# Blue Paper 2: The expected impacts of climate change on the ocean economy

## 1. Introduction

The ocean is critically important to our global economy. Collectively, ocean-based industries and activities contributed approximately 31 million jobs and US$1.5 trillion, or 2.5% of world-wide gross value added, in 2010 (OECD 2016). In addition, the non-market 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 (Costanza et al. 2014).

Anthropogenic climate change, driven by the exponential increase in emissions of greenhouse gasses (GHGs) since the industrial revolution, will impact the ocean through a variety of channels. The severity of effects will depend on the extent of warming realized. The resulting changes to ocean processes and functioning have implications for our economy that must be taken into account, to both 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 resilience-building to ensure they can continue to provide valued functions as the climate changes. We also briefly discuss other marine-based sectors, some of which generate higher monetary value at a global scale, but which either face no significant existential risk from the changing climate (e.g., shipping), or which 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 (BP3, BP7).

## 2. The Ocean Economy: Essentials

The ocean economy consists broadly of all ocean-based human activities that generate revenue, employment, and other monetary and non-monetary 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: wild capture and farmed marine species; 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.

Other ocean benefits are not traded on markets, and their value is thus more difficult to assess. The set of non-market benefits, sometimes referred to as ecosystem services, obtained from the ocean is very large (Polasky and Segerson 2009; Costanza et al. 2014). Examples include swimming, recreational fishing, enjoying the beach, observing sea life, and the existence value of the ocean’s diverse biota. Other examples include the ocean’s contribution to the global water, energy, and chemical circulation systems, as well as its role in climate regulation, CO₂ uptake, and coastal protection.

All of these ocean benefits can be affected by the activities associated with the generation of the market-based benefits. For example, excessive harvest of marine life can damage ecotourism potential; excessive extraction of oil, gas, and minerals can harm ocean habitats and biodiversity that underpin the biogeochemical processing functions of the ocean; and pollution from shipping can harm ocean ecosystems and the goods and services they produce by contributing to nitrogen deposition, global warming, and ocean acidification.

### 2.1 The market-based ocean economy

The Organization 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. According to the OECD (2016), the current ocean industries that contribute the most in terms of production value and employment are:

% of % of

Production Value 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. Other 1% 1%

The rankings of ocean industries are quite different for these two economic outputs. Energy production, shipping, and tourism dominate production values, while nearly half of all ocean employment arises from food production. Therefore, the impacts of climate disruptions on these different industries can have quite disparate social and economic consequences.

### 2.2 The non-market 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 non-market services from the ocean are nearly comparable in value to the entire global gross (market-based) product. For example, a prominent evaluation by Costanza et al. (2014) assessed the value of global ocean ecosystem services to be almost US$50 trillion in 2011. This translates to more than 80% of the global gross product in that year or 30 times more than the ocean-based gross value added.

## 3. How rising greenhouse gasses alter the oceans

Climate change is altering ocean climate, chemistry, circulation, sea level, and ice distribution. Collectively these system changes have critical impacts on habitats, biotic productivity, and species assemblages that underpin many of the economic benefits of the sea (Barange 2018; Gattuso et al. 2015). They also affect the risks of various human activities and developments (Gattuso et al. 2015). Unprecedented ocean changes are already occurring across all latitudes (Barange 2018; Gattuso et al. 2015) with high risks of negative impacts to many ocean organisms, ecosystems, and services (Gattuso et al. 2015). These impacts are likely to increase dramatically towards the end of this century, depending on the extent of future GHG emissions, with potentially dire consequences for ecosystem services, the ocean economy, and human welfare (Pecl et al. 2017). Below we describe these effects individually, but many of these influences may synergistically or antagonistically interact, potentially with additional consequences (e.g., 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 (AR5) 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 W/m2, respectively). They roughly correspond to projected increases in planetary surface air temperatures of an additional 0.2, 1.1, 1.6, and 2.7 oC, respectively, through this century (Barange 2018; IPCC 2014).

### 3.1 Altered ocean temperatures and disturbances

Climate change has already contributed to substantial warming of the oceans over most of the globe. The oceans have absorbed ~93% of additional heat, leading to significant warming of the upper ocean (above 700 m) and warming of deeper waters (700 - 2000 m) increasing in strength since the 1980s (Cheng et al. 2017). Sea surface temperatures (SSTs) have increased by an average of 0.7 °C globally since 1900 (Barange 2018; Jewett and Romanau 2017). RCP scenarios suggest that these trends, which already exceed the range in natural seasonal variability in subtropical areas and the Arctic, will continue (Barange 2018). 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 2018; Gattuso et al. 2015).

