reduce anthropogenic greenhouse gas emissions are needed to maintain a robust ocean economy. The recent Intergovernmental Panel on Climate Change report estimates that climate-induced declines in ocean health will cost the global economy $428 billion/year by 2050 and $1.98 trillion/year by 2100.
- Climate change is reducing the productivities and changing the spatial distributions of economically important marine species and their habitats. All countries stand to gain significant benefits relative to a business-as-usual trajectory by implementing climate-adaptive fisheries management reforms that address both changes in species' distributions and productivities due to climate change. Many countries could maintain or improve profits and catches into the future with effective adaptation.
- The potential of marine aquaculture (mariculture) is likely to remain high under climate change and, with careful planning, mariculture could offset losses in food and income from capture fisheries in those countries that will experience losses in that sector. Expanding the potential for marine aquaculture will require enhancing technical capacities, defining best practices, easing undue regulatory burdens, increasing access to credit and insurance, breeding stocks for faster growth and improving feed technology.
- The combined effects of ocean warming and acidification result in predictions of negative impacts on coral reef cover and tourism values for all countries, with magnitudes dependent on the strength of climate change. For a high emissions scenario (Representative Concentration Pathway 8.5), coral cover is expected to decline by 72–87%, causing on-reef tourism values to decrease by over 90% in 2100.
- Climate change impacts will differ by country and sector and solutions must be context-specific. By exploring climate change impacts at the country level for fisheries, aquaculture and reef tourism, countries can assess what they stand to gain or lose due to climate change and understand how they might capitalise on these predictions to inform their investments and actions.
- Implementing certain key strategies will help build socio-ecological resilience to climate change and ensure the continued, or improved, provision of functions and services from the ocean, especially for the most vulnerable coastal nations. These strategies include the following:
  - **A focus on equity.** Climate change is likely to cause and exacerbate global inequities, reducing resilience and thereby likely worsening outcomes under all climate change scenarios. It will thus be profoundly important to examine the equity implications of all new and existing management decisions across all three sectors.

The original version of the chapter has been revised. A correction to this chapter can be found at https://doi.org/10.1007/978-3-031-16277-0_23

Originally published in:
Gaines, S., R. Cabral, C. Free, Y. Golbuu, et al. 2019. *The Expected Impacts of Climate Change on the Ocean Economy*. Washington, DC: World Resources Institute. Available online at www.oceanpanel.org/expected-impacts-climate-change-ocean-economy.
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J. Lubchenco, P. M. Haugan (eds.), *The Blue Compendium*, https://doi.org/10.1007/978-3-031-16277-0_2

- **Looking forward.** The future of the ocean economy is expected to drastically change given climate change, and the nature and magnitude of these changes can be highly variable. Each of these three sectors will need to work to understand risks and anticipate changes, and build precautionary and adaptive strategies into their management decisions.
- **Cooperating across boundaries.** As suitable habitats shift and change, marine species will move across jurisdictional boundaries and regional, national and international cooperative agreements will be necessary to ensure that these species are well-managed, and that the benefits are fairly distributed during and after the transitions.

1 Introduction

1.1 Overview

The ocean is critically important to our global economy. Collectively, it is estimated that ocean-based industries and activities contribute hundreds of millions of jobs and approximately US $2.5 trillion to the global economy each year, making it the world's seventh-largest economy when compared with national gross domestic products (GDPs) (Hoegh-Guldberg 2015; IPCC 2019). In addition, the nonmarket services and benefits provided by the ocean are significant and may in fact far exceed the value added by market-based goods and services (Costanza et al. 2014).

Anthropogenic climate change, driven by the exponential increase in emissions of greenhouse gasses (GHGs) since the industrial revolution, will continue to impact the ocean through a variety of channels. The severity of effects will depend greatly on the extent of warming reached through GHG emissions (IPCC 2018, 2019). The resulting changes to ocean processes and functioning have broad implications for our global economy that must be taken into account, both to inform adaptation efforts and motivate urgent mitigation strategies.

In this paper, we focus on those sectors of the ocean economy that are most in need of adaptation to ensure they can continue to provide valued functions as the climate changes: capture fisheries, marine aquaculture, and marine and coastal tourism. We also briefly discuss other marine-based sectors, some of which generate higher monetary value at a global scale, but either face less significant existential risks from the changing climate (e.g. shipping), or must be drastically transitioned to avoid worsening the climate crisis (e.g. oil and gas extraction). However, we leave deeper discussion of these important industries and the issues surrounding them to other Blue Papers (*Ocean Energy and Mineral Sources and Coastal Development*).

1.2 The Ocean Economy: Essentials

The ocean economy consists broadly of all ocean-based human activities that generate revenue, employment and other monetary and nonmonetary benefits (OECD 2016). Some of the ocean benefits, and the resources needed to generate them, are market-based in that they are traded on global markets and have market prices. Examples of market-based ocean benefits include the following: wild capture fisheries and marine aquaculture (also known as mariculture); pharmaceuticals; fossil fuel energy resources such as oil and gas; renewable energy resources such as wave, wind or thermal energy; the use of the ocean surface for transportation (shipping); ocean-based tourism; and emerging blue carbon markets. Following the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) framework, most of the marketable benefits mentioned are material contributions (e.g. food, energy sources, genetic resources), but other important marketable contributions to people are regulating services (e.g. carbon sequestration) and nonmaterial (e.g. tourism).

Many other ocean benefits are not traded on markets, and their values are thus far more difficult to assess. The set of nonmarket ocean benefits is very large (Polasky and Segerson 2009; Costanza et al. 2014) and ranges from different ecosystem services to the broader category of nonmaterial contributions to people. In terms of ecosystem services, nonmarket benefits include most of the ocean's cultural services (e.g. swimming, recreational fishing, observing sea life, the existence value of the ocean's diverse biota). In addition, ecosystem services include regulating services—the ocean's contribution to the global water, energy and chemical circulation systems, as well as the ocean's role in climate regulation, carbon dioxide (CO_2) uptake and coastal protection—which are typically not accounted for in existing markets. The IPBES framework further adds to the ocean's nonmaterial contributions by including learning and inspiration (i.e. education, scientific information), psychological experiences (i.e. relaxation, healing, aesthetic enjoyment), supporting identities (i.e. the basis for spiritual and social-cohesion experiences, myths and traditional knowledge) and maintenance of options for future generations and innovations and needs (Díaz et al. 2015, 2018).

1.2.1 The Market-Based Ocean Economy

The Organisation for Economic Co-operation and Development (OECD) projects that market-based ocean industries will expand at least as fast as the global economy as a whole over the next decade. The OECD (2016) outlines the ocean industries that contribute the most in terms of production value and employment (see Table 2.1).

The rankings of ocean industries are quite different for these two economic outputs. Energy production, shipping

Table 2.1 Ocean industries contributing most to the ocean economy

	% of production value	% of employment
1. Offshore oil and gas	34	6
2. Marine and coastal tourism	26	22
3. Port activities	13	5
4. Maritime equipment	11	7
5. Fisheries, marine aquaculture and fish processing	6	49
6. Ocean transportation	5	4
7. Shipbuilding and repair	4	6
8. Offshore wind	1	1

Source: OECD (2016)
Note: Data are from 2010

and tourism dominate production values, while nearly half of all ocean employment arises from food production. Therefore, the impacts of climate disruptions on these industries can have quite disparate social and economic consequences.

1.2.2 The Nonmarket Ocean Economy

Despite the complexities and theoretical challenges, a number of researchers have attempted to calculate the value of the diverse ecosystem services provided by the ocean. Although there is much debate, these assessments generally conclude that nonmarket services from the ocean are nearly comparable in value to the entire market-based gross global product (i.e. from the entire global economy). For example, a prominent evaluation by Costanza et al. (2014) assessed the value of global ocean ecosystem services to be almost $50 trillion in 2011. This translates to more than 80% of the gross global product in that year, or 30 times more than the ocean-based gross value added. Recent initiatives, such as IPBES, broaden the concept of valuation of nonmarket goods and ecosystem services even further to the more inclusive Nature’s Contributions to People (NCP). The ocean provides a number of these important contributions, which arise from a diversity of human-ocean relationships, including those of indigenous people and local communities (Díaz et al. 2015; Pascual et al. 2017). Although we focus on measuring the impacts of climate change on the market ocean economy in this assessment, it is clear that solutions to those challenges could generate far larger returns from the added benefits they provide to these nonmarket components of the ocean economy.

2 How Rising Greenhouse Gasses Alter the Ocean

Climate change is altering ocean climate, chemistry, circulation, sea level and ice distribution (Brander 2010; García Molinos et al. 2016; IPCC 2019). Collectively, these system changes have critical impacts on the habitats, biotic productivities and species assemblages (Doney et al. 2012; Poloczanska et al. 2013; Pinsky et al. 2013; Visser 2016; Bryndum-Buchholz et al. 2019; Lotze et al. 2019) that underpin many of the economic benefits of the sea (Barange et al. 2018; Cheung et al. 2010; Free et al. 2019a; Lam et al. 2016; Sumaila et al. 2011). They also affect the risks of various human activities and developments (Gattuso et al. 2015; de Suarez et al. 2014; Barange et al. 2014). Unprecedented ocean changes are already occurring across all latitudes (Barange et al. 2018; Friedrich et al. 2012; Holbrook et al. 1997; IPCC 2019; Kleisner et al. 2017; Walther et al. 2002), with a high risk of negative impacts to many ocean organisms, ecosystems and services (Gattuso et al. 2015; IPCC 2019; Lotze et al. 2019). These impacts are likely to increase dramatically toward the end of this century, depending on the extent of future GHG emissions, with potentially direct consequences for ecosystem services, the ocean economy and human welfare (IPCC 2019; Pecl et al. 2017). Below, we describe these effects individually, but many of these influences may synergistically or antagonistically interact, potentially with additional consequences (see, for example, Rosa and Seibel 2008).

Throughout this paper, we rely on the Representative Concentration Pathways (RCPs) (van Vuuren et al. 2011) adopted by the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report to describe potential GHG emission trajectories and associated climate futures. The RCP scenarios are named according to the projected radiative forcing experienced in 2100 (2.6, 4.5, 6.0 and 8.5 Watts per square metre [W/m^2], respectively). They roughly correspond to projected increases in planetary surface temperatures relative to 1850–1900 of 1.6, 2.5, 2.9 and 4.3 °C, respectively, by the end of this century (IPCC 2019).

2.1 Altered Ocean Temperatures and Disturbances

Climate change has already contributed to substantial warming of the ocean over most of the globe. The ocean has absorbed ~93% of additional heat, leading to significant warming of the upper ocean (above 700 metres [m]) and warming of deeper waters (700–2000 m), increasing in strength since the 1980s (Cheng et al. 2017). Sea surface temperatures have increased by an average of 0.7 °C globally since 1900 (Barange et al. 2018; Jewett and Romanou 2017). RCP scenarios suggest that these trends, which already exceed the range in natural seasonal variability in subtropical areas and the Arctic, will continue (IPCC 2014, 2019). Future upper ocean warming is expected to be most pronounced in tropical and Northern Hemisphere subtropical regions, while deep water warming is expected to be more pronounced in the Southern Ocean (Barange et al. 2018;

IPCC 2019; Gattuso et al. 2015). By 2100, the ocean as a whole is likely to have warmed by two to four times (RCP 2.6) to five to seven times (RCP 8.5) as much as the warming observed since 1970 (IPCC 2019).

As these warming trends continue, the suitable distribution ranges of many marine species are expected to shift poleward. In general, species that are able to move to cooler waters, and have suitable habitats to move to, will do so (Barange et al. 2018; Cheung et al. 2010; IPCC 2019; Pinsky et al. 2013). Organisms and habitats that cannot move will either adapt to the new conditions caused by climate change or become extirpated, unless extensive transplantation or other initiatives are mounted to prevent this. Significant habitat losses are predicted in many areas, especially in the Arctic and coral reef ecosystems, resulting in altered community assemblages, predator-prey mismatches and local extinctions (Doney et al. 2014; Free et al. 2019a; Gattuso et al. 2015; Holbrook et al. 1997; IPCC 2019).

Warming waters, along with an increase in episodic ‘marine heat waves’, ocean acidification (discussed below) and the spread of diseases, will lead to mass coral bleaching and mortality throughout the ranges of most coral species (Donner et al. 2005; FAO 2018; Gattuso et al. 2015; Hoegh-Guldberg 1999; IPCC 2019; Kubicek et al. 2019; McClanahan et al. 2002). Intense reshufflings of current biodiversity patterns are also anticipated in biogeographical transition zones, where local populations of multiple species are at or close to their thermal tolerance limits. As a result of these movements, studies have predicted 30–70% average increases in potential fish production at high latitudes, and decreases of up to 40% in the tropics (Barange et al. 2018; Cheung et al. 2010). Indeed, ongoing rapid replacement of cold-affinity species by warm-affinity species has been recently documented in tropical-to-temperate (Kumagai et al. 2018; Verges et al. 2014) and boreal-to-Arctic (Fossheim et al. 2015) regions.

Furthermore, tropical cyclones, extreme sea level events including storm surges and flooding and precipitation over the ocean are predicted to increase in intensity and frequency through the first half of this century due to ocean circulation changes (discussed below) (Barange et al. 2018; Hartmann et al. 2013; IPCC 2014, 2019; Kirtman et al. 2013; Kopp et al. 2014; Ren et al. 2013). In addition, recent models and observational data indicate that recurring climate patterns such as the El Niño-Southern Oscillation are likely to increase in frequency and intensity as the ocean warms (Barange et al. 2018; Cai et al. 2014, 2015; IPCC 2019; Wang et al. 2017), with potentially important impacts on fishing, aquaculture and tourism operations. River flows and flooding may also change with increased snowmelt and more variable land-based precipitation, reducing salinity, increasing sedimentation and impacting productivity in nearshore waters (IPCC 2019; Jha et al. 2006; Pervez and Henebry 2015; Siderius et al. 2013; Loo et al. 2015). Finally, ocean warming leads to increased stratification of the water column and reduced water circulation and mixing (Barange et al. 2018; FAO 2018; IPCC 2019; Jacox and Edwards 2011; Oschlies et al. 2018).

2.2 Sea Level Rise and an Altered Distribution of Ice

Polar areas have seen drastic changes including shifts in the timing of the annual melt seasons, changes in snow cover and changes in ice sheet and glacier mass, which have resulted in sea level rise. Globally, mean sea level rose on average by 0.16 m from 1902 to 2015, and estimates indicate that by 2100, the global mean sea level will rise between 0.29 m and 0.59 m under RCP 2.6, and between 0.61 m and 1.1 m under RCP 8.5 (Barange et al. 2018; IPCC 2019; Kopp et al. 2014). The rate of increase varies across regions—in the western Pacific, sea level is increasing at three times the global average, while the rate of increase in the eastern Pacific is null or negative (Barange et al. 2018; Dangendorf et al. 2017). The economic consequences of global sea level rise will therefore also be highly heterogeneous across regions, as well as across sectors, with likely significant impacts stemming from the modification of coastlines, reduced coastal productivity as reefs and seagrasses are submerged and increased flooding (Barange et al. 2018; IPCC 2019).