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 2018; Doney et al. 2014; Gattuso et al. 2015). 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 extirpation. 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. 2019; Gattuso et al. 2015; Holbrook et al. 1997). 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 (FAO 2018; Gattuso et al. 2015). 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. 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 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 2018). In addition, recent models and observational data indicate that recurring climate patterns such as the El Niño-Southern Oscillation (ENSO) are likely to increase in frequency and intensity as the oceans warm (Barange 2018), 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 (Loo et al. 2015). Finally, ocean warming leads to increased stratification of the water column and reduced water circulation and mixing (Barange 2018; FAO 2018; Oschlies et al. 2018).

### 3.2 Altered ocean chemistry

Ocean acidification, driven primarily by oceanic absorption of CO₂, has increased by 26% since the industrial revolution, with regional variability in severity and rate of change (Barange 2018; Gattuso et al. 2015). Ocean uptake of CO₂ lowers ocean pH (by increasing bicarbonate and hydrogen ion concentrations) and carbonate ion concentrations, and increases the partial pressure of CO₂ and dissolved inorganic carbon. These changes can impact many marine organisms, particularly in early life stages, but they are especially detrimental to corals and organisms that form carbonate shells (Barange 2018; FAO 2018), whilst benefiting some photosynthetic non-calcifying taxa. 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 2018; Gattuso et al. 2015; Henson et al. 2017). High latitude waters, deep waters, and upwelling regions will be the first to become carbonate ion unsaturated (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 pH (Barange 2018). Warm water corals will be impacted by decreased carbonate ion saturation levels even where waters do not become undersaturated (Hoegh-Guldberg et al. 2017). 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, and fishing (Gattuso et al. 2015).

Climate change is also impacting dissolved oxygen content in ocean systems across the globe. Warming-driven stratification of the water column, exacerbated by eutrophication from coastal pollution, reduces dissolved oxygen content in ocean water (Barange 2018; Gattuso et al. 2015; Oschlies et al. 2018). Decreases in oxygen concentration in coastal waters and the prevalence and size of “oxygen minimum zones (OMZs),” areas where oxygen consumption by sediment bacteria exceeds the availability of oxygen, have increased significantly in recent decades, especially in the tropics (Barange 2018; Breitburg et al. 2018; Oschlies et al. 2018; Stramma et al. 2010; Levin 2002). This trend is expected to continue, with the whole-ocean oxygen inventory expected to decrease from -1.81 ± 0.31% (RCP2.6) to -3.45 ± 0.44% (RCP8.5), and the global volume of OMZs expected to increase by 10 – 30% by 2100 (Barange 2018; Gattuso et al. 2015). Increased deoxygenation will likely lead to habitat compression, shifts in distribution, and loss of biodiversity (Stramma et al. 2010; Levin 2002). However, observed deoxygenation is generally worse than modelled results, which emphasizes the need to improve our understanding of the processes driving deoxygenation to reduce model uncertainty in our projections (Oschlies et al. 2018).

Deoxygenation and OMZs affect different 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 range from reduced vertical migration and compressed vertical habitats to death from asphyxiation (Barange 2018; Gattuso et al. 2015; Oschlies et al. 2018).

### 3.3 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 fresh water (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, and may potentially even stop, some of these global conveyor belts (Barange 2018; Liu et al. 2017). The Atlantic Meridional Overturning Circulation (AMOC) 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 already showing signs of weakening (Barange 2018) and may continue to do so under all RCP scenarios. 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 also expected to weaken in the coming decades (Barange 2018; Liu et al. 2017). These changes could lead to dramatic shifts in weather and local and regional climate patterns, which would have significant impacts on the ocean economy, and on 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 2018). 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 shift, although there is more uncertainty around impacts (Barange 2018). As the land and ocean warm at different rates, stronger upwelling-favorable winds may strengthen these patterns; however increased thermal stratification may also restrict the depth of upwelling waters, and thus limit the amount of nutrients brought with them (Barange 2018). The impacts of intensified upwelling may result in a net increase in nutrient inputs and primary productivity, or alternatively it could increase the presence of low oxygen and more acidic waters along the continental shelf (Barange 2018).

### 3.4 Altered distribution of ice and altered sea level

Polar areas have seen drastic changes including shifts in 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 0.19 m from 1901 to 2010, and estimates indicate that by 2100 the global mean sea level will rise between 0.4 m to 0.9 m under RCP4.5, and between 0.5 m and 1.2 m under RCP8.5 (Barange 2018; 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 2018). In the Arctic, annual sea ice extent has decreased at a rate of 3.5 – 4.1% per decade, climbing to -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 multi-year sea ice with over 50% of its extent lost during the period 1999 – 2017 (Kwok 2018). Meanwhile, Antarctic sea ice gradually increased by 1.2 – 1.8% over the past three decades (Barange 2018), but then began to decline rapidly in 2014, leading to the lowest average monthly and yearly Antarctic sea ice extents on record in 2017 (Parkinson 2019). Glaciers and land-based ice sheets across the world over have also shrunk (Barange 2018) and their influences on sea level rise are expected to outpace that of other sources in the near future (Dutton et al. 2015).

## 4. Connecting the links between climate change and the ocean economy

### 4.1 Capture fisheries

#### 4.1.1 Importance of capture fisheries to the ocean economy

In 2016, the UN Food and Agriculture Organization (FAO) estimated that marine capture fisheries produced 79.3 million metric tons (mt) of landings, representing 46.4% of global seafood production (170.9 million mt), and US$130 billion in first sale value (FAO 2018). They also estimated that approximately 30.6 million people participated (either full-time, part-time, or occasionally) in capture fisheries operated by approximately 4.6 million fishing vessels. Small-scale fisheries are the backbone of socioeconomic well-being in many coastal communities (Béné 2004; Béné et al. 2007, 2010), especially in the tropics where the majority of fish-dependent countries are located (Golden et al. 2016). Fish and fish products are among the most traded food commodities in the world. In 2016, approximately 35% of production entered international trade for either human consumption or non-food uses (FAO 2018). The 60 million mt (US$143 billion) of fish products exported in 2016 constitute a 245% increase relative to 1976 exports (US$8 billion). Over this time period, the rate of growth of exports from developing countries has 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 grows and becomes increasingly wealthy (FAO 2018).

#### 4.1.2 Impacts of climate change on capture fisheries

The dynamics of harvested marine fish and invertebrate populations are sensitive to climate change (Rijnsdorp et al. 2009; Hollowed et al. 2013) via changes in both environmental (e.g., warming, deoxygenation, acidification, etc.) and biological (e.g., phenology, food webs, predator-prey dynamics, etc.) conditions. In some cases, these changes can increase fisheries productivity. For example, warming can increase the suitable thermal habitat range available to a species, leading to range expansions, or negatively impact a key predator or competitor species. In other cases, these changes can decrease fisheries productivity. For example, hypoxia can increase mortality, acidification can decrease growth rates, and spatial-temporal mismatches in the availability of prey can reduce the recruitment of juveniles. In the sections below, we detail how retrospective and forward-looking studies have revealed the impact of climate change on marine fisheries and the opportunity for fisheries management to mitigate the negative impacts of climate change on the ocean economy.

**1. Climate change modifies the life history of marine fish and invertebrates, including their growth, natural mortality, and recruitment rates. Managers will have to increasingly account for environmentally-driven changes in fish life history under climate change.**

Observed changes: Climate change has resulted in reduced growth rates and smaller body sizes in many marine fishes (Sheridan and Bickford 2011), which translates to reduced yield per recruit (Baudron et al. 2014) and by extension, reduced catch potential. Climate change has also altered the timing and location of the phytoplankton and zooplankton blooms that support marine food webs (Cushing 1990; Edwards and Richardson 2004; Poloczanska et al. 2013). Spatial-temporal mismatches in prey availability have increased mortality rates of some species (Beaugrand et al. 2003; Clausen et al. 2018) while matches have reduced mortality rates of others (MacKenzie and Köster 2004). Finally, recruitment of juveniles is often more strongly driven by environmental factors than by spawned biomass (Szuwalski et al. 2015, 2019). However, the net effect of historical environmental change on recruitment is under debate: Britten et al. (2016) document a net decline while Szuwalski (2016) documents a net increase.

Forecasted changes:Fish growth rates and body sizes are expected to decline further under continued warming and deoxygenation, with consequences for catch potential (Cheung et al. 2012 but see Lefevre et al. 2017 and Pauly and Cheung 2017 correspondences). On average, maximum body weights are expected to shrink by 14-25% globally from 2000-2050 under a high emission scenario (Cheung et al. 2012). Furthermore, changes in physical oceanography are expected to transport nutrients from surface waters into the deep ocean, driving a 24% reduction in the primary productivity that supports marine food webs by 2300 (Moore et al. 2018).

Implications for adaptation: In data-rich regions, fisheries stock assessments will increasingly have to account for environmentally-driven, time-varying natural mortality, growth rates, and recruitment. This will involve one of many potential strategies (Pinsky and Mantua 2014) including: (1) using assessments with time-varying parameters; (2) restricting assessments to the current environmental regime; and/or (3) using climate-adaptive reference points (Queirós et al. 2018). In data-poor regions, this will involve implementing “primary fisheries management” (Cochrane et al. 2011) to enhance fisheries potential and resilience to climate change (see details in the next section).

**2. Although the net global impacts of climate change on fisheries productivity (catch potential) are modest, regional impacts are much stronger, with some regions experiencing large gains in productivity and others experiencing large losses. Vulnerable regions must be the focus of management reform and adaptation. Resilience to climate change can be enhanced by implementing “primary fisheries management” and by accounting for shifting productivity in assessment and management.**

Observed changes: Free et al. (2019) estimate that ocean warming has 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 world’s largest industrial fisheries over the past eighty years (Free et al. 2019). In five regions, including the North Sea and ecosystems of East Asia, losses in MSY have ranged 15-35%. Meanwhile, the Baltic Sea and other regions have seen increases in MSY up to 15%. Analyses of historical changes in juvenile recruitment, another metric of productivity, yield conflicting results (Britten et al. 2016; Szuwalski 2016), and are also difficult to interpret in terms of food and income security. Well-managed fisheries have been the most resilient to ocean warming while overexploited fisheries have been the most vulnerable (Free et al. 2019).