In the Arctic, annual sea ice extent has decreased at a rate of 3.5–4.1% per decade, plummeting to a rate of −13% in September, the month marking the end of the melt season. This strong downward trend in extent is accompanied by a progressive loss of multiyear sea ice with over 50% of its extent lost during the period 1999–2017 (Kwok 2018; IPCC 2019). Meanwhile, mass lost from the Antarctic ice sheet tripled between 2007 and 2016 relative to the previous decade, leading to the lowest average monthly and yearly Antarctic sea ice extents on record in 2017 (IPCC 2019; Parkinson 2019). The Greenland Ice Sheet’s mass loss doubled over this same period, and the rates of mass loss for both Greenland and Antarctic sea ice are expected to increase throughout the twenty-first century and beyond (IPCC 2019). Together, these two ice sheets are projected to contribute 0.11 m to global mean sea level rise under RCP 2.6, and 0.27 m under RCP 8.5 (IPCC 2019). While reductions in sea ice have opened new routes for international shipping, potentially reducing costs to this sector, these changes have also resulted in losses to sea ice–based travel and tourism, and pose risks to cultural livelihoods such as subsistence fishing and hunting for polar species (IPCC 2019). Glaciers and land-based ice sheets across the world have also shrunk (Barange et al. 2018; IPCC 2019) and their combined influence was the dominant source of sea level rise between 2006 and 2015 (IPCC 2019).

Sea level rise, combined with increased storm frequency and intensity, is expected to have significant negative impacts on ocean and coastal economy infrastructure, including damage to ports, aquaculture operations and offshore energy structures, and added risks and constraints on shipping (IPCC 2019). These impacts are likely to be among the costliest and potentially most disruptive of all the climate-driven ocean changes. For example, global annual flood costs from sea level rise under RCP 8.5 are estimated at $14 trillion/year (Jevrejeva et al. 2018). Furthermore, although there is uncertainty around exact numbers, sea level rise and other climate-related ocean changes will likely lead to the displacement of millions of people worldwide, with the poorest households facing the greatest risk (IPCC 2019). Low-lying island nations, such as Maldives, Marshall Islands, Tuvalu and Nauru, are especially vulnerable, with sea level rise threatening their entire economies and populations.

2.3 Altered Ocean Chemistry

Ocean acidity has increased by 26% since the industrial revolution, with regional variability in severity and rate of change (Barange et al. 2018; Gattuso et al. 2015; IPCC 2014, 2019; Jewett and Romanou 2017).

This increase has been driven primarily by the oceanic absorption of CO_2, which lowers ocean pH (by increasing bicarbonate and hydrogen ion concentrations) and carbonate ion concentrations, and increases the partial pressure of CO_2 and dissolved inorganic carbon. These changes can impact many marine organisms, particularly in early life stages, but are especially detrimental to corals and organisms that form carbonate shells (Barange et al. 2018; FAO 2018; Pörtner et al. 2014), and perhaps beneficial for some photosynthetic, non-calcifying taxa (Kroeker et al. 2013). Observed trends of declining ocean pH already exceed the natural seasonal variability throughout most of the open ocean, and they are expected to continue throughout this century (Barange et al. 2018; Gattuso et al. 2015; Henson et al. 2017; IPCC 2019).

By 2100, surface ocean pH is projected to decline by 0.036–0.042 pH units under RCP 2.6, or 0.287–0.29 pH units under RCP 8.5. High-latitude waters, deep waters and upwelling regions will be the first to see carbonate ion concentrations drop below the ‘saturation point’ (meaning below the point at which shell and reef formation is possible; the Arctic Ocean, the northeastern Pacific and the California upwelling system already experience seasonally undersaturated conditions), while the tropical ocean (where current carbonate ion concentrations are higher) will experience the largest absolute decreases in carbonate ion concentration and pH (Barange et al. 2018; Harris et al. 2013). Warm water corals will be impacted by decreased carbonate ion saturation levels even where waters do not become undersaturated (Hoegh-Guldberg et al. 2017).

Even if global warming is limited to 1.5 °C, warm water corals are likely to suffer significant negative impacts, including changes to community composition and diversity, local extinctions and reductions in range and extent (IPCC 2019). Coastal seawater acidification can be intensified by additional carbon from riverine input or through coastal productivity stimulated from land-based nutrient inputs, or nutrients released from sediments, aquaculture, sewage discharges and other point sources (Gattuso et al. 2015). These impacts will have significant negative effects on coral reef–related tourism and fishery operations as well as on shellfish aquaculture operations (although see below for a discussion of the potential for aquaculture adaptation and expansion).

Climate change is also impacting the dissolved oxygen content in ocean systems across the globe. Warming-driven stratification of the water column, exacerbated by other physical and biogeochemical processes, reduces the dissolved oxygen content in ocean water (Barange et al. 2018; Breitburg et al. 2018; Gattuso et al. 2015; IPCC 2019; Jacox and Edwards 2011; Oschlies et al. 2018). In recent decades, oxygen concentration in coastal waters and the open ocean has decreased, while the prevalence and size of ‘oxygen minimum zones’ (OMZs), areas where oxygen consumption by sediment bacteria exceeds the availability of oxygen, have increased, especially in the tropics, although it is difficult to conclusively attribute these shifts to human activity in these regions (Barange et al. 2018; Breitburg et al. 2018; IPCC 2019; Oschlies et al. 2018; Stramma et al. 2010; Levin 2002). These trends are expected to continue, with the whole-ocean oxygen inventory expected to decrease by 1.6–2% (RCP 2.6) to 3.2–3.7% (RCP 8.5), and the global volume of OMZs expected to increase by 7.0 ± 5.6% by 2100 under RCP 8.5 (Barange et al. 2018; Fu et al. 2018; Gattuso et al. 2015; IPCC 2019). Increased deoxygenation will likely lead to habitat compression, shifts in distribution and losses in species abundance and biodiversity (Breitburg et al. 2018; Stramma et al. 2010; Levin 2002). Furthermore, observed deoxygenation is generally worse than modelled results, which emphasises the need to improve our understanding of the processes driving deoxygenation to reduce the model uncertainty in our projections (Bopp et al. 2013; Oschlies et al. 2018).

Deoxygenation and OMZs affect species in different ways and to different degrees depending on varying oxygen tolerances. While some hypoxia-adapted species may benefit, impacts on most fish and invertebrates will be negative, and may include restricted vertical and horizontal migration, compressed habitats, alterations to predator-prey interactions and increased competition, impairment of reproductive capacity, reduced growth, vision impairments, increased disease incidence, epigenetic changes and death from asphyxiation (Barange et al. 2018; Breitburg et al. 2018; Eby and Crowder 2002; Gattuso et al. 2015; IPCC 2019; Oschlies et al. 2018). The combination of ocean warming, increased acidity and decreased oxygen availability is predicted to result in significant decreases in both the average size and abundance of many important fishery species (Breitburg et al. 2018).

2.4 Altered Circulation Patterns

Water circulation in the ocean, known as the 'global conveyor belt', is responsible for the redistribution of heat and freshwater, influencing local climates, productivity levels and ocean chemistry. A warming climate increases inflows of warm freshwater (from increased precipitation and melting glaciers and sea ice), which can reduce the formation of sea ice and sinking of cold salt water. This influx slows parts of global conveyor belt circulation (Barange et al. 2018; IPCC 2019; Liu et al. 2017). The Atlantic Meridional Overturning Circulation and Gulf Stream, which are responsible for a significant portion of the redistribution of heat from the tropics to the middle and high latitudes as well as of the ocean's capacity to sequester carbon, are showing signs of weakening (Caesar et al. 2018; IPCC 2019; Thornalley et al. 2018; Barange et al. 2018) and may continue to do so under all RCP scenarios (IPCC 2019). In the Atlantic, this weakening is driving lower sea surface temperatures in the subpolar Atlantic Ocean and a warming and northward shift of the Gulf Stream, which is expected to further weaken in the coming decades (Caesar et al. 2018; Thornalley et al. 2018; Barange et al. 2018; Liu et al. 2017). These changes could lead to dramatic shifts in weather and local and regional climate patterns (IPCC 2019), which would have significant impacts on the ocean economy (e.g. through damage to infrastructure) and society as a whole.

All western boundary currents other than the Gulf Stream are expected to intensify in response to tropical atmospheric changes and shifts in wind patterns resulting from climate change and GHG concentrations, likely strengthening coastal storm systems (Barange et al. 2018; Yang et al. 2016). The intensity of the eastern boundary currents, responsible for the major coastal upwelling zones and thus for some of the most productive waters in the world, will also likely change, although there is more uncertainty around the severity and direction of these changes, as well as around the resulting impacts (Bakun et al. 2015; Barange et al. 2018; Brady et al. 2017). As the land and ocean warm at different rates, stronger upwelling-favourable winds may strengthen these patterns; however, increased thermal stratification may restrict the depth of upwelling waters, and thus limit the amount of nutrients brought with them (Bakun 1990; Barange et al. 2018; Jacox and Edwards 2011; Rykaczewski et al. 2015; Sydeman et al. 2014; Wang et al. 2015). The impacts of intensified upwelling may result in a net increase in nutrient inputs and primary productivity or, alternatively, increase the presence of low oxygen and more acidic waters along the continental shelf (Bakun et al. 2015; Barange et al. 2018). Changes in either direction will have critical impacts for the many valuable marine capture fisheries located in and around upwelling zones. The most recent estimations at a global scale show a decrease in primary productivity of 7–16% by 2100 for RCP 8.5, largely driven by changes to circulatory and upwelling patterns as well as thermal stratification (IPCC 2019). However, the interaction and relative importance of these forces, as well as of regional processes and seasonal variability, will vary across geographies (Barange et al. 2018; IPCC 2019), and thus local data collection and modelling will be necessary to inform management.

3 Connecting the Links Between Climate Change and the Ocean Economy

3.1 Capture Fisheries

3.1.1 Importance of Capture Fisheries to the Ocean Economy

In 2016, the United Nations Food and Agriculture Organization (FAO) estimated that marine capture fisheries produced 79.3 million metric tonnes (mmt) of landings, representing 46.4% of global seafood production (170.9 mmt) and $130 billion in first sale value (FAO 2018). It also estimated that approximately 30.6 million people participated—either full time, part time, or occasionally—in capture fisheries, operating approximately 4.6 million fishing vessels. Small-scale fisheries are the backbone of socioeconomic well-being in many coastal communities (Bene 2004; Béné et al. 2007, 2010), especially in the developing tropics where the majority of fish-dependent countries are located (Golden et al. 2016). Fish and fish products are also among the most traded food commodities in the world. In 2016, approximately 35% of production entered international trade for either human consumption or nonfood uses (FAO 2018). The 60 mmt ($143 billion) of fish products exported in 2016 constituted a 245% increase relative to 1976 exports ($8 billion). Over this time period, the rate of growth of exports from developing countries surpassed that from developed countries (FAO 2018). Finally, the average annual increase in fish consumption (3.2%) has outpaced the average annual increase in human population growth (1.6%), and demand for fish is projected to increase as the human population continues to grow and become increasingly wealthy (FAO 2018).

3.1.2 Impacts of Climate Change on Capture Fisheries

Climate change is significantly altering the ability for marine fisheries to provide food and income for people around the world (IPCC 2019). These changes are commonly viewed as occurring through impacts on either the distribution of fish stocks (i.e. where fish can be caught and by whom) or the productivity of fish stocks (i.e. how much fish can be caught). In general, productivity is predicted to decrease in tropical and temperate regions and increase toward the poles (Lotze et al. 2019) as marine organisms shift their distributions to maintain their preferred temperatures (Pinsky et al. 2013; Poloczanska et al. 2013; Poloczanska et al. 2016). These regional shifts in productivity, range and fishing opportunity are likely to result in regional discrepancies in food and profits from fisheries (Lam et al. 2016), with tropical developing countries and small island developing states exhibiting the greatest vulnerability to the climate change (Allison et al. 2009; Blasiak et al. 2017; Guillotreau et al. 2012).

In the remainder of this Sect. 3.1.2, we detail how both retrospective and forward-looking studies have revealed the impact of climate change on the distributions and productivities of marine fisheries and the implications of these observations and predictions for adapting fisheries management to climate change. In Sect. 3.1.3, we present results from a new study (Free et al. 2019b) that demonstrate the country-level economic and food provisioning benefits of reforming fisheries management to account for shifting distributions and productivities. Finally, in Sect. 3.1.4, we outline how fisheries could implement climate-adaptive reforms along a gradient of scientific, management and enforcement capacities.

Marine fish and invertebrates are shifting distributions to track their preferred temperatures. Adaptive international agreements that prioritise equitable outcomes will be necessary to ensure that management remains sustainable and just as species shift in and out of management jurisdictions.

Observed changes: As the ocean has warmed, marine fish and invertebrates have shifted their distributions to track their preferred temperatures (Perry et al. 2005; Dulvy et al. 2008; Poloczanska et al. 2013; Pinsky et al. 2013). In general, this has resulted in shifts poleward and into deeper waters. At a mean rate of 72 kilometres (km) per decade, marine species have been moving an order of magnitude faster than terrestrial species (Poloczanska et al. 2013). These distribution shifts are already generating management challenges (Pinsky et al. 2018). For example, a 'mackerel war' erupted in 2007 when the northeast Atlantic mackerel stock shifted from waters managed by the European Union, Norway and Faroe Islands into Icelandic and Greenland waters. Disagreements over the drivers of the shift, the expected duration of the shift, and appropriate catch reallocations resulted in the stock becoming increasingly overfished (Spijkers and Boonstra 2017).

Forecasted changes: The rate of distribution shifts and associated management conflicts are anticipated to increase under climate change. All studies forecast generally poleward shifts in species distribution and productivity under continued warming (Lotze et al. 2019), often with a decrease in species diversity in equatorial regions, an increase in diversity in poleward regions and the subsequent formation of novel marine communities (García Molinos et al. 2016; Cheung et al. 2016). These shifts are likely to increase the risk of management conflicts over transboundary stocks. For example, 23–35% of exclusive economic zones (EEZs) are expected to receive a new stock by 2100 under strong greenhouse gas mitigation (RCP 2.6) to business-as-usual mitigation (RCP 8.5) scenarios, respectively (Pinsky et al. 2018).

Implications for adaptation: Establishing and strengthening international institutions and agreements to better manage stocks shifting in and out of jurisdictions will be important. These agreements will need to be both adaptive, to ensure that management remains effective under continued uncertainty, and inclusive of all impacted groups, to ensure that outcomes are equitable. As with management decisions made at the fishery and community scales, these international agreements must engender procedural, distributional and recognitional equity if they are to be truly resilient (Matin et al. 2018; Meerow et al. 2019). See Opportunity for Action #3 in Sect. 3.1.4 for more detail.

Climate change is reducing the productivity of marine fisheries globally. Regional impacts are especially pronounced, with some regions experiencing large gains in productivity while others experiencing large losses. Resilience to climate change can be enhanced by implementing adaptive, inclusive and transparent 'primary fisheries management', by accounting for shifting productivity in assessment and management and by rebuilding overfished stocks. Solutions should be developed through processes that ensure procedural, distributional and recognitional equity at all stages.

Observed changes: Free et al. (2019a) estimate that ocean warming has already driven a 4.1% decline in the maximum sustainable yield (MSY), the maximum amount of catch that can be harvested for perpetuity, of 235 of the largest industrial fisheries over the past 80 years. The North Sea, which supports large commercial fisheries, and four East Asian marine ecoregions, which support some of the fastest-growing human populations, have experienced losses in MSY of 15–35%. Meanwhile, the Baltic Sea and other regions have seen increases in MSY of up to 15%. Changes in productivity are driven by changes in growth, mortality or recruitment rates resulting from changing environmental conditions, phenologies (i.e. mismatches in the timing of juvenile recruitment and food availability), disease or food web structures, as well as changes in carrying capacities resulting from distribution shifts or habitat degradation (Hollowed et al. 2013). In general, well-managed fisheries have been the most resilient to these changes while overexploited fisheries have been the most vulnerable (Britten et al. 2016; Free et al. 2019a).