Forecasted changes: Net global catch potential is not expected to change considerably under climate change (though see RCP 8.5 results below), but strong regional impacts are expected to result in pronounced equatorial “losers” and poleward “winners”. For example, Cheung et al. (2010) project modest changes in global catch potential of +1% and -1% from 2005-2055 under low and high emissions scenarios, respectively. Gaines et al. (2018) project modest changes in global MSY of +1%, -1%, and -5% from 2012-2100 under RCPs 2.6, 4.5, and 6.0, but forecast a considerable decline of -25% under RCP 8.5. Cheung et al. (2010) predict 30-70% increases in catch potential in poleward regions and 40% decreases in equatorial regions, with similar patterns predicted by Gaines et al. (2018). The redistribution of catch potential will drive a concomitant redistribution of revenues (Lam et al. 2016) and nutrition (Golden et al. 2016).

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. 2019) and socioeconomically resilient to climate change. In low capacity fisheries systems, this can be achieved through “primary fisheries management” as detailed in Cochrane et al. 2011. In high capacity fisheries systems, this will involve accounting for shifting productivity in fisheries stock assessments and management procedures. This will involve one of many strategies (Pinsky and Mantua 2014) including: (1) using assessments with time-varying productivity; (2) using climate-adaptive harvest control rules and more precautionary buffers; and (3) targeting age- and genetically-diverse populations that are more resilient to climate change (Ojea et al. 2017).

**3. Marine fish and invertebrates are shifting distributions to track their preferred temperatures. International agreements will be necessary to ensure that management remains sustainable as species shift in and out of new management jurisdictions.**

Observed changes: As the oceans have 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 km per decade, marine species have been shifting 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 (Cheung et al. 2008, 2010; Blanchard et al. 2012), often with a decrease of 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% to 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: Establish and strengthen international institutions and agreements to better manage stocks shifting in and out of jurisdictions. Pinsky et al. (2018) make the following recommendations: (1) promote data sharing to foster the identification of shifting stocks; (2) use pooled data to inform collaborative management; (3) use side payments to incentivize cooperation and prevent asymmetry in winners and losers; and (4) develop permits that are tradable across political boundaries to foster dynamic catch allocations.

#### 4.1.3 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 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 new analysis (Free et al. in prep) that documents the benefits countries stand to gain by implementing climate-adaptive fisheries management reforms that address both changes in species productivity and distribution due to climate change.***

Methods: We forecasted the distribution and productivity of 779 harvested marine species out to 2100 under two greenhouse gas emissions scenarios (RCPs 6.0 and 8.5), and compared the status of these fisheries and the amount of catch and profits derived from them under climate-adaptive management and business-as-usual management (Free et al. in prep). Under climate-adaptive management, fisheries stock assessments and management procedures account for 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. We then measured the extent to which climate-adaptive management would (1) maintain catch and profits into the future and (2) generate catch and profits relative to a 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 (**Figure 1**). Furthermore, in many countries, adaptive management would not only reduce the impacts of climate change, but would actually increase catch and profits relative to today (**Figure 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 this interactive web application: <https://sfg-ucsb.shinyapps.io/fishcast2/>

### Implications for adaptation: Fisheries management that accounts for shifts in species distributions and productivity due to climate change will generate better outcomes than business-as-usual management in all countries, even those hardest hit by climate change. In the section below, we detail four key recommendations for implementing such reforms.

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### **Figure 1.** Panel **(A)** shows that maximum sustainable yield (MSY) is forecast to decrease in equatorial exclusive economic zones (EEZs) and increase in poleward EEZs through 2100. Panel **(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. Panel (**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.

#### 4.1.4 Recommendations and key conclusions

Building a socio-ecological system that is resilient to climate change is key to ensuring healthy, productive fisheries in the future. Below are four overarching, high priority recommendations for designing fishery management approaches in the context of a changing climate:

1. **Implement best practices in fisheries management:** Implementing fisheries reforms and reaping their benefits depends on strong user rights. Thus, building resilience will first and foremost require the engagement and empowerment of fishing communities. Best practices in fisheries management -- such as science-based harvest control rules, user rights with effective accountability measures, and the protection of essential habitat -- will foster climate resilience through two mechanisms: (1) well-managed fisheries are the most resilient to the negative effects of climate change (Free et al. 2019) and (2) a portfolio of well-managed fisheries buffers fishers against declines in a subset of targeted stocks.
2. **Implement forward-looking adaptive science and management:** Management targets and reference points must be revised to be realistic relative to expected future conditions, as historic baselines will no longer be appropriate. Where possible, managers should engage in forecasting, scenario planning, tradeoff evaluation, and other similar exercises to define desired outcomes towards which to manage. In data- and resource-limited settings, primary fisheries management techniques that are combined with stakeholder participation and polycentric governance can be used to address uncertainty and foster adaptation.
3. **Establish and strengthen international institutions and agreements to better manage stocks shifting in and out of jurisdictions:** Better international cooperation will be necessary due to shifting stocks. Pinsky et al. (2018) make the following recommendations: (1) promote data sharing to foster the identification of shifting stocks; (2) use pooled data to inform collaborative management; (3) use side payments to incentivize cooperation and prevent asymmetry in winners and losers; and (4) develop permits that are tradable across political boundaries to foster dynamic catch allocations. In cases where establishing international cooperation proves difficult, the use of marine protected areas (MPAs) along country borders may provide more time for policy makers to come to agreement while stocks are moving.
4. **Use principles of fairness and equity to drive policy decisions:** Challenges of fairness and equity 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. At a more local level, climate change can change the distribution of resources, thereby changing the impact on human populations from past patterns. Without adequate response, these impacts could lead to inequalities, unrest and severe social disruption. Addressing inequities created by climate change is valuable in its own right in order 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.

### 4.2 Aquaculture

#### 4.2.1 Importance of aquaculture to the ocean economy

Aquaculture, the cultivation of aquatic animals and plants, is one of the fastest growing industries in the world (Bostock et al. 2010) and now produces more seafood than wild capture fisheries (FAO 2018). Although marine aquaculture, hereafter called “mariculture”, currently represents only a third of total aquaculture (freshwater/inland aquaculture represents the remainder), this proportion is increasing. In 2016, mariculture produced 38.6 million metric tons (mt) of seafood worth US$67.4 billion. Over half of this production was shelled molluscs (58.8%), while finfish and crustaceans represented 23% and 17%, respectively (FAO 2018). However, 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 non-fed bivalve aquaculture, due to increasing demand for these commodities (Tacon et al. 2011; Hasan 2017).

#### 4.2.2 Impacts of climate change on ocean aquaculture

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). As with capture fisheries, the impacts of climate change on aquaculture are expected to vary by location, species, and method of production. Of these effects, the primary threats are as follows:

1. Ocean warming is expected to raise mortality rates and lower productivity for higher trophic-level species (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.
3. Increasing storm strength and frequency poses a risk to infrastructure (De Silva 2012), and increased weather variability has been associated with lower profits (Li et al. 2016).
4. Ocean acidification impedes the calcification of mollusk shells (Gazeau et al. 2013) resulting in reduced recruitment, higher morality (Barton et al. 2012; Green et al. 2013) and increased vulnerability to disease and parasites.
5. Increasing rainfall will increase the turbidity and nutrient loading of rivers, potentially causing more harmful algal blooms (HABs) that reduce production and threaten human health (Himes-Cornell et al. 2013; Rosa et al. 2014).
6. The emergence, translocation, and virulence of disease, pathogens, and parasites are all 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 (Fabbri and Dinelli 2014).

#### 4.2.3 Adaptation to climate change through selective breeding

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 programs have focused on increasing growth rates and maximizing productivity and have been met with success. For example, Atlantic salmon breeding programs have increased harvest weight by 12% per generation with cumulative genetic gains of ~200% over multiple generations (Janssen et al. 2016). Similarly, seabream breeding programs 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 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. 2017). Some selective breeding programs have successfully resulted in increased temperature tolerances (Sae-Lim et al. 2017), but these breeding programs 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 reduction in fitness in wild populations (Hutchings and Fraser 2008). Thus, the benefits of selective breeding must be evaluated against the potential ecological costs of escapement when considering breeding as a tool for climate adaptation.

#### 4.2.4 Forecasted impacts of climate change on the potential for ocean aquaculture

Current production potential: Gentry et al. (2017) recently 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 depth, temperature, dissolved oxygen, and primary production tolerances as well as existing human uses. Overall, they estimate an enormous untapped potential for mariculture: bivalve and finfish aquaculture could generate 767.7 million mt (over 2.5 million km2 of suitable habitat) and 15.6 billion mt per year (over 11.4 million km2), respectively. By comparison, bivalve and finfish mariculture currently produce only 15.3 and 7.7 million mt per year, respectively (FAO 2018).

Forecasted production potential: Froehlich et al. (2018) extended this work to forecast how finfish and bivalve mariculture would change from now to 2090 under the warming, acidification, and shifts in primary productivity 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. *Note: Froehlich et al. (2018) do not make specific statements about the sum magnitude of these declines.*

Caveats: Although Froehlich et al. (2018) forecast declines in the biological potential for global mariculture, the relevance of these declines to food and income provisioning is unclear because of the sheer magnitude of the estimated biological production potential (Gentry et al. 2017; Froehlich et al. 2018) and the potential for selective breeding to compensate for reductions in habitat availability and growth performance (Sae-Lim et al. 2017). The sum 16.4 billion mt of mariculture production potential documented by Gentry et al. (2017) is more than 200 times current global aquaculture production (80 million mt, including freshwater production). In other words, if climate change reduced the biological production potential of marine aquaculture by 99%, marine aquaculture would still be doubly as productive as today.