Forecasted changes: An ensemble of six marine ecosystem models (Bryndum-Buchholz et al. 2019; Lotze et al. 2019) forecasts decreases in marine animal biomass of 4.8, 8.6, 10.4 and 17.2% by 2100 under RCPs 2.6, 4.5, 6.0 and 8.5, which represent increasingly severe greenhouse gas emissions scenarios. The ensemble model and its constituent models consistently predict reduced productivity in tropical to temperate regions and increased productivity at the poles. For example, marine animal biomass is forecast to decline by 15–30% in the North/South Atlantic, North/South Pacific and Indian Ocean basins by 2100 while increasing by 20–80% in the polar Arctic and Southern Ocean basins (Bryndum-Buchholz et al. 2019). Regional disparities in marine animal biomass become increasingly pronounced under increasingly severe emissions scenarios. The redistribution of catch potential will drive a concomitant redistribution of revenues (Lam et al. 2016) and nutrition (Golden et al. 2016; Hicks et al. 2019).

Implications for adaptation: First and foremost, in both low- and high-capacity fisheries systems, implementing general fisheries reforms will enhance resilience to climate change as well-managed fisheries are the most ecologically (Free et al. 2019a) and socioeconomically resilient to climate change. In low-capacity fisheries systems, this can be achieved through 'primary fisheries management' (Cochrane et al. 2011), which uses the best available science to inform precautionary management while building institutional capacity for adaptive and participatory co-management. To do so, adaptation policy should target the most vulnerable communities, which in fisheries are typically women and migrant fishers; those with highly fisheries-dependent livelihoods in terms of nutrition and income; and the agency of these individuals to adapt (Cinner et al. 2018). In high-capacity fisheries systems, this will involve accounting for shifting productivity in fisheries stock assessments and management procedures. See Opportunities for Action #1–2 and #4–5 in Sect. 3.1.4 for more detail.

3.1.3 Ability for management to mitigate the impacts of climate change

Most forecasts of the impacts of climate change on fisheries compare the maximum biological potential for food production today with that in the future (Cheung et al. 2010; Lam et al. 2016). While this is useful for understanding the biological limits of the ocean under climate change, it fails to consider the effects of alternative human responses (Barange 2019), which could either limit or exacerbate the impacts of climate change on society. The actions of fishers, management institutions and markets all influence the benefits derived from fisheries (Costello et al. 2016) and could mitigate many of the negative impacts of climate change (Gaines et al. 2018). *Thus, we present a recent analysis* (Free et al. 2019b)[1] *that documents the benefits countries stand to gain by implementing climate-adaptive fisheries management reforms that address both changes in species distribution and productivity due to climate change.*

Methods: Free et al. (2019b) forecasted the distributions and productivities of 779 harvested marine species out to 2100 under three greenhouse gas emissions scenarios (RCPs 4.5, 6.0 and 8.5), and compared the status of these fisheries and the amount of catch and profits derived from them under both climate-adaptive management and business-as-usual management. Under climate-adaptive management, fisheries management dynamically updates economically optimum harvest rates to match shifts in productivity, and transboundary institutions maintain management performance as shifts in distribution move stocks into new management jurisdictions. Under business-as-usual management, current (rather than economically optimal) harvest rates are initially applied and are gradually transitioned to open access as stocks shift into new management jurisdictions (see Free et al. 2019b for details on the management scenarios). Free et al. (2019b) then measured the extent to which climate-adaptive management could maintain catch and profits into the future and generate catch and profits relative to business-as-usual management.

Results: Even countries experiencing declines in fisheries productivity and catch potential would derive more catch and profits through climate-adaptive management than through business-as-usual management (Fig. 2.1). Furthermore, in many countries, adaptive management would not only reduce the impacts of climate change, but actually increase catch and profits relative to today (Fig. 2.1). Climate-adaptive fisheries management results in greater cumulative profits than business-as-usual management for 99% of countries under RCPs 6.0 and 8.5. It results in greater cumulative catches than business-as-usual management in 98% and 67% of countries in RCPs 6.0 and 8.5, respectively. Furthermore, under adaptive management, 71% and 45% of countries derive more catch and profits from fisheries in 2100 relative to today under RCPs 6.0 and 8.5, respectively. The impacts of climate change on fisheries and the opportunities and benefits of climate-adaptive fisheries management reforms can be explored for specific countries in an interactive web application created by the Sustainable Fisheries Group at the University of California, Santa Barbara (UCSB 2019).

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[1] This paper is currently under peer review but a pre-print is publicly available on BioRxiv here: https://www.biorxiv.org/content/10.1101/804831v1.

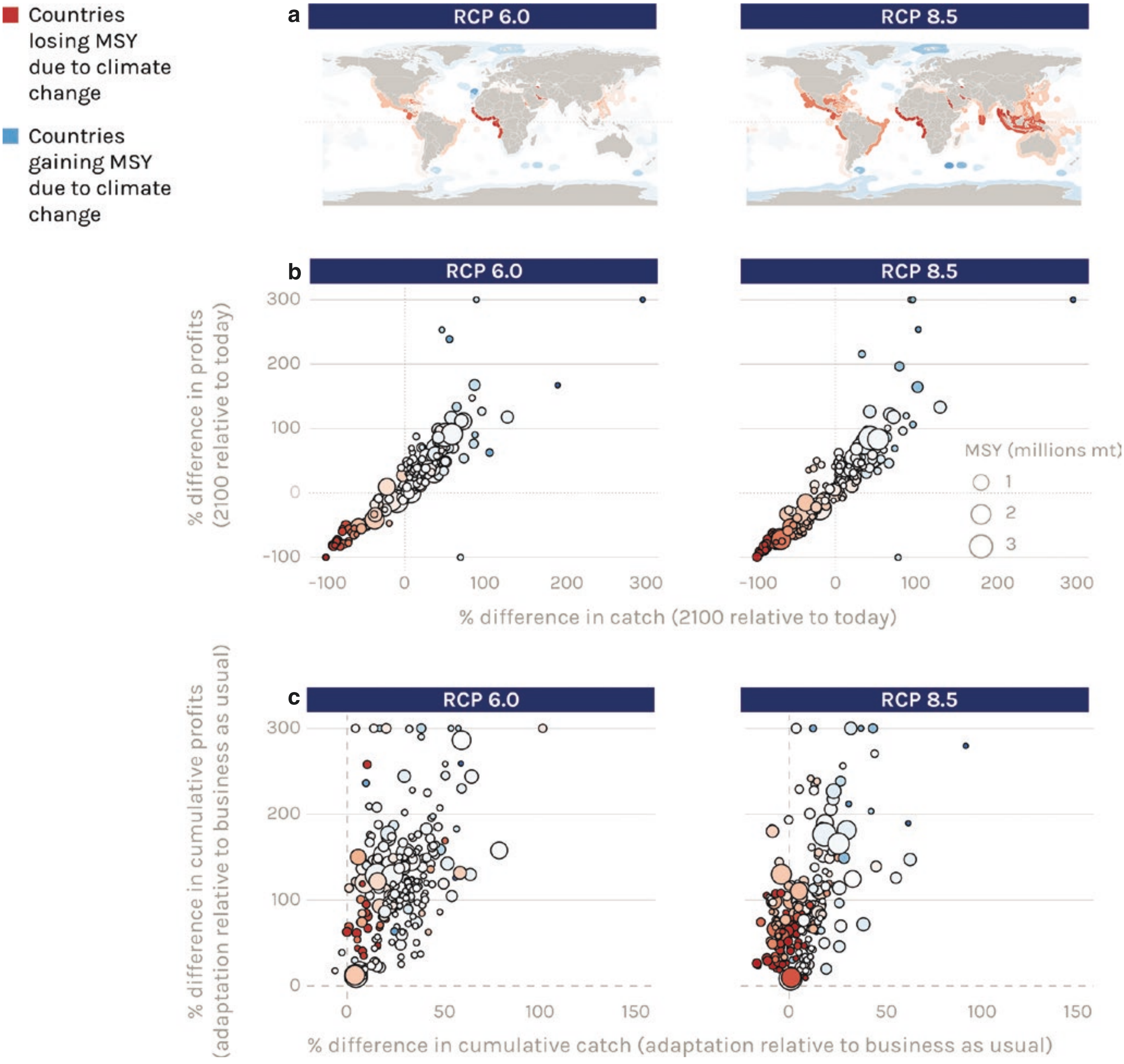

Fig. 2.1 Ability for adaptive fisheries management to mitigate impacts of climate change. *Notes:* (**a**) *shows that maximum sustainable yield (MSY) is forecast to decrease in equatorial exclusive economic zones (EEZs) and increase in poleward EEZs through 2100.* (**b**) *shows that adaptive management results in higher catch and profits in 2100 relative to today for many, but not all, EEZs despite climate change.* (**c**) *shows that adaptive management nearly always yields more cumulative profits than business-as-usual management and frequently yields more cumulative catches than business-as-usual management. In all panels, deeper reds show countries losing MSY and deeper blues show countries gaining MSY under climate change.* (Source: Adapted from Free et al. 2019b)

Implications for adaptation: Fisheries management that accounts for shifts in species distributions and productivities due to climate change will generate better outcomes than business-as-usual management in all countries, even those hardest hit by climate change.

Challenges for improving management include the lack of financial and technical capacity for monitoring and evaluating fisheries in many regions of the world, both for small-scale and industrial fisheries, and the conflicts emerging in fisheries due to climate change and other drivers (Spijkers et al. 2019). In the next section, we detail five key opportunities for action for implementing such reforms.

3.1.4 Opportunities for action and key conclusions

Building a socioecological system that is resilient to climate change is key to ensuring healthy, productive fisheries in the future. Below are five overarching, high-priority opportunities for designing fisheries management approaches in the context of a changing climate along a gradient of scientific, management and enforcement capacities:

1. **Implement best practices in fisheries management.** Historically, well-managed fisheries have been among the most resilient to climate change (Free et al. 2019a), and our results predict that well-intended, albeit imperfect, management will continue to confer climate resilience. Together, these results indicate that the wider implementation of best practices in fisheries management will mitigate many of the negative impacts of climate change.

   In higher-capacity systems, best practices include scientifically informed catch limits, accountability measures, regional flexibility in policy practices and the protection of essential fish habitats (Miller et al. 2018b). In the United States, such measures have contributed to dramatic declines in overfishing, increases in biomass and maintenance of catch and profits (NOAA 2018).

   In lower-capacity systems, best practices include implementing ‘primary fisheries management’ (Cochrane et al. 2011)—which uses the best available science and precautionary principles to manage data-poor and capacity-limited fisheries—and establishing local, rights-based management (Ojea et al. 2017) to incentivise sustainable stewardship.

   Rights-based management systems include catch share programmes, such as Individual Transferable Quotas (ITQs) and Territorial Use Rights in Fisheries (TURFs), which define property rights over catch and space, respectively (Costello et al. 2010). By giving users ownership of the resource, well-designed, rights-based management systems incentivise long-term stewardship and have been shown to promote compliance, prevent overfishing and increase profits (Costello et al. 2016; Costello et al. 2008; Melnychuk et al. 2011). Enforcement and the strength of fishing pressure limits are also key for successful fisheries management (Melnychuk et al. 2017) and contribute to a precautionary approach in the face of climate change. Overall, fisheries best practices confer ecological resilience by maintaining healthy stock sizes, age structures, and genetic diversity and building socioeconomic resilience by providing a portfolio of options to fishers and a buffer against climate-driven losses in any one target stock.
2. **Be dynamic, flexible and forward-looking.** Adapting to climate change will require dynamic, flexible and forward-looking management. This can be achieved by aligning management policies with the spatiotemporal scales of climate change, ecosystem change and socioeconomic responses (Holsman et al. 2019). In higher-capacity systems, this could involve four broad strategies. First, managers can envision and prepare for alternative futures using tools such as forecasts (Hobday et al. 2016), structured scenario planning (Moore et al. 2013), holistic ecosystem models (Gaichas et al. 2016), risk assessments (Holsman et al. 2017) and climate vulnerability analyses (Hare et al. 2016). Second, the proliferation of near real-time biological, oceanographic, social and/or economic data can be harnessed for proactive and dynamic adjustments in spatial and temporal management actions (Hazen et al. 2018).

   Third, developing harvest control rules that account for or are robust to changing environmental conditions affecting productivity can increase catch while reducing the probability of overfishing (Tommasi et al. 2017). Finally, all of these management procedures should be simulation tested through management strategy evaluations (Punt et al. 2016) to measure the efficacy of alternative strategies and their robustness under different climate scenarios (Punt et al. 2014).

   In lower-capacity systems, forward-looking fisheries management could include precautionary management to buffer against uncertainty (Richards and Maguire 1998) as well as management strategies that preserve a population’s resilience, age structure and genetic diversity. For example, size limits, seasonal closures and protected areas can be used to protect the big, old, fecund females (BOFFs) that disproportionately contribute to reproductive output (Hixon et al. 2014) and to maintain the genetic diversity required to promote evolutionary adaptations to climate change.
3. **Establish and strengthen international institutions and agreements to better manage stocks shifting in and out of jurisdictions**. Shifting distributions are already generating management challenges and the rates of these shifts and associated conflicts are expected to increase with climate change (Pinsky et al. 2018; Spijkers and Boonstra 2017; Spijkers et al. 2019). New or strengthened international institutions and agreements will be necessary to ensure that management remains sustainable as stocks shift between jurisdictions.

   First, this will require sharing data between regional fisheries management organisations or countries to identify, describe and forecast shifting stocks. Second, it will require a commitment to using these shared data to inform collaborative management. For example, these data could be used to regularly and objectively update national allocations of catch or effort based on changes in distribution rather than historical allocations (e.g. Havice 2013; Aqorau et al. 2018). An alternative approach could be to develop fisheries permits that are tradeable across political boundaries, which would provide future resource users access to fisheries not yet in their waters and incentivise good management (Serdy 2016). Finally, incentivising the cooperation necessary to establish data sharing and collaborative management will require overcoming prevailing management mentalities that one party 'wins' while the other 'loses' when stocks shift across boundaries. This could involve broadening negotiations to allow for alternative avenues of compensation or 'side payments' (Miller and Munro 2004). In cases where establishing international cooperation proves difficult, marine protected areas (MPAs) placed along country borders could buy time for negotiations by protecting stocks as they shift across borders (Roberts et al. 2017). A more precautionary approach would be to put new fishing areas on hold until adaptive management can be put in place, as illustrated by the Central Arctic Ocean Fisheries Agreement (Schatz et al. 2019).

4. **Build socioeconomic resilience.** The impact of climate change on fishing communities can be reduced through measures that increase socioeconomic resilience and adaptive capacity to environmental variability and changing fisheries (Cinner et al. 2018; Charles 2012; Fedele et al. 2019). Across low- to high-capacity systems, these measures include policies that do the following:
   (a) facilitate flexibility, such as by supporting access to multiple fisheries and alternative livelihoods
   (b) provide better assets, such as the enhancement of fisheries technology and capacity
   (c) provide better organisation in the system, including through multilevel governance, community-based management and other governance structures (Holsman et al. 2019; Ojea et al. 2017)
   (d) promote agency and learning (Cinner et al. 2018)

   For example, policies that promote access to multiple fisheries provide fishers with a portfolio of fishing opportunities that can buffer against variability (Kasperski and Holland 2013; Cline et al. 2017), while policies that help diversify livelihoods reduce reliance on fisheries (Cinner et al. 2009; Daw et al. 2012). Increased mobility through technological enhancements can increase social resilience by allowing fishers to follow shifting stocks (Cinner et al. 2018), but can also result in the migration of fishers. Multilevel governance promotes flexibility in resource governance by matching ecological resilience and management across scales (Hughes et al. 2005).

   Community-based management can increase adaptive capacity by incorporating local knowledge and can improve sustainability by fostering a sense of stewardship (Gutiérrez et al. 2011). Spatial rights-based approaches such as TURFs may confer social resilience insofar as they are often community managed and allow fishers to generate revenues through other compatible activities such as tourism, recreation and aquaculture (Moreno and Revenga 2014). On the other hand, ITQs may confer a different kind of resilience because rights are defined over fish catches, not spatial areas, so they may be more resilient to range shifts arising from climate change. Furthermore, all of these measures can be designed to reduce fishing pressure and promote ecological resilience to climate change.