For this reason, we present a new analysis (also featured in Blue Paper 1: The Future of Food from the Sea) to compare current and potential country-level aquaculture production. Notably, this analysis extends the work of Gentry et al. (2017) to account not only for environmental constraints on mariculture, but also for economic constraints and limitations in the availability of feed for finfish aquaculture.

**In many countries, current mariculture production is far below capacity, even after accounting for economic and feed constraints. Thus, the negative impacts of climate change on mariculture production potential could be offset by redesigning regulations to foster sustainable mariculture development.**

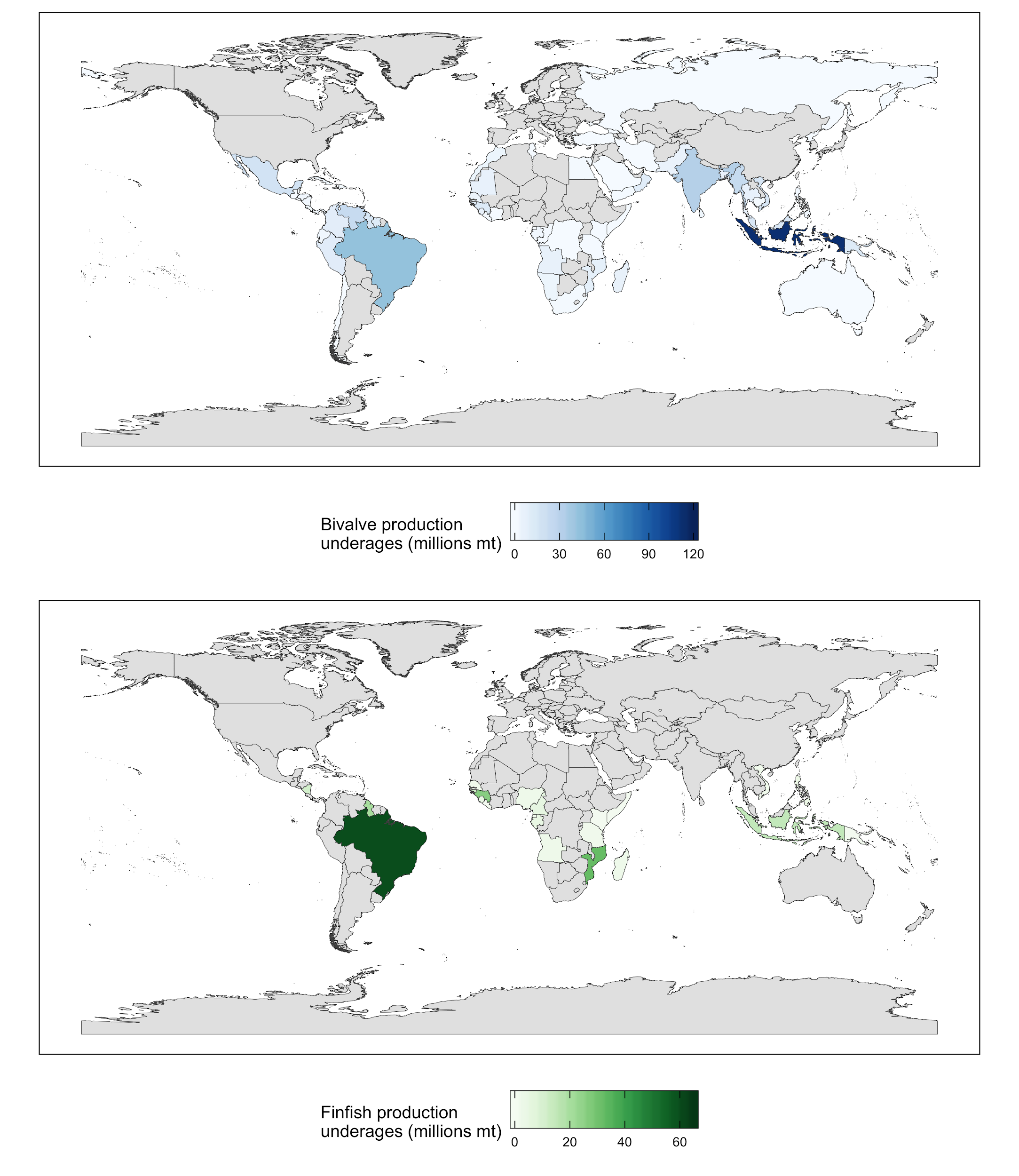
Methods: The “true potential” for mariculture can be estimated as the biological potential constrained by (1) ocean zoning conflicts; (2) financial feasibility; (3) fishmeal availability; and (4) other social and regulatory barriers. Here, we map the cost and profitability of finfish and bivalve mariculture and assume that production will only occur in areas that are profitable (constraint #2) and not already allocated for other uses (constraint #1; i.e., marine protected areas, oil rigs, shipping). We also constrain finfish production based on the present day (1) proportion of capture landings directed to the production of feed ingredients; (2) proportion of feed that is composed of fish ingredients; and (3) efficiency with which feed is converted to cultivated fish (constraint #3). We also consider a scenario in which technological advances reduce the reliance of feed on fish ingredients by 95% (Oliva-Teles et al. 2015). We do not account for social barriers such as public perceptions of aquaculture sustainability (Froehlich et al. 2017) or regulatory barriers such as precautionary aquaculture permitting (Krause et al. 2015; Knapp and Rubino 2016; constraint #4). However, the farm design employed in the model employs best practices for aquaculture and thus represents sustainable design under best current knowledge.