5. **Use principles of fairness and equity to drive policy decisions.** The challenges of maintaining fairness and equity, such as adequately including the representation and needs of vulnerable marine livelihoods (i.e. those of women, migrants, indigenous peoples), are likely to be created or amplified by climate change. For example, on a regional level, we expect to see greater impacts in the equatorial region, which could exacerbate existing patterns of food insecurity and poverty. In the case of more informal or unregulated economies and fishing activities (e.g. shellfish gathering, fish processing), which are most times performed by women (Harper et al. 2017) and marginalised groups (Barange et al. 2018), there is a risk to being left out from regulations, leading to maladaptation.

At a more local level, climate change can shift the distribution of resources, thereby changing the impact on human populations from past patterns. Without an adequate response, these impacts could lead to inequalities, unrest and severe social disruption, thus likely worsening outcomes in the face of climate change. Addressing the inequities created by climate change is valuable in its own right to stem these potential negative consequences and deliver increased social resilience and stability. At the same time, using fairness and equity to guide policies can also help foster important buy-in to policies necessary for addressing climate change effects so that adoption is swifter and more complete. Finally, developing equitable solutions can help uncover and target the underlying drivers of both existing inequities and climate change itself, thereby allowing for wholesale system transformation when it is necessary to create equitable resilience (Cohen et al. 2019; Matin et al. 2018; Meerow et al. 2019; Mikulewicz 2019). Thus, equity is not just a valuable goal of management and policy reform; it is also a critical input into these decisions as it serves as a functional driver of climate resilience.

3.2 Marine Aquaculture

3.2.1 Importance of Mariculture to the Ocean Economy

Aquaculture, the cultivation of aquatic animals and plants, is one of the fastest-growing industries in the world and now produces more seafood than wild capture fisheries (FAO 2018). Although marine aquaculture, hereafter called 'mariculture', currently represents only one-third of total aquaculture production (freshwater/inland aquaculture represents the remainder), this proportion is increasing. In 2016, mariculture produced 38.6 mmt of seafood worth $67.4 billion at first sale. Over half of this production was shelled molluscs (58.8%), while finfish and crustaceans represented 23% and 17% of production, respectively (FAO 2018). When converted to edible food equivalents, finfish mariculture provides the most food by volume (Edwards et al. 2019). Additionally, fed aquaculture (including finfish and crustaceans), which requires feed inputs, is growing faster than unfed bivalve aquaculture due to increasing demand for these commodities (Tacon et al. 2011; Hasan 2017).

3.2.2 Impacts of climate change on mariculture

Mariculture production is vulnerable to climate change through impacts both on the cultivated organisms as well as on the cost and infrastructure of conducting mariculture operations. Like wild marine species, cultivated marine species are impacted by changing environmental conditions (Weatherdon et al. 2016), but unlike wild species, humans can induce accelerated adaptation in cultivated species through selective breeding (Sae-Lim et al. 2017). Unlike most wild capture fisheries, mariculture operations require a significant amount of shore- and ocean-based infrastructure for cultivating marine species through multiple life stages. Both shore- and ocean-based infrastructure are vulnerable to storms, which are expected to increase in frequency and intensity under climate change (IPCC 2019), and ocean-based infrastructure such as lines, cages and pens must be actively moved in response to poor environmental conditions such as harmful algal blooms, hypoxia, or changing salinity or temperature, which increases costs and disproportionately impacts farmers unable to relocate (Dabbadie et al. 2018). As with capture fisheries, the impacts of climate change on aquaculture are expected to vary by location, species and method of production (Soto et al. 2018). The primary threats to unfed bivalve aquaculture and fed finfish and crustacean aquaculture are the following:

1. **Ocean warming** is expected to raise mortality rates and lower productivity for higher-trophic-level species (bivalves, finfish, crustaceans) (Rosa et al. 2014).
2. **Sea level rise** will increase the intrusion of saline water into deltas and estuaries compromising brackish-water aquaculture (De Silva 2012; Garai 2014), and shifting shoreline morphology could reduce habitat availability (bivalves, finfish, crustaceans).
3. **Increasing storm strength and frequency** pose risks to infrastructure (De Silva 2012), and increased weather variability has been associated with lower profits (bivalves, finfish, crustaceans) (Li et al. 2014).
4. **Ocean acidification** impedes the calcification of mollusc shells (Gazeau et al. 2013) resulting in reduced recruitment, higher mortality (Barton et al. 2012; Green et al. 2013) and increased vulnerability to disease and parasites (bivalves).
5. **Increasing rainfall** will raise the turbidity and nutrient loading of rivers, potentially causing more harmful algal blooms (HABs) that reduce production and threaten human health (bivalves, finfish, crustaceans) (Himes-Cornell et al. 2013; Rosa et al. 2014).
6. **The emergence, translocation and virulence of disease, pathogens and parasites** are impacted by climate change. For example, warming can increase susceptibility to disease, promote the influx of new pathogens (Rowley et al. 2014) and increase the toxicity of common pollutants (bivalves, finfish, crustaceans) (Fabbri and Dinelli 2014).
7. **Reduced feed availability** resulting from climate change and/or overfishing could challenge the growth potential for fed aquaculture (finfish, crustaceans) (Froehlich et al. 2018a).

3.2.3 Potential for mariculture production to grow under climate change

While marine capture fisheries production has stagnated over the past three decades, mariculture production has expanded rapidly, and is likely to become the source of new seafood production as the human population and demand for seafood grow (FAO 2018). However, the extent to which climate change could impede the ability for sustainable mariculture to meet growing food demand is unknown (IPCC 2019). **Although there are no global-scale estimates of how climate change is likely to impact mariculture profitability and productivity, four recent studies collectively suggest that the potential for sustainable and profitable mariculture is likely to remain high under climate change.**

First, Gentry et al. (2017) mapped the biological potential for mariculture and estimated that bivalve and finfish mariculture could respectively generate 767.7 mmt and 15.6 billion mt of production per year (>700 times more production than today). Second, the Blue Paper *The Future of Food from the Sea* (Costello et al. 2019) refined this analysis to account for economic feasibility and the limited availability of feed for fed finfish aquaculture, and estimated that bivalve and finfish mariculture could respectively generate 483.0 mmt and 10.5 mmt of production per year under current prices and feed compositions (~21 times more production than today). Third, Froehlich et al. (2018b) forecasted mariculture production potential under a high emissions scenario (RCP 8.5) and found only slight declines in suitable habitat and production potential across continents.

Finally, Klinger et al. (2017) suggest that breeding a larger proportion of mariculture stocks for fast growth could, on its own, more than offset the forecasted declines in productivity. In the remainder of this Sect. 3.2.3, we provide a brief overview of this chain of evidence.

1. **Enormous areas of the ocean are suitable for bivalve and finfish mariculture and the vast majority of countries would need to farm less than 1% of their exclusive economic zones to match current levels of seafood consumption.** Gentry et al. (2017) mapped the biological production potential for finfish and bivalve mariculture based on the growth potential of 180 mariculture species (120 finfish, 60 bivalves) constrained by their temperatures, dissolved oxygen levels, primary production tolerances and existing human uses (i.e. protected areas, shipping lanes and oil rigs). Overall, they estimated an enormous untapped potential for mariculture: bivalve and finfish mariculture could generate 767.7 mmt (over 2.5 million square kilometres [km^2] of suitable habitat) and 15.6 billion mt per year (over 11.4 million km^2), respectively. By comparison, bivalve and finfish mariculture currently produce only 15.3 and 7.7 mmt per year, respectively (FAO 2018). However, their analysis did not consider the economic feasibility of this production or the limited availability of feed for fed mariculture.
2. **Current mariculture production is far under capacity even after accounting for economic feasibility and limited feed availability. Advancements in feed technology would dramatically expand the production potential of finfish mariculture.** In their Blue Paper, Costello et al. (2019) refined the Gentry et al. (2017) analysis by calculating the cost and feed demand of their production estimates and assuming that mariculture production will occur only in profitable areas and that finfish mariculture production is capped by feed availability. They show that global- and country-level mariculture production is significantly under capacity. Bivalve production of 483.0 mmt should be possible at today's prices for maricultured bivalves ($1400 per mt of blue mussels). This is 467.7 mmt (>3000%) more than the current production of 15.3 mmt. Additionally, 10.5 mmt of finfish production should be possible at today's prices for maricultured finfish ($7000 per mt of Atlantic salmon) and today's feed composition. This is 2.8 mmt (36%) more than the current production of 7.7 mmt. However, technological advances resulting in a 95% reduction in the reliance of feed on fish ingredients (Oliva-Teles et al. 2015) would unlock a 209.6 mmt (>2700%) increase in finfish production to 217.3 mmt. The majority of these underages in mariculture production occur in equatorial countries (Fig. 2.2 on the following page), suggesting that mariculture expansion could mitigate the losses in capture fisheries productivity expected for these regions, potentially offsetting some of the inequities associated with these climate change impacts. Furthermore, mariculture operations can provide a critical source of jobs and income to local communities, especially to vulnerable groups such as unskilled workers (Irz et al. 2007) who might otherwise be made significantly worse off by climate change.
3. **Although climate change is expected to reduce mariculture production potential, the magnitude of this reduction is small relative to the sheer potential for production.** Froehlich et al. (2018b) extended the work of Gentry et al. (2017) to predict how finfish and bivalve mariculture will change from now to 2090 under the warming, acidification and primary productivity shifts associated with a high emissions scenario (RCP 8.5). They forecast a global increase in the suitable habitat available for finfish mariculture, particularly in polar and subpolar regions. Conversely, they forecast a global decrease in the suitable habitat available for bivalve mariculture due to the negative impact of ocean acidification. In both sectors, the growth and production potential of the suitable habitat decreases over time. As a result, global mariculture production is likely to decline by mid-century, with the greatest certainty around bivalve declines. However, the relevance of these declines is unclear, because Froehlich et al. (2018b) do not publish the nominal production potential (i.e. metric tonnes of food) for 2090. Even if climate change reduced the 495.5 mmt of mariculture production estimated to be economically feasible with today's feed technology (Costello et al. 2019) by 90%, mariculture would still be 28% more productive than it is today (49.4 mmt versus 38.6 mmt).
4. **Breeding a larger proportion of mariculture stocks for fast growth could more than offset the negative impacts of climate change on mariculture production potential.** Klinger et al. (2017) mapped the production potential of three important finfish mariculture species—Atlantic salmon (*Salmo salar*), gilthead seabream (*Sparus aurata*) and cobia (*Rachycentron canadum*)—under a

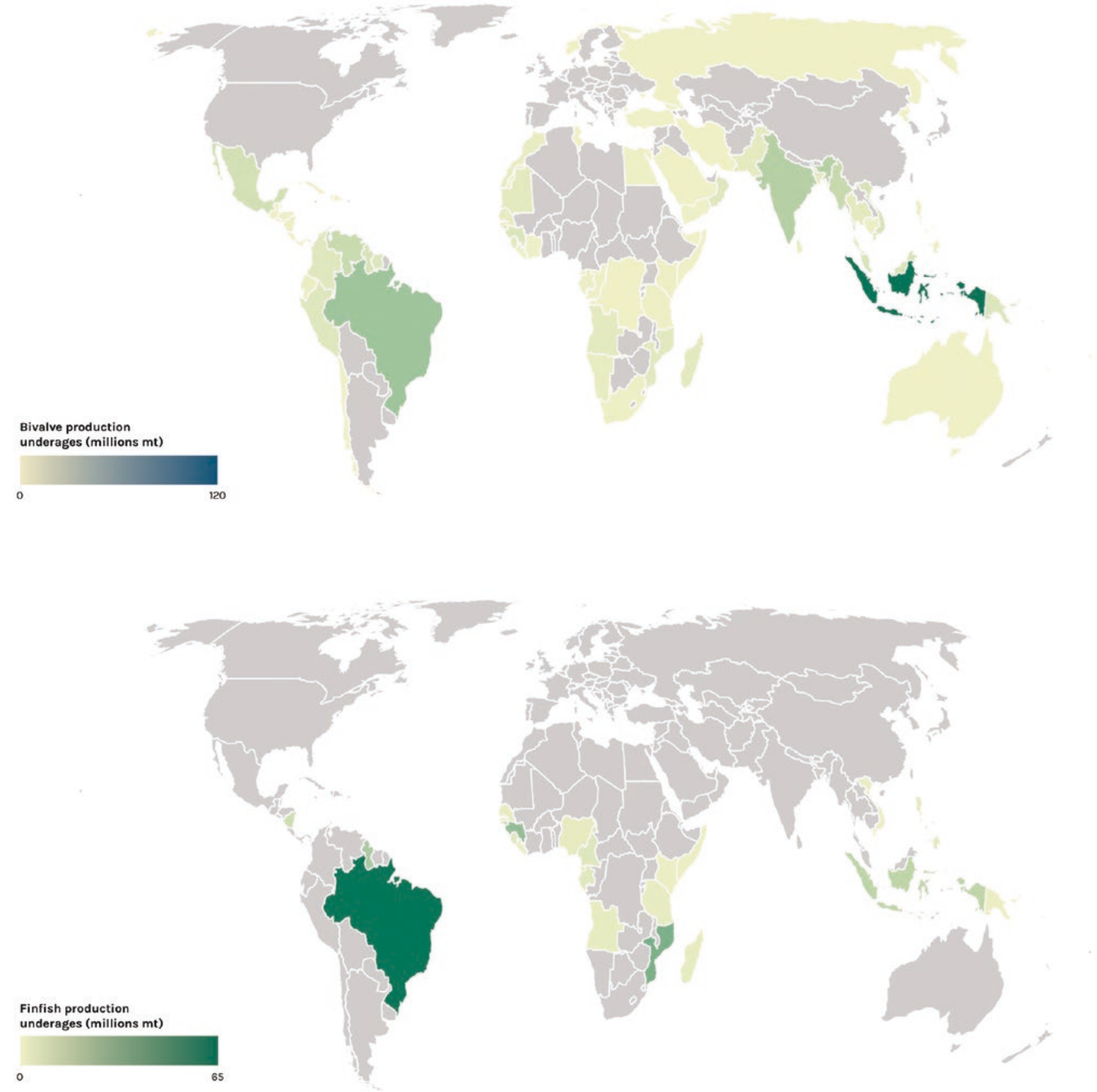

Fig. 2.2 Mariculture production underages for bivalves and finfish. *Notes: Mariculture production underages for bivalves at current prices ($1700/mt for blue mussels) (top map) and finfish at current prices ($7000/mt for Atlantic salmon) with a 95% reduction in the reliance of feed on fish ingredients (bottom map).* (Source: Adapted from Costello et al. 2019)

high emissions scenario (Geophysical Fluid Dynamics Laboratory Climate Model version 2.5 and estimated that increases in annual growth rates of 25–41% would be required to offset warming-induced declines in annual growth rates. They found that selective breeding programmes for faster growth in these species would increase growth rates by 10–15% per generation or by 100–200% over multiple generations—more than enough to offset the negative impacts of climate change. Given that only 10% of global mariculture production is currently derived from selectively bred stocks (Gjedrem et al. 2012), breeding a larger proportion of stocks for fast growth could, on its own, offset the negative impacts of climate change predicted by Froehlich et al. (2018b).

Although these four studies collectively present a chain of evidence to suggest that mariculture potential will remain high under climate change, they do not consider the social

(Froehlich et al. 2017), regulatory (Abate et al. 2016) or capacity barriers to mariculture development (Gentry et al. 2019); the challenges posed by climate-driven increases in HABs, diseases and storm frequency (IPCC 2019); or the environmental impacts of mariculture (Clavelle et al. 2019). In the next Sect. 3.2.4, we detail these challenges.

3.2.4 Barriers and Trade-Offs in the Expansion of Mariculture

If the potential for mariculture production is so large, why is current production so low? This gap is likely driven by two factors: a lack of expertise and capacity for conducting mariculture operations in many developing countries; and challenging regulatory barriers for developing mariculture operations in many developed countries. First, countries with low or crashed mariculture production exhibit lower GDPs and business friendliness scores than countries with stable or increasing mariculture production (Gentry et al. 2019). In Palau, for example, many mariculture operations have been initiated with outside funding but failed once the initial funding period ended. The longest-running mariculture operation in Palau is a government subsidised clam hatchery that would be unprofitable without government support (Y. Golbuu, personal communication). Second, countries with stricter environmental regulations have exhibited lower production and production growth than countries with more lenient regulations (Abate et al. 2016). For example, despite having one of the largest EEZs and longest coastlines, the United States produces only 1% of global mariculture (FAO 2018) due to precautionary regulations on mariculture zoning (Wardle 2017; Sea Grant California et al. 2019).

Mariculture operations can also pose a risk to marine ecosystems and the wild capture fisheries supported by these ecosystems (Clavelle et al. 2019). They can degrade habitats (Richards and Friess 2016), reduce water quality (Price et al. 2015), spread disease (Lafferty et al. 2015), hybridise with wild species (Lind et al. 2012) and introduce invasive species (Diana 2009). The expansion of mariculture should depend on adopting best practices for preventing or reducing these impacts (Klinger and Naylor 2012) including by doing the following:

1. using marine spatial planning to site mariculture in productive and profitable areas that minimise impacts on ecosystems
2. conducting offshore or integrated multitrophic mariculture to reduce eutrophication risk
3. expanding unfed bivalve mariculture, which has lower environmental impacts compared with fed finfish mariculture

See the Blue Paper *The Future of Food from the Sea* (Costello et al. 2019) for more details regarding the ecosystem impacts of mariculture and the opportunities for adaptation to reduce these impacts.

3.2.5 Adapting marine aquaculture to climate change

Selective Breeding for Fast Growth

Although selective breeding—the breeding of cultivated plants and animals to inherit specific traits—has historically been implemented less in aquaculture than in terrestrial farming (Gjedrem et al. 2012), aquaculture species are increasingly being bred to increase productivity and disease resistance (Gjedrem and Baranski 2009). The majority of breeding programmes have focused on increasing growth rates and maximising productivity and have been met with success. For example, Atlantic salmon breeding programmes have increased harvest weight by 12% per generation with cumulative genetic gains of ~200% over multiple generations (Janssen et al. 2016). Similarly, seabream breeding programmes have increased harvest weight by 10–15% per generation with cumulative genetic gains of ~100% over multiple generations (Janssen et al. 2016). These cumulative gains exceed the 25–41% total increase in annual growth rate thought to be necessary to offset the most extreme climate-induced decreases in mariculture productivity (Klinger et al. 2017); thus, selective breeding for fast growth rates alone could be sufficient to offset many of the negative impacts of climate change on mariculture.

Selective Breeding for Temperature Tolerance

Selective breeding for fast growth rates at elevated temperatures could further offset the impacts of climate change on mariculture but has yet to be widely implemented (Gjedrem et al. 2012) and has been met with mixed success (Gjedrem and Baranski 2009; Sae-Lim et al. 2015). Some selective breeding programmes have successfully resulted in increased temperature tolerances (Sae-Lim et al. 2017), but these breeding programmes can be costly (Ponzoni et al. 2008; Gjedrem et al. 2012). Furthermore, the use of selectively bred fish can pose risks to wild populations and ecosystems (Lind et al. 2012). Cultured fish frequently escape from aquaculture facilities (Jensen et al. 2010) and can interbreed with wild fish, leading to reduced genetic variability and a reduction in fitness in wild populations (Hutchings and Fraser 2008). However, in tropical countries where wild populations are projected to diminish (Lotze et al. 2019), this risk may be inherently reduced or deemed acceptable under climate change.

Risk-Based Planning and Environmental Monitoring Systems

The siting of mariculture farms based on risk-based zoning coupled with the active monitoring and responsive relocation of pens, cages and lines could help to minimise the impacts of both climate change and climate variability on mariculture production potential (Soto et al. 2018). To date, most mariculture site selections have been ad hoc, but a growing number of national and regional authorities are beginning to plan mariculture zoning using risk analysis (Aguilar-Manjarrez et al. 2017; Xinhua et al. 2017; Lester et al. 2018; Sainz et al. 2019). After siting mariculture farms in locations forecast to experience low climate risk, environmental monitoring systems could be used to track changes in environmental conditions, provide early warnings about oncoming environmental risks (e.g. HABs) and give farmers the opportunity to prepare for adverse conditions or relocate cages, pens and lines if logistically feasible (Soto et al. 2018).

Access to Affordable Credit and Insurance

Policies that increase mariculture farmers' access to credit and insurance options will also help promote the development and expansion of mariculture in the face of climate change (Soto et al. 2018). Access to affordable credit is necessary for funding both the upfront capital costs of establishing a mariculture farm as well as the annual operating costs required to adapt to or recover from climate-induced stressors (Karim et al. 2014). Increased access could be promoted through microfinance schemes or loan guarantee funds (Soto et al. 2018). Similarly, increasing storm frequency and intensity will necessitate providing more insurance options for mariculture farmers. Pilot programmes in China and Vietnam indicate that insuring small-scale farms, which are particularly vulnerable and also major contributors to food security, is a profitable investment (Nguyen and Pongthanapanich 2016; Xinhua et al. 2017).

The expansion of mariculture depends on it becoming a more efficient and lower-risk business endeavour and the insurance-pooled model used in these pilot programmes has helped raise production efficiencies while reducing production and market risks.

Reducing Feed Limitations for Fed Mariculture

Innovations in feed technology could greatly enhance the potential for fed mariculture (Costello et al. 2019; Froehlich et al. 2018a) and increase the opportunities for production under climate change. The amount of feed available for mariculture can be increased through a variety of mechanisms including the following:

1. ending over- and underfishing of the forage fish fisheries targeted for the production of fish meal (FM) and fish oil (FO) from whole fish (Froehlich et al. 2018a)
2. processing a larger proportion of landings for trimmings and diverting these by-products to the production of FM and FO (Jackson and Newton 2016)
3. reducing the amount of FM and FO used in the diets of non-carnivorous aquaculture species such as carp and other freshwater fishes, and terrestrially farmed species such as pigs and chickens (Froehlich et al. 2018a)
4. replacing fish ingredients with alternative sources of protein
5. increasing feed conversion rates

3.2.6 Opportunities for action and key conclusions

1. **Mariculture can provide food and income in countries losing access to capture fisheries.** Current mariculture production is far below potential production in many countries and the continued development of mariculture could provide food and employment in countries with climate-driven declines in capture fisheries.
2. **Expanding mariculture will require preventing, reducing and accepting the environmental trade-offs of mariculture.** Mariculture poses risks to marine ecosystems and capture fisheries and its expansion has frequently been impeded by these concerns. Expanding mariculture will depend on preventing and reducing these risks and establishing clear best practices that will help ease the regulatory burden.
3. **Finfish mariculture could generate more food and income through advancements in feed technology.** The production potential of finfish mariculture is challenged by the availability of fishmeal and fish oil from capture fisheries. Optimally managing forage fisheries, processing by-products for FM and FO, removing FM and FO from the diets of non-carnivorous fish and terrestrially farmed animals and replacing fish ingredients with alternative sources of protein would increase the viability of finfish mariculture.
4. **Mariculture species should be selectively bred for fast growth and robustness to climate change.** Despite the advantages of selective breeding, only 10% of global mariculture production is currently derived from selectively bred stocks (Gjedrem et al. 2012). Breeding a larger proportion of aquaculture stocks for fast growth could, on its own, offset the negative impacts of climate change on mariculture (Klinger et al. 2017). However, this will also necessitate increased efforts to reduce escapement, minimise pollution and mitigate other potential negative environmental impacts of mariculture.
5. **Increase access to financial services such as credit and insurance.** Mariculture is expected to become more expensive and riskier under climate change; increased access to credit and insurance for mariculture farmers will be necessary to assist with these costs and risks.
6. **Siting mariculture farms in low-risk areas and actively monitoring and responding to changing environmental conditions can enhance resilience to climate change.**

3.3 Marine and Coastal Tourism

3.3.1 Importance of marine tourism to the ocean economy

Marine and coastal tourism, referred to collectively as ocean tourism in this report, was the second-largest ocean-related economic sector in 2010, next to offshore oil and gas (OECD 2016). Ocean tourism is projected to be the top contributor of ocean industries by 2030 in terms of production value, when it will account for 26% of the ocean-based economy, compared with 21% for oil and gas (OECD 2016). Ocean tourism dwarfs the contribution of industrial capture fisheries, which constitute only 1% of ocean-based industries' production value (not accounting for artisanal fisheries, which are a critical component of the economies of Asia and Africa). The range of ocean tourism activities include beach tourism, recreational fishing, swimming, snorkelling, diving, whale watching, and taking cruises, among others. Ocean tourism's global direct value added was estimated at $390 billion in 2010, directly providing seven million full-time jobs. In addition, the ocean is a source of recreation for millions of people in the developed and developing worlds (Ghermandi and Nunes 2013; Arlinghaus et al. 2019). For comparison, the global value added of industrial capture fisheries was $21 billion in 2010 (OECD 2016), providing 11 million full-time jobs (artisanal fisheries not included).

Ocean tourism directly supports the livelihoods of millions of people and the economies of the developing tropics and many small island developing states. For example, coral reef tourism alone contributes over 40% of the gross domestic products of Maldives, Palau and St. Barthélemy (Spalding et al. 2017; Siegel et al. 2019). Despite the importance of ocean tourism in the economy, data and research on the impacts of climate change in the tourism sector are limited (Scott et al. 2012). Because coral reef tourism is one of the best-studied sectors (Scott et al. 2012), and potentially one of the most valuable ocean tourism options for many coastal nations, we focus our analysis on this sector.

Coral reef tourism is worth $35.8 billion globally every year (Spalding et al. 2017). We present a first- of-its-kind analysis of how climate change will affect coral reef tourism values at a country/territory level and explore options for nations and local communities to best prepare for the impacts of climate change.

3.3.2 Impacts of climate change on marine tourism

Weather conditions and attractiveness/uniqueness of the environment are key factors drawing people to ocean tourism (Moreno and Amelung 2009), and climate change impacts both. Understanding the potential impacts of climate change on tourism requires understanding how climate change will impact the physical and ecological resources on which tourism depends.

Marine heatwaves, or periods of extremely high ocean temperatures, have affected marine organisms and ecosystems (e.g. fisheries, coral reefs) in the last two decades and are expected to increase in frequency, intensity, duration and spatial extent (IPCC 2019). Marine heatwaves have critical impacts over habitat formation species (e.g. seagrasses, corals, kelps) that can disrupt the provision of ecosystem services (Smale et al. 2019). Future ocean warming will increase the frequency, intensity and spatial extent of bleaching events (Donner et al. 2005; IPCC 2019) that cause coral reef mortality (e.g. Arceo et al. 2001) and a subsequent reduction in reef fish diversity and numbers (e.g. Graham et al. 2007) that on-reef tourism depends on. Storms and storm surges are also expected to increase in intensity and become more frequent (IPCC 2019), causing a reduction in the desirability of a place for tourism, disrupting transportation (flights and ferries), and potentially destroying the coastal infrastructure that supports tourism. Sea level rise impacts coastal integrity and coastal assets and, together with extreme events, causes coastal erosion that, if constrained by urbanisation, can lead to coastal squeeze (Toimil et al. 2018; Scott et al. 2012). This has a known negative impact on visitors' perceptions and associated economic impacts (Scott et al. 2012). Ocean warming also affects fisheries productivity (Free et al. 2019a) and the migration patterns of species that are major draws for tourism (e.g. whales, sharks, turtles) (e.g. Lambert et al. 2010).

Climate change interacts with coral reef tourism through its direct impact on the following:

1. coral reefs and associated species on which some reef tourism directly depends (e.g. snorkelling, diving, recreational fishing)
2. weather conditions that drive a user's preference for the place
3. coastal infrastructure that supports tourism

For ocean tourism that directly depends on healthy coral reef ecosystems, such as diving and snorkelling (on-reef tourism), changes in reef conditions are expected to impact tourists' preferences and coral reef tourism's economic values. While activities that do not directly depend on reefs (i.e. reef-adjacent activities such as white sand beaches and sunbathing) are also expected to be affected by climate change (directly and indirectly through processes such as the wave attenuation role of reefs and coral reefs as a source of white sand), the magnitude of the impact is hard to measure.

3.3.3 Economic Impacts

Economic Impacts on Coral Reef Tourism

We use the coral reef tourism values per country and territory reported by Spalding et al. (2017) to represent current coral reef tourism values. These values are composed of on-reef and reef-adjacent tourism values.

Chen et al. (2015) performed a meta-analysis of how climate change impacts, in the form of changes in sea surface temperature (SST) and ocean acidification (using atmospheric CO_2 levels as a proxy), have affected and will continue to affect coral reef health and coral reef tourism values at the regional and global levels. We used their model to project how changes in SST and ocean acidification will change coral cover at the country level and how these changes in reef conditions would translate to changes in tourism values.

We project per-country future tourism value changes (with 2019 as a baseline) using the SST and CO_2 projections for RCP 2.6, 4.5, 6.0 and 8.5 climate scenarios from the CMIP5 Coupled Model Intercomparison Project (Taylor et al. 2012). For this report, we present the results for 2100 only to be consistent with the fisheries and aquaculture projections. These are the model's assumptions about how ocean warming and acidification affect coral reef cover and tourism values:

SST effect

- When the annual mean SST is less than 22.37°, a 1% increase in SST leads to a 0.67% increase in live coral coverage (relative to the percent of live corals available prior to changes in temperature).
- When SST is between 22.37° and 26.85°, a 1% increase in SST leads to a 1.59% increase in live coral coverage.
- When SST is greater than 26.85°, a 1% increase in SST leads to a 2.26% decrease in live coral coverage.

Ocean acidification effect

- Using atmospheric CO_2 as a proxy (Table 2.2), a 1% increase in CO_2 decreases live coral coverage by 0.61%.

Effect of changes in coral cover to coral reef tourism values

- A 1% decline in coral cover decreases coral reef value by 3.81%. We limit the effect of climate change to on-reef tourism values only.

Table 2.2 Global atmospheric CO_2 concentrations (ppm) for different RCPs using CMIP5

Year\RCP	2.6	4.5	6.0	8.5
2019	409.80	408.88	407.40	412.82
2030	430.78	435.05	428.88	448.83
2050	442.70	486.54	477.67	540.54
2100	420.90	538.36	669.72	935.87

Source: Royal Netherlands Meteorological Institute. "Time Series, Annual RCP45 CO2." KNMI Climate Explorer. http://climexp.knmi.nl/getindices.cgi?WMO=CDIACData/RCP45_CO2&STATION=RCP45_CO2&TYPE=i&id=someone@somewhere&NPERYEAR=1

Notes: PPM stands for parts per million, RCP for Representative Concentration Pathway and CMIP5 for Coupled Model Intercomparison Project 5

Other factors not accounted for in the model above are the effects of climate change–associated increases in ocean disturbances such as storms, mass bleaching events that cause extensive reef mortality (Donner 2009; Frieler et al. 2013; Hughes et al. 2017, 2018), heat waves (Smale et al. 2019), sea level rise (Gattuso et al. 2018), algal blooms, jellyfish blooms, climate change–related diseases (Sokolow 2009) and water and electricity supply disruptions (Weatherdon et al. 2016). Also important and not included is the confounding effect of local stressors such as nutrient pollution and illegal and destructive fishing, which negatively impact tourism values.