Results: Overall, we find that global and country-level mariculture production is significantly under capacity (**Figure 2**). 483.0 million mt of bivalve production should be possible at today’s prices for maricultured bivalves (US$1,400 per mt of blue mussels). This is 467.7 million mt (>3,000%) more than the current production of 15.3 million mt. Additionally, 10.5 million mt of finfish production should be possible at today’s prices for maricultured finfish (US$7,000 per mt of Atlantic salmon) and today’s feed composition. This is 2.8 million mt (36%) more than the current production of 7.7 million mt. 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 million mt (>2,700%) increase in finfish production to 217.3 million mt. The majority of these underages in mariculture production occur in equatorial countries (**Figure 2**) suggesting that mariculture expansion could mitigate the losses in capture fisheries productivity expected for these regions.

**If the potential for production is so large, why is current mariculture production so low?** This gap is likely driven by two factors: (1) a lack of expertise and capacity for conducting mariculture operations in many developing countries; and (2) challenging regulatory barriers for developing mariculture operations in many developed countries. In Palau, for example, many mariculture operations have been initiated with outside funding but have failed once the initial funding period ends. The longest running mariculture operation in Palau is a government subsidized clam hatchery that would be unprofitable without government support (Y. Golbuu, personal communication). In the United States, on the other hand, precautionary regulations restrict mariculture development (Wardle 2017; Sea Grant 2019). Thus, despite having one of the largest EEZs and longest coastlines, the United States produces only 1% of global mariculture (FAO 2018).

Implications for adaptation: Overall, these results suggest that the negative impacts of climate change on mariculture potential may be small relative to the constraints of capacity limitations and precautionary regulations. Thus, elucidating the impact of mariculture on marine ecosystems, identifying best practices for sustainable mariculture production, and removing overly precautionary regulations will all be necessary to foster the growth of mariculture and offset the negative impacts of climate change.

Caveats: This model was parameterized using mariculture equipment maintenance costs and growing seasons typical to the United States and not in regions with higher environmental risk and variability (e.g., tropical monsoons in Asia and elsewhere). Thus, it may overestimate mariculture production potential in these regions by (1) underestimating costs of maintenance and overestimating profitability or (2) overestimating the amount of time available for production.



**Figure 2.** Mariculture production underages for (a) bivalves at current prices (US$1,700/mt for blue mussels and (b) finfish at current prices (US$7,000/mt for Atlantic salmon) and a 95% reduction in the reliance of feed on fish ingredients.

#### 4.2.5 Recommendations 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. **Growth in mariculture will require a better understanding of the impact of mariculture on marine ecosystems and the implementation of more appropriate regulations:** Because little is known about the impacts of large-scale mariculture on marine ecosystems, regulations on mariculture have tended to be precautionary and have restricted production potential. Easing the regulatory burden on mariculture will thus require a more detailed understanding of the impacts of mariculture on marine ecosystems and the best practices for managing these impacts.
3. **Finfish mariculture could generate more food and income through advancements in feed technology:** The production potential of finfish mariculture is capped by the availability of fishmeal and fish oil from capture fisheries. Developing feeds that replace fish ingredients with alternative sources of starch and protein and that more efficiently convert feed to fish would therefore increase the potential for 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, minimize pollution, and mitigate other potential negative environmental impacts of mariculture.