Nutrient enrichment has been shown to increase the susceptibility of coral reefs to bleaching (Wiedenmann et al. 2013), increase the severity of coral diseases (Bruno et al. 2003) and increase the vulnerability of coral reefs to ocean acidification (Silbiger et al. 2018). Furthermore, the poleward movement (Price et al. 2019), potential thermal evolution/adaptation (Speers et al. 2016; Donner 2009) and species-specific responses of corals (Fabricius et al. 2011) are not accounted for in our projections. All these additional climate change–induced stressors and the confounding effect of local stressors impact local and national economies (Hoegh-Guldberg et al. 2018).

The combined effect of warming (SST) and ocean acidification as factors affecting coral reef cover and tourism values results in predictions of negative effects for all countries, with magnitudes dependent on the climate pathways (Fig. 2.3, Table 2.3).

For the high-emissions scenario of RCP 8.5, which is characterised by considerable increases in greenhouse gas emissions, coral cover is expected to be reduced by 72–87% (relative to the present coral cover) and on-reef tourism values by over 90% from 2019 to 2100 due to combined ocean warming and acidification. The reduction will be less severe under a stabilisation scenario of RCP 4.5 with an expected reduction of 12–28% and 36–66% in coral cover and on-reef tourism values, respectively. Note that the reduction in coral cover is still conservative as other factors such as bleaching events, storms and other climate stressors, which are expected to intensify and become more frequent, are not included in the model.

Brander et al. (2012) projects that ocean acidification will cause a 27.5% reduction in global coral cover by 2100 under RCP 8.5 (with 2000 as the baseline year). This value is in line with Chen et al. (2015), which our projections are based on,

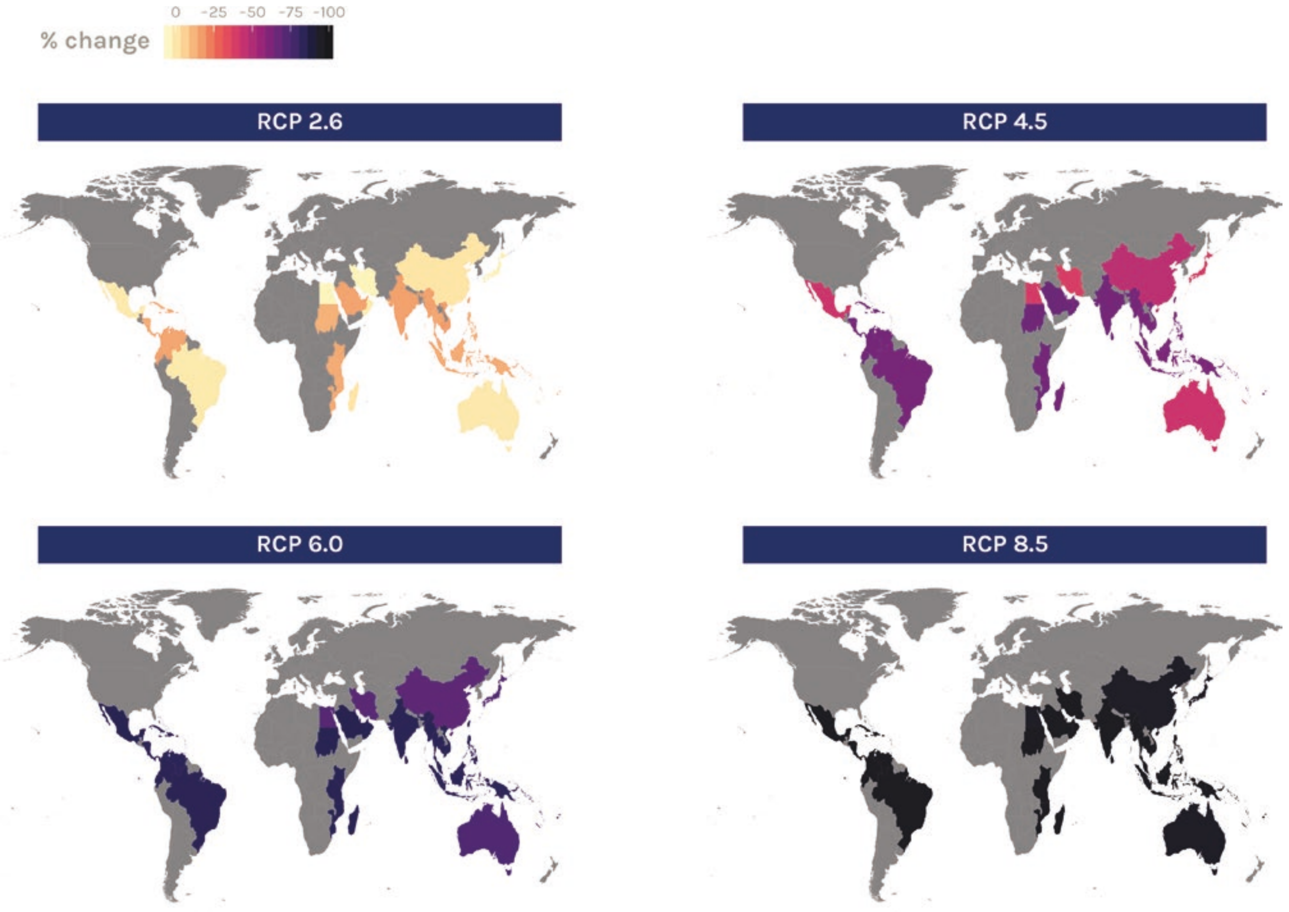

Fig. 2.3 Percent change in coral reef tourism values in 2100 for different climate projections. *Notes: Values in 2100 are relative to those in 2019. See* Table 2.3 *for country values*. (Source: Model adapted from Chen et al. 2015)

Table 2.3 Percent change in coral reef tourism values in 2100 for different climate projections, by country

Country	Total coral reef tourism value (US $1000 per year)	% on-reef	% change in coral cover (RCP 4.5)	% change in tourism values (RCP 4.5)	% change in coral cover (RCP 8.5)	% change in tourism values (RCP 8.5)
Egypt	6,917,028	86.3	−12.9	−39.4	−72.4	−94.0
Indonesia	3,097,453	64.3	−25.2	−62.4	−81.7	−95.8
Mexico	2,999,883	44.8	−14.2	−42.4	−82.6	−96.0
Thailand	2,410,154	44.8	−25.4	−62.7	−81.8	−95.8
Australia	2,176,084	78.3	−14.1	−42.2	−73.1	−94.2
China	1,871,814	15.3	−16.2	−46.6	−71.8	−93.9
Philippines	1,385,144	67.4	−25.2	−62.4	−81.8	−95.8
Hawaii	1,230,894	44.8	−13.6	−41.1	−73.0	−94.1
Japan	1,177,549	53.9	−13.2	−40.2	−72.7	−94.1
Malaysia	1,148,955	64.3	−25.2	−62.4	−81.8	−95.8
Maldives	1,085,273	84.4	−25.9	−63.5	−82.2	−95.9
Puerto Rico	648,867	21.3	−26.4	−64.2	−82.1	−95.9
Brazil	612,864	8.3	−25.9	−63.4	−82.3	−95.9
Bahamas	526,058	60.5	−26.2	−63.9	−82.2	−95.9
Dominican Republic	511,669	26.5	−26.3	−64.0	−82.0	−95.9
India	464,082	15.3	−26.4	−64.1	−82.4	−95.9
Honduras	446,628	85.8	−26.0	−63.6	−82.1	−95.9
United Arab Emirates	445,654	15.3	−26.4	−64.2	−83.1	−96.0
Jamaica	333,386	35.1	−26.1	−63.8	−82.1	−95.9
Taiwan	323,440	15.3	−25.9	−63.5	−82.2	−95.9

(continued)

Table 2.3 (continued)

Country	Total coral reef tourism value (US $1000 per year)	% on-reef	% change in coral cover (RCP 4.5)	% change in tourism values (RCP 4.5)	% change in coral cover (RCP 8.5)	% change in tourism values (RCP 8.5)
Guam	323,244	64.3	−25.9	−63.4	−82.2	−95.9
Mauritius	312,389	47.4	−25.5	−62.8	−82.3	−95.9
Cayman Islands	292,794	83.2	−25.8	−63.4	−82.1	−95.9
Cuba	283,290	35.1	−25.8	−63.3	−82.0	−95.9
Venezuela	281,865	35.1	−26.2	−63.8	−82.0	−95.9
Virgin Islands of the United States	276,056	53.9	−26.3	−64.0	−82.0	−95.9
Saudi Arabia	268,681	49.7	−27.6	−65.8	−83.5	−96.1
Fiji	234,676	65.4	−24.9	−62.0	−81.9	−95.9
Bermuda	223,639	69.2	−13.3	−40.3	−73.3	−94.2
Oman	221,164	35.1	−27.2	−65.2	−83.1	−96.0
Aruba	218,226	35.1	−26.1	−63.7	−82.0	−95.9
Barbados	180,082	38.7	−26.0	−63.5	−81.9	−95.9
Costa Rica	169,518	35.1	−26.0	−63.6	−82.3	−95.9
Panama	154,178	38.7	−26.2	−63.9	−82.1	−95.9
Colombia	147,202	35.1	−26.3	−64.0	−82.3	−95.9
Vietnam	137,445	15.3	−25.6	−63.0	−81.9	−95.9
Tanzania	131,076	49.7	−26.3	−64.0	−82.5	−95.9
Kuwait	117,236	35.1	−12.4	−38.2	−71.7	−93.8
Bahrain	115,837	21.3	−11.5	−36.1	−86.6	−96.5
French Polynesia	113,657	63.1	−24.6	−61.6	−81.6	−95.8
Qatar	108,066	8.3	−25.8	−63.3	−83.2	−96.1
Turks and Caicos Islands	97,587	69.2	−26.4	−64.2	−82.3	−95.9
Palau	92,503	86.3	−25.1	−62.2	−81.9	−95.8
Guadeloupe	90,463	38.7	−26.3	−64.0	−81.9	−95.9
Martinique	89,337	35.1	−26.0	−63.6	−81.9	−95.9
Kenya	84,152	31.0	−26.4	−64.2	−82.6	−96.0
Sri Lanka	82,371	8.3	−26.0	−63.5	−82.2	−95.9
Belize	80,611	70.8	−25.7	−63.2	−81.3	−95.7
Seychelles	73,141	47.4	−26.1	−63.7	−82.5	−95.9
Mozambique	68,356	80.9	−26.6	−64.4	−82.5	−95.9
Northern Mariana Islands	61,302	73.0	−25.9	−63.4	−82.2	−95.9
Ecuador	58,883	60.5	−26.8	−64.7	−83.0	−96.0
Saint Lucia	56,574	41.9	−25.9	−63.4	−81.9	−95.8
Madagascar	50,496	47.4	−26.1	−63.8	−82.5	−95.9
Vanuatu	49,991	59.0	−24.7	−61.6	−82.0	−95.9
Papua New Guinea	32,024	73.0	−25.2	−62.4	−81.8	−95.8
Sudan	28,480	85.8	−27.1	−65.1	−83.0	−96.0
New Caledonia	28,465	57.4	−15.0	−44.2	−82.6	−96.0
Brunei	28,259	26.5	−24.9	−62.0	−81.8	−95.8
Grenada	23,150	53.9	−25.8	−63.4	−81.9	−95.8
Solomon Islands	21,984	79.5	−25.0	−62.1	−81.6	−95.8
Anguilla	19,685	41.9	−26.6	−64.4	−82.1	−95.9
Cook Islands	19,106	41.9	−25.0	−62.1	−81.6	−95.8
Cambodia	18,285	15.3	−25.6	−63.0	−81.9	−95.8
Micronesia	18,108	86.3	−25.3	−62.5	−81.9	−95.8
Haiti	15,206	31.0	−26.5	−64.3	−82.2	−95.9
Iran	13,345	0.0	−12.4	−38.2	−84.3	−96.2
Tonga	13,291	71.6	−15.2	−44.5	−82.1	−95.9
Samoa	12,490	31.0	−24.9	−62.0	−81.5	−95.8
Myanmar	11,581	51.9	−26.0	−63.6	−81.9	−95.8
Nicaragua	10,975	41.9	−25.9	−63.4	−81.9	−95.8

Source: Country-level tourism values data provided by M. Spalding. Model for change in coral cover adapted from Chen et al. (2015)

Notes: Climate change effect. Summary table for all countries and territories with over 50 square kilometres of reef, and total reef-related expenditures of more than $10 million per year. On-reef tourism value pertains to in-water activities such as diving, snorkelling and glass-bottom boats. Adjacent-reef tourism value captures a range of indirect benefits from coral reefs, including the provision of sandy beaches, sheltered water, seafood and attractive views which indicates a coral cover reduction of ~31% due to ocean acidification and ~28% due to ocean warming (for RCP 8.5). Our projections have not incorporated the effects of bleaching, which is expected to be more frequent in the future and can be a greater driver of coral mortality under climate change. Speers et al. (2016) modelled the effects of combined ocean warming, acidification and intensifying bleaching on changes in coral cover and projects that current global coral cover will be reduced by 92% by 2100 under RCP 8.5.

The top five countries with the highest coral reef tourism values are Egypt (~$7 billion/year), Indonesia (~$3.1 billion/year), Mexico (~$3 billion/year), Thailand (~$2.4 billion/year) and Australia (~$2.2 billion/year). These five countries have 45–86% of their coral reef tourism values based on on-reef activities (e.g. snorkelling and diving), and climate change impacts (ocean warming plus acidification) will reduce on-reef tourism values by over 90% in 2100 for RCP 8.5 (39–63% for RCP 4.5).

The projections above should be interpreted as the effect of climate change on future potential tourism values, holding all other factors equal. Our projections indicate that the degree of climate change impacts depends on the emissions pathways taken in the future, although any of the emissions scenarios would still negatively impact reef tourism values.

When most of a country's coral reef tourism value comes from reef-adjacent activities, climate change may not severely affect that country. The reef-adjacent values, however, will be affected by increased extreme weather events in the area, algal blooms and coastal erosion, which we have not yet incorporated into the current calculations.

We reported here how climate change impacts coral cover and the corresponding on-reef tourism values of several national economies. While the coral reef tourism values of all nations are projected to be negatively affected by climate change, nations can still incur positive tourism values in the future as our estimate has not accounted for increases in tourism demand and arrivals in the future—international arrivals are expected to increase 3–5% per year (UNWTO 2016; Lenzen et al. 2018). In accounting for the improvements in tourism values due to an increase in tourist arrivals, it should be noted that the tourism value is a hump shape, or concave function, of tourism arrivals. Additional arrivals increase tourism values up to some point after which the desirability of a place for tourism decreases as tourist numbers further increase. Future research can incorporate the Shared Socioeconomic Pathways (SSPs) to future projections of tourism under climate change to account for not only ecosystem changes, but also changes in the demand for tourism.

Economic Impacts in Other Systems

Coral reef tourism is not the only tourism sector that will be impacted by climate change. Other non-reef coastal attractions such as the coastal glaciers in Ilulissat Icefjord, Denmark, a UNESCO World Heritage site, and places such as coastal cities like Venice, Italy (Moreno and Amelung 2009) or Alexandria, Egypt (Scott et al. 2012) will also be heavily affected by climate change. Beach tourism in tropical and temperate areas is expected to be significantly affected by climate change, especially due to the effect of sea level rise and storms on shoreline erosion (Scott et al. 2012). For example, in the Mexican Caribbean, the estimated total beach replenishment cost for the main five ocean tourism cities under a future 1 m sea level rise scenario is $330 million (Ruiz-Ramírez et al. 2019), and in the United States, the total beach nourishment cost for 2060 based a 0.32 m scenario amounts to $20.40 billion (Scott et al. 2012). The breaking of ice in the polar region also poses potential danger to cruise ships and navigation. For all these systems, 'last chance tourism' is emerging, attracting people to the most vulnerable areas (IPCC 2019).

Consequences need to be further explored to understand the implications and dimensions of this trend.

Quantifying the impacts of climate change on other ocean tourism activities and beyond will provide a more complete picture of the impacts of climate change on local and national economies, which could potentially motivate local, national and global actions.

Ocean Tourism and Equity

Ocean tourism has the potential to alleviate poverty, especially in coastal fishing and farming communities where poverty incidences are high. It can boost local and national economic development and improve local welfare. However, unregulated ocean tourism development can bring in several unwanted consequences, such as the degradation of the environmental resource base that the tourism industry depends on, destruction of local cultures and traditional livelihoods and inequitable distribution of economic benefits (Cabral and Aliño 2011). Actions that ensure an equitable and sustainable tourism industry include proper planning of tourism developments, promotion of ecotourism activities that respect local cultures and traditions (including indigenous peoples' rights over ancestral domains) and implementation of policies that ensure that economic benefits from tourism activities accrue locally (i.e. provide local opportunities).

3.3.4 Opportunities for action and key conclusions

1. **Enhance coral reef resilience to climate change.** Reducing the negative impacts of climate change and associated ocean disturbances to coastal economies requires improving the resilience of marine and coastal ecosystems to climate change (Gattuso et al. 2018; James et al. 2019; Weatherdon et al. 2016). Establishing marine protected areas and MPA networks can help improve the

ecological resilience of coral reefs. MPAs protect marine ecosystems and their services from environmental uncertainties (Roberts et al. 2017), help minimise the footprints of human activities such as fishing (Lester et al. 2009), secure the continuous supply of genetic materials and serve as climate refugia when sited in cooler, less-impacted areas (Roberts et al. 2017; Mcleod et al. 2009). Furthermore, MPAs help ensure that coral reefs and associated species that are important draws for tourism are protected.

However, conventional management approaches that include MPAs may be insufficient to protect global coral reefs under warming and acidifying ocean conditions (Anthony et al. 2017). Assisted relocation and evolution (van Oppen et al. 2017) together with new biotechnology practices can enhance the resilience of coral reefs, but with associated costs. Protection should prioritise ecosystem connectivity—while there are preferences for some physical attributes of coastal tourism, like white sand, and there is a tendency to alter the ecosystem to favour some components (e.g. removing mangroves to access sandy beaches) (e.g. Cabral and Aliño 2011), it is important to recognise the huge role these ecosystems play in maintaining coastal integrity. For example, protecting mangroves and seagrass beds—which serve as nursery areas for a number of coral reef fish species and protect coral reefs by trapping sediments—enhances reef health and productivity.

2. **Protect and regenerate natural habitats.** Preserving and restoring natural coastal habitats such as coral reefs, beaches and mangroves increases the resilience of coastal areas to climate change (James et al. 2019), providing an alternative to hard infrastructure that allows for wave attenuation and shoreline stabilisation (James et al. 2019; Gattuso et al. 2018), as well as providing additional protections from storm surges and excess flooding (Ruiz-Ramírez et al. 2019). Traditional infrastructures for tourism such as urbanised beach fronts are expected to suffer shoreline erosion (coastal squeeze) due to climate change (Toimil et al. 2018; Scott et al. 2012). In these cases, coastal natural habitats can allow for landward retreat; otherwise, beach nourishment will be required to maintain tourism in heavily urbanised areas at very high costs (Scott et al. 2012). The quality of nearby sand habitats can be important to reduce those costs (Ruiz-Ramírez et al. 2019).
3. **Diversify development portfolios.** Diversifying tourism activities and investments to include linked ecosystems will help maintain diverse ecosystem functions, while simultaneously capturing the tourism potential of various ecosystems. Ecotourism, or tourism activities that support nature conservation and education, should be prioritised. Pressures on and drivers of reef health are often associated with governance and the socioeconomic needs of the people dependent on reefs. Linking fisheries, aquaculture and tourism to local food and livelihood security will improve the portfolio of policies that can be applied to reduce climate change's impacts on local and national economies. Marine spatial planning will play a key role in maintaining healthy reefs by strategically siting activities in the ocean so that negative interactions can be reduced. Actions include properly siting tourism infrastructure and making investments that account for potential future coastal and ocean changes. Management plans should explicitly address the role of natural habitats functioning as buffers to climate change on tourism (Ruiz-Ramírez et al. 2019). Communities that directly depend on coral reef tourism for their livelihoods need to increase their adaptive capacities, as this sector is expected to be negatively impacted by the changing climate in all countries. Local governments, private investors and development agencies can help by improving and developing social and institutional arrangements that allow for learning (i.e. technical education and skills development) and diversifying livelihoods and income sources (Cinner et al. 2018) while incorporating local and indigenous knowledge into the planning and decision process.
4. **Ensure that waste is properly disposed of and that waste treatment facilities are included in coastal tourism infrastructure.** As described above, nutrient enrichment exacerbates ocean acidification.

   Controlling nutrient input from coastal and terrestrial activities will help reduce the impact of climate change on coral reefs and reef tourism. Strategies can include ensuring that waste management, such as waste treatment facilities/recycling, is included in tourism development plans. Pollution combined with overfishing that degrades coral reefs caused the Caribbean to lose $95–140 million/year in net revenue from coral reef–associated fisheries, $100–300 million/year in reduced tourism revenue and $140–420 million/year in reduced coastal protection (Burke et al. 2011).
5. **Reduce the environmental footprint of tourism through ecotourism and clean energy investments.** While climate change will inevitably affect tourism, tourism is also a major contributor of greenhouse gas emissions (Scott et al. 2012). It is estimated that tourism contributes 8% of global GHG emissions, with transport, shopping and food as major contributors (Lenzen et al. 2018). With tourism expected to grow 3–5% per year, it is important to ensure that the environmental footprint of tourism is minimised. Future increases in international arrivals do not necessarily translate to economic benefits for countries; hence, policies that ensure optimal benefits

for national economies while reducing tourism's footprint, such as those that promote ecotourism activities, should be prioritised. Furthermore, investments in clean and efficient energy in the tourism sector help reduce tourism's environmental footprint.

3.4 Improving the Energy Efficiency of the Ocean Economy

Improving the energy efficiency of ocean-related industries, especially shipping/transportation, would generate climate change benefits as well as benefits to the industries themselves. While significant improvements to the offshore oil and gas industry would require extensive transitioning of investments away from exploration and extraction of fossil fuels and into renewable energy (Allison and Bassett 2015), the shipping industry can make relatively large energy efficiency gains using existing technologies (Allison and Bassett 2015; Ash and Scarbrough 2019; Hoegh-Guldberg et al. 2019). For example, switching international shipping to solar-generated, ammonia-based fuel would allow for significant reductions in greenhouse gas emissions (Ash and Scarbrough 2019). Related topics are discussed in more depth in the Blue Papers *Ocean Energy and Mineral Sources* and *Coastal Development*. Fisheries and aquaculture are already relatively energy efficient, especially when compared with the terrestrial production of animal protein (Allison and Bassett 2015; Hoegh-Guldberg et al. 2019), but there is great potential in the expansion of carbon- and energy-efficient shellfish aquaculture as well as in the reduction of overcapacity in fisheries (Allison and Bassett 2015). Finally, the tourism sector involves a diverse array of opportunities for improving energy efficiency—from increasing fuel efficiency and using carbon offsets for various modes of travel to improving the energy efficiency of hotels and other tourism destinations around the world (Allison and Bassett 2015).

4 Impacts of Climate Change Mitigation in the Sea

Global efforts to mitigate climate change include a variety of approaches that may themselves have impacts on ocean ecosystems, species assemblages and the ocean economy. Here, we discuss the potential marine impacts and opportunities of four major categories of climate change mitigation methods that directly affect the ocean: efforts to conserve and increase 'blue carbon' storage; expansion of ocean-based renewable energy generation; deep-sea mining to meet demand for rare earth elements; and geoengineering techniques. We limit our discussion of the three latter topics to their direct impact on the ocean.

4.1 Conserving and Expanding Blue Carbon

The term 'blue carbon' refers to the capacity of marine ecosystems to store organic carbon over centuries or millennia (Serrano et al. 2019). The ocean is the largest carbon sink on Earth; it has already absorbed more than 90% of Earth's additional heat and captured nearly one-third of all atmospheric CO_2 emissions since the 1700s (Gattuso et al. 2015). Through a process known as the 'biological pump', marine organisms convert CO_2 into biomass (referred to as carbon 'fixation') through photosynthesis. A portion of this carbon is deposited and buried on the seafloor, thus removing it from the atmospheric carbon cycle on a long enough time scale to constitute a carbon sink (at which point this carbon is referred to as having been 'sequestered') (Barange et al. 2017; Duarte et al. 2013; Mcleod et al. 2011; Serrano et al. 2019; Vaughan and Lenton 2011). Marine carbon sequestration occurs both in the open ocean and along the coast, and there are opportunities to increase the sequestration capacity and contribute to climate change mitigation in both areas. These opportunities are becoming an important sector of the ocean economy as efforts mature to quantify and monetise (e.g. with carbon pricing) marine ecosystem restoration and management for carbon sequestration (Alongi et al. 2016; Lavery et al. 2013; Lovelock et al. 2017; Mcleod et al. 2011; Pendleton et al. 2012). As this sector develops, it is critical to consider the implications for vulnerable and marginalised groups, including small-scale fishers, who may be overlooked in blue carbon decision-making (Cohen et al. 2019).

Vegetated coastal ecosystems—primarily seagrasses, mangrove forests and tidal marshes—occupy only 0.2% of the global ocean surface, but have an outsize capacity for carbon sequestration, contributing up to 50% of carbon burial in marine sediments (Duarte 2017; Duarte et al. 2013; Hoegh-Guldberg et al. 2019; Mcleod et al. 2011; Serrano et al. 2019), far outpacing the capacity per unit area of terrestrial habitats (Hoegh-Guldberg et al. 2019; Serrano et al. 2019). Kelp and other macroalgal beds have also recently been identified as contributors to global blue carbon storage (Serrano et al. 2019), and although there is significant debate around whether coral reefs act as carbon sources or sinks, the presence of coral reefs adjacent to seagrass beds and mangrove forests may improve the blue carbon efficacy of the system as a whole (Watanabe and Nakamura 2019).

While the capacity to expand the existing inventories of fixed and sequestered carbon in vegetated coastal ecosystems is limited, there is a critical need to protect them from degradation and conversion to alternative land uses (Allison and Bassett 2015; Hoegh-Guldberg et al. 2019). These ecosystems are among the most threatened habitats on Earth, and their current and projected loss not only reduces global CO_2 uptake, but also releases large amounts of carbon currently stored in their biomass and soils (Allison and Bassett 2015; Duarte 2017; Gattuso et al. 2015; Hoegh-Guldberg et al. 2019; Serrano et al. 2019). There may be sizable blue carbon potential in the restoration of marine vegetation where large portions of the coastline have been lost to development, as well as in the expansion of macroalgae aquaculture (Duarte 2017). In addition to their carbon sequestration capacity, vegetated marine ecosystems provide coastal protection and sea level rise mitigation services, regulate water quality, provide critical habitat for many marine species including commercially important fishery targets and enhance system biodiversity and resilience (Serrano et al. 2019). Thus, their protection and restoration would have multiple synergistic benefits (Allison and Bassett 2015).

There are also potential opportunities to increase the open ocean's capacity to sequester carbon where the biological pump moves biogenic carbon to depths of 1000 m or more, capturing it for centuries or longer (Burd et al. 2016). The main sources of this biogenic carbon are faeces, mucus and dead organisms.

Researchers have recently suggested that fisheries could be managed to have higher standing stock biomass, even in the face of climate change (Gaines et al. 2018; Hilborn and Costello 2018), which could theoretically increase the input of organic matter (including carbon) to the biological pump, especially when cascading ecosystem impacts of increasing standing stock biomass are considered (Roman and McCarthy 2010). Fostering the recovery of larger, deeper-diving fish and marine mammals could also increase upward fluxes of fixed nitrogen and other limiting nutrients from the deep ocean, thereby spurring additional primary productivity and subsequent CO_2 fixation (Aumont et al. 2018). These potential deep-sea carbon sequestration opportunities have thus far been inadequately studied, and would benefit from further exploration.

4.2 Expanding Ocean Renewables

Marine renewable energy sources have significant potential for reducing human demand for fossil fuels and reducing climate-changing GHGs (Boehlert and Gill 2010; Hoegh-Guldberg et al. 2019). Technologies capable of producing energy from the ocean are vast and expanding, with most taking advantage of wind, waves, currents, tides or thermal gradients, collectively referred to as offshore renewable energy developments, or ORED (Boehlert and Gill 2010). As these technologies expand, they will impact the ocean both above and below the water's surface through the following six channels, discussed in depth in Boehlert and Gill (2010):

1. **Physical presence**: Stationary structures such as support pillars and cables will alter pelagic habitats and bottom communities. Structures not treated with anti-fouling chemicals will create new settlement habitats, essentially forming artificial reefs and de facto 'fish aggregation devices'. ORED structures may also create barriers to species migration above and below the water.
2. **Dynamic effects**: Structures with moving parts (e.g. wind energy devices and below-water turbines) may be especially hazardous to migratory birds, cetaceans and fish. Oscillating structures, such as buoys and rotors, will modify water movement, turbulence and stratification, potentially altering the associated movements of marine species.
3. **Chemical effects**: Anti-fouling and other chemicals used on ORED technologies can leach into the surrounding water. Constructing, servicing and decommissioning structures brings additional risk of chemical spills. Furthermore, the movement of deep water to the surface during ocean thermal energy conversion can change chemical conditions through the increased input of nutrients, heavy metals and carbon dioxide, which can also outgas to the atmosphere.
4. **Acoustic effects**: Acoustic ORED impacts will be most severe during survey and construction phases, but noise from moving ORED structures may impact marine species during the operational phase as well.
5. **Electromagnetic field effects**: The transmission of electricity from ORED structures to shore generates low-frequency electromagnetic fields in the surrounding water, which may change the behaviours of marine species that use natural electric and/or magnetic fields for a variety of behaviours. Electricity-transmitting cables may also increase the temperature of the surrounding water and sediment, but the effects of this are still unknown.
6. **Effects of the energy removal itself**: Removing energy from the water can change local water movement (e.g. seasonal or tidal opening and closing of estuary systems), more distant current patterns, tidal ranges and thermal regimes. All of these changes may impact productivity patterns and species movement.

Each of these impacts must be evaluated throughout the stages of development, and across spatial and temporal scales (i.e. local versus far-reaching, and short- versus long-term impacts). The cumulative impacts of multiple adjacent developments must also be understood (Boehlert and Gill 2010). In addition, both the feasibility and the potential impacts of marine renewable energy technologies may be altered by the effects of climate change, including sea level rise, increased storms and extreme events, and changes to wave and circulatory energy patterns. These eventualities will need to be considered, and operations will need to be designed for climate resilience if they are to be successful and sustainable.

4.3 Expanding Deep-Sea Mining to Meet Demand for Rare Earth Elements

Rare earth elements (a group of 17 elements comprised of 15 lanthanides, plus yttrium and scandium) are critical to the development and operation of a variety of renewable energy technologies, including solar cells, wind turbines and electric vehicles (Dutta et al. 2016), but current land-based supply streams may not meet growing demand (Dutta et al. 2016; Miller et al. 2018a). The deep-sea floor, especially areas around hydrothermal vents, contains relatively vast quantities of rare earths that could help to meet this demand, and mining contracts for deep-sea resources including rare earths have been awarded to a number of countries and companies (Kato et al. 2011; Miller et al. 2018a). However, the costs associated with extracting rare earth elements are thus far prohibitive, and no commercial-scale mines are as yet operational (Miller et al. 2018a).