### 4.3 Marine and coastal tourism

#### 4.3.1 Introduction

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, when it will account for 26% of the ocean-based economy, compared to 21% for oil and gas (OECD 2016). Ocean tourism dwarfs the contribution of industrial capture fisheries, which constitute only 1% of ocean-based industries (not accounting for artisanal fisheries, which are a critical component of the economy of Asia and Africa). The range of ocean tourism activities include beach tourism, recreational fishing, swimming, snorkeling, diving, whale watching, and cruise ships, among others. Ocean tourism’s global direct value added was estimated at US$390 billion, directly providing seven million full-time jobs. In addition, ocean tourism is a source of recreation for millions of people in the developed and developing world (e.g. Arlinghaus et al. 2019). For comparison, the global value added of industrial capture fisheries was US$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 product of Maldives, Palau, and St. Barthelemy (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 is 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 for many coastal nations, we focus our analysis on this sector. **Coral reef tourism is worth US$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 and explore options for nations and local communities to best prepare for the impacts of climate change. Using the economic value of coral reefs for tourism to a given country, we project the cost of inaction and discuss the benefits of action.

#### 4.3.2 Losses of key biological draws for tourists

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.

Bleaching events, for example, cause coral reef mortality and a subsequent rapid reduction in reef fish diversity and numbers (e.g. Arceo et al. 2001). More frequent and intensifying storms reduce the desirability of a place for tourism, disrupt transportation (flights and ferries), and can destroy coastal infrastructure that supports tourism. Marine heatwaves have critical impacts over habitat formation species (seagrasses, corals, and kelps) that can disrupt the provision of ecosystem (Smale et al. 2019). Sea level rise impacts coastal integrity and coastal assets and, together with extreme events, cause coastal erosion that if constrained by urbanization can lead to coastal squeeze (Toimil et al. 2018; Scott et al. 2012). This has a known negative impact on visitor’s perceptions and economic impacts associated (Scott et al. 2012). Ocean warming also affects fisheries productivity (Free et al. 2019) and the migration patterns of species that are major draws for tourism (e.g. whales, sharks, and turtles).

Climate change interacts with coral reef tourism through its direct impact on: (1) coral reefs and associated species on which some reef tourism depends directly (such as snorkeling, diving, and recreational fishing); (2) weather conditions that drive a user’s preference for the place; and (3) coastal infrastructure that supports tourism. For ocean tourism that directly depends on healthy coral reef ecosystems such as diving and snorkeling (on-reef tourism), changes in reef condition are expected to impact tourist preference and coral reef tourism economic values. While activities that do not directly depend on reefs (i.e. reef-adjacent activities such as white sand beaches and sun bathing) are also expected to be affected (directly and indirectly such as the wave attenuation role of reefs and coral reefs as a source of white sand) by climate change, the magnitude of the impact is hard to measure.

#### 4.3.3 Economic Impacts

4.3.3.1 *Economic impacts in 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 CO2 levels as proxy), have and will continue to affect coral reef health and coral reef tourism values at the regional and global level. 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 condition would translate to changes in tourism values.

We project per-country tourism value changes for 2030, 2050, and 2100 (with 2019 as baseline) using the SST and CO2 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) although for brevity, we present the result for 2050 only. Below, we list our 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 0.67% increase in live coral coverage (relative to the percent live corals available prior to changes in temperature)
* When SST is between 22.37 ℃ and 26.85 ℃, a 1% increase in SST leads to 1.59% increase in live coral coverage
* When SST is >26.85 ℃, a 1% increase leads to 2.26% decrease in live coral coverage

*Ocean acidification effect*

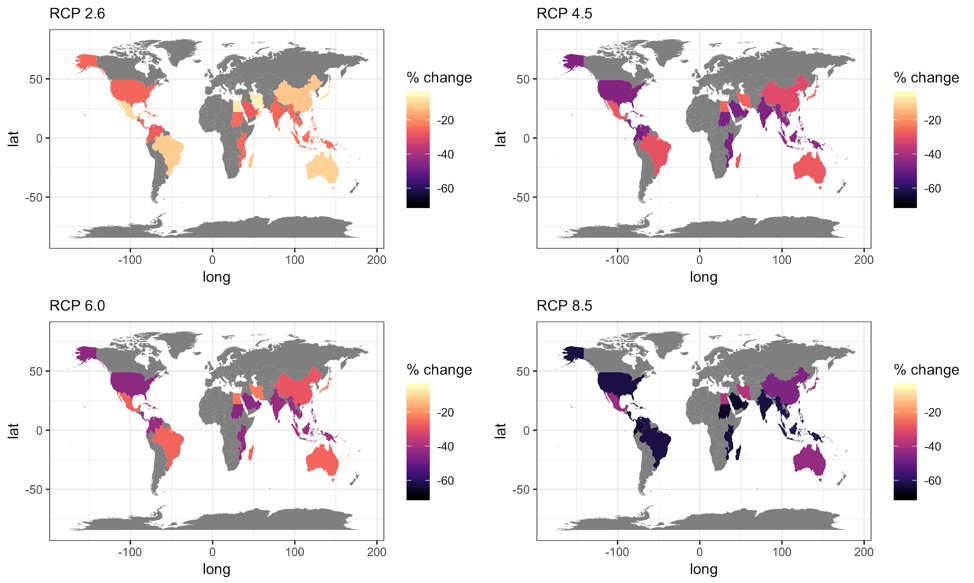