In addition to the usual risks associated with mining and other extractive industries in the ocean (including the potential for the release of toxic elements, contamination from dredge spoils, increased noise, heat and light pollution, and loss of biodiversity), these deep-sea mining operations carry risks related to impacts to the fragile marine ecosystems and unique and endemic species communities found on the deep-ocean floor, many of which have been recognised as vulnerable (Miller et al. 2018a; Van Dover et al. 2017). Furthermore, impacts may extend many kilometres away from mining sites and the long-term impacts will be much more significant than in shallow water because deep-sea habitats can take decades to millennia to recover (Miller et al. 2018a). Finally, deep-sea mining carries additional challenges, such as the potential for conflict with other marine uses and the legal and political complexities of operating under international waters in the open ocean (Miller et al. 2018a).

4.4 Geoengineering Solutions

A variety of ocean-based geoengineering concepts have been suggested to help mitigate climate change including ‘cloud brightening’, by mechanical or biological means, to increase atmospheric albedo; fertilising patches of the ocean with limiting nutrients (iron, nitrogen or phosphorus) to enhance primary productivity and sequestration of carbon (see blue carbon discussion above); inducing upwelling to do the same; inducing downwelling to increase the sinking of CO_2-rich waters; and ‘enhanced weathering’, wherein materials such as carbonate or silicate are added to the water to increase alkalinity, thereby stimulating removal of CO_2 from the atmosphere (Allison and Bassett 2015; Vaughan and Lenton 2011). Together, these efforts could theoretically reduce global radiative forcing by an estimated ~4.2 W/m^2, with cloud brightening contributing the bulk of that reduction (Vaughan and Lenton 2011).

While the costs of implementing any of these techniques are currently prohibitive, and the carbon-balance effects are highly uncertain (Allison and Bassett 2015; Vaughan and Lenton 2011), even if they prove cost-effective and sequester substantial amounts of carbon they may result in unwanted ocean impacts. For example, ocean fertilisation could lead to increased deoxygenation and eutrophication, and making adjustments to natural upwelling and downwelling patterns could alter primary productivity and change community structures and functions (Vaughan and Lenton 2011). Increasing cloud cover could generate unwanted weather patterns (Irvine et al. 2010; Jones et al. 2009) and address only global temperature changes without reducing other impacts, such as ocean acidification (Gattuso et al. 2015; Vaughan and Lenton 2011; Williamson and Turley 2012). Each of these impacts could have significant consequences for other sectors of the ocean economy, as discussed above. Finally, there may be important ethical implications associated with many of these geoengineering options related to the uneven distribution of impacts (Allison and Bassett 2015; Jones et al. 2009; Vaughan and Lenton 2011). Thus, near-term efforts should be focused on drastically reducing CO_2 emissions while research into the risks and benefits of these geoengineering technologies continues.

5 Conclusions and Opportunities for Action

The ocean is critically important to the global economy. Collectively, it is estimated that ocean-based industries and activities contribute hundreds of millions of jobs and approximately $2.5 trillion to the global economy each year, making it the world’s seventh-largest economy when compared with national GDPs (Hoegh-Guldberg 2015; IPCC 2019). In this paper, we reviewed the impact of climate change on the three key components of the ocean ecosystem economy—fisheries, marine aquaculture and coral reef tourism—and the opportunities for effective institutions and markets to reduce these impacts.

Building on existing work, we developed three models to forecast the economic impacts of climate change and potential benefits of adaptation in each sector for every coastal country under diverse climate scenarios. For capture fisheries, we find that all countries would benefit from implementing climate-adaptive reforms and that many countries could maintain current profits and catches into the future with adaptation. For aquaculture, we show that production is under capacity in many countries and the negative effects of climate change could be more than offset by developing and expanding sustainable mariculture. For ocean tourism, we find that all countries will be negatively impacted, and both local and global actions that reduce the magnitude of climate change effects would help lessen the economic impacts.

Maintaining a robust ocean economy will depend on swift efforts to reduce greenhouse gas emissions. The recent IPCC (2019) report estimates that climate-induced declines in ocean health will cost the global economy $428 billion/year by 2050 and $1.98 trillion/year by 2100. The magnitude and inequity of these losses is highly sensitive to future greenhouse gas emissions across sectors of the ocean economy. The ability for climate-adaptive fisheries management to mitigate losses under climate change deteriorates under increasingly severe emissions scenarios. The ability for mariculture to be a viable substitute for declining capture fisheries is also diminished under increasingly severe climate futures. Finally, the magnitude of losses in marine and coastal tourism increases dramatically under increasingly severe emissions scenarios. In all cases, these impacts are especially pronounced in the tropical developing countries, which have contributed the least to growing greenhouse gas emissions. Thus, it will be the responsibility of the industrial nations to take a leadership role in curbing emissions and reducing the impacts of climate change on the ocean economy.

Since climate change impacts differ by country and sector, possible solutions will be context-specific. By exploring the climate change impacts at the country level for fisheries, aquaculture and reef tourism as described in this report, countries will be able to assess what they stand to gain or lose due to climate change. Below, we outline solutions for each sector based on whether a country will experience gains, no change or losses.

5.1 Capture Fisheries

An interactive web interface developed by the Sustainable Fisheries Group at the University of California, Santa Barbara, summarises the impact of climate change on marine fisheries around the world and the opportunities for countries to mitigate these impacts through climate-adaptive fisheries management reforms (UCSB 2019). It illustrates how the health of fisheries and the catches and profits provided by them will change under four increasingly severe climate change scenarios (+0.3 °C, +0.9 °C, +1.2 °C and +2.3 °C increases in sea surface temperature by 2100) with and without climate-adaptive fisheries reform. This tool can be used to determine whether a country is likely to experience negative, positive or neutral impacts of climate change.

1. **Lower-capacity countries** (often tropical, developing countries experiencing negative impacts of climate change) should implement or strengthen their fisheries management (see Cochrane et al. 2011) to enhance resilience to the negative effects of climate change.
2. **Higher-capacity countries** (often temperate, developed countries experiencing mixed impacts of climate change) should account for shifting productivity in fisheries stock assessments and management procedures (see Pinsky and Mantua 2014) to capitalise on the positive effects of climate change and mitigate the negative effects.
3. **All countries** will derive benefits from international cooperation that both ensures that management does not degrade as stocks shift distributions and results in fairness and equity in fisheries outcomes under climate change.

5.2 Aquaculture

1. **In countries with underdeveloped mariculture potential** (Fig. 2.2), the negative effects of climate change can be offset by both sustainably expanding current mariculture operations and investing in science and technologies that enhance mariculture efficiency and productivity amidst a changing climate.
2. **In countries with fully developed mariculture potential** (Fig. 2.2), mariculture production can be maintained by selectively breeding for fast growth or heat tolerance or by shifting portfolios of mariculture species to match the new thermal regime.
3. **In all countries**, studying the impact of large-scale mariculture on marine ecosystems will be essential to identifying and promoting best practices in sustainable mariculture. Making strategic investments and expanding mariculture operations can boost local food supply without interacting negatively with other ecosystem services.

5.3 Ocean Tourism

Climate change will reduce the potential of ocean tourism to boost the local economies of countries with coral reefs. The magnitude of the impact will depend on the realised global emissions pathways, confounding effects of local stressors, dependency of the local economy to ocean tourism and type of ocean tourism. While on-reef tourism (e.g. snorkelling and diving) will be more vulnerable than reef-adjacent tourism (e.g. sunbathing, white sand), the latter will also likely be affected, although the magnitude of the impact is uncertain. Table 2.3 summarises the predicted changes in coral cover and reef tourism values given climate change as well as the current on-reef and reef-adjacent tourism values of each coastal country with coral reefs.

1. **In countries with a high proportion of their local economy dependent on tourism**, such as Maldives, Palau and St. Barthélemy (i.e. over 40%of their GDPs are from reef tourism), options include slowly diversifying to other

industries, such as mariculture, and creating opportunities for alternative forms of tourism, such as wreck diving and other novel activities, while at the same time increasing investments in the management of and improvements to reef ecosystems, fisheries and ocean tourism.

2. **In countries with high reef-adjacent values and where ocean tourism is important**, it is still imperative to improve and maintain coral reef health to secure the continuous provision of many of the ecological processes and services that support reef-adjacent activities (e.g. white sand from corals, wave attenuation function of coral reefs).
3. **For countries with disproportionately high on-reef tourism values**, investments in reef-adjacent tourism activities and ecotourism activities can both enhance the economic potential of coral reefs and motivate more investments in protecting reef health.
4. **Coral reef tourism can be a viable industry in countries that are expected to experience losses in aquaculture and capture fisheries**. Although climate change will hinder countries' abilities to tap into the full potential of ocean tourism, that does not mean that coastal tourism cannot improve the local economy.
5. **Given that current ocean tourism activities impact future ocean tourism economic output and ecosystem health** (feedback loops), all countries must aim to efficiently enhance ocean tourism gains by prioritising high-economic-gain activities while reducing the ecological footprints of ocean tourism activities (i.e. by investing in ecotourism and clean and efficient energy).

Across each of the above sectors of the ocean economy, the recommendations to build socioecological resilience to climate change and ensure the continued, or improved, provision of valued functions and services can be captured in three high-level mandates:

(a) **Be forward looking:** The future of the ocean economy is expected to drastically change given climate change, and the nature and magnitude of these changes can be highly variable. It will no longer be appropriate (or possible) to make predictions based on historical benchmarks or to assume that our usual metrics for measuring outcomes will remain stable. As the climate changes, each of the above-discussed ocean sectors will need to work to understand risks, anticipate changes and make decisions aimed at improving ecosystem health. In many cases, the risks and changes will become increasingly uncertain, which means that all management decisions need to factor in the likelihood of increasing surprises by being a bit more precautionary. **For wild-capture fisheries**, looking forward will entail things like scenario planning and management strategy evaluation, while stock assessments, harvest controls, allocation systems and even marine protected areas will all need to be more flexible, adaptive and precautionary. **Mariculture operations** will need to invest in things like selective breeding, improvements to feed conversion ratios, and technologies that continue to reduce risks from increasingly frequent and stronger storms. **Ocean tourism operations** may need to engage in practices aimed at building ecosystem resilience and health and be efficient by catering to tourism activities that provide high economic returns and have smaller ecological footprints. The designs of spatial management systems should account for future shifts in species ranges and productivities to both facilitate the successful movement of species to other areas and enhance marine population resilience to environmental and social changes.

(b) **Cooperate across boundaries**: It will also be critical to expand the current boundaries of our management decisions to allow for effective systems-level problem identification and solution development. As suitable habitats shift and change, marine species will move across jurisdictional boundaries and regional, national and international cooperative agreements will be necessary to ensure that these species are well-managed, and that the benefits are fairly distributed during and after the transitions. **For mariculture**, it will be critical to incorporate other marine uses and sectors in the planning and implementation of operations. Whole-systems thinking would also benefit tourism by ensuring the durability of this sector into the future as well as taking advantage of tourism opportunities that emerge in new areas (i.e. for the case where new coral reefs may establish in subtropical areas). In addition, it will be critical to share lessons learned and tools applied across and between sectors and jurisdictions to ensure lower-capacity regions will not fall behind in the implementation of solutions.

(c) **Focus on equity**: Finally, it will be profoundly important to examine the equity implications of all new and existing management decisions across these sectors, as climate change is likely to cause and exacerbate global inequities. Inequity reduces resilience, thereby likely worsening outcomes under all climate change scenarios.

Furthermore, equity considerations should be an input to decision-making in terms of both the design and implementation of management reforms and the creation and execution of new international agreements. Equitable solutions are more likely to garner buy-in from impacted groups and will thus be more likely to be effectively implemented. Focusing on equity can also lead to the development of more effective solutions that target the underlying system dynamics and power differentials that are, in fact, the root drivers of climate change. These solutions should consider equity issues in

> access and participation in the blue economy, including through the provision of no-cost skills development opportunities, and they must involve different world views and knowledge systems, integrating local and indigenous knowledge and avoiding poverty traps and the marginalisation of already vulnerable groups.
>
> Truly inclusive, representative, participatory decision-making processes are needed in all sectors to ensure procedural equity in all policy and management decisions. In addition, new solutions and interventions must seek to ensure distributional equity (i.e. equitable access to benefits and exposure to risks stemming from decisions) and to engender recognitional equity (i.e. recognition of and respect for differences within and between groups, and understanding of how these differences alter the perception and experience of impacts) if systems are to become equitably resilient to climate change.

It is imperative that countries explore the synergistic impacts of climate change across all three economic sectors (fisheries, mariculture and ocean tourism) and identify whether they are vulnerable to universally negative impacts, have options to offset negative impacts in some sectors through adaptation or could benefit from potentially positive impacts in other sectors. Countries should also note the magnitude of climate change impacts to the three major components of their ocean ecosystem economies to best plan their investments for climate change adaptation and mitigation strategies. While the solutions we put forward above are targeted to individual economic sectors, the three marine ecosystem economies are connected ecologically and socioeconomically, and positive actions to one sector often act synergistically with other sectors, especially when the actions are aimed at maintaining and enhancing ecosystem health.

Unregulated economic developments in fisheries, aquaculture and tourism have brought many unintended environmental and social consequences, including the degradation of non-use values and the provision of many other ecosystem services, both in developing and developed nations. While investments in these three sectors could improve national and local food and livelihood security amidst the challenges brought by anthropogenic climate change, sustaining the development and benefits they bring requires a development path that promotes and maintains a healthy ocean ecosystem. After all, the productivity and resilience of aquaculture, tourism and fisheries depend on clean water, intact habitats (e.g. mangroves and seagrass beds that serve as nursery grounds for commercial marine species) and diverse marine organisms, among others. Since this paper primarily focuses on ocean ecosystem sectors, the majority of the outlined recommendations and actions drive sustainable improvements in the ocean economy and, therefore, can provide positive synergistic effects for the underlying natural resource and its nonmarket values. Faster development and greater economic values in these three sectors can be realised if trade-offs between use and non-use values, which vulnerable communities often directly depend on, are avoided.

We expect that the variable directions of impacts of climate change across the three economic sectors for each country will draw new investments in some sectors while other sectors are expected to continually suffer.

It is imperative that developments are well-planned and properly regulated to avoid unwanted environmental impacts, degradation of local cultures and livelihoods, and the inequitable distribution of benefits. For instance, including access to technical education and skills development will ensure that resources are available for people to transition from one form of livelihood to another, hence ensuring that the economic benefits of local developments accrue locally. There is also huge potential for local investments in renewable energy and energy-efficient technologies that can improve local livelihoods, enhance local economic benefits and reduce the carbon footprints of human activities. Finally, we envision that our results will ultimately help guide new ocean investments and positive conservation actions by governments, nongovernmental organisations, development agencies, philanthropies and international communities.

Acknowledgements The authors thank Jane Lubchenco, Merrick Burden and Kate Bonzon for helpful comments on earlier drafts of this Blue Paper and Mark Spalding for reef tourism data. The paper's technical reviewers, Manuel Barange, Sarah Cooley, Salif Diop, Silvia Patricia González Díaz and Boris Worm, as well as its arbiter, Andreas Merkl, all provided helpful technical comments. The authors also thank World Resources Institute for providing support as the Ocean Panel Secretariat.

While our colleagues were very generous with their time and input, this report reflects the views of the authors alone. The authors thank Sarah DeLucia for copyediting and Jen Lockard for design.

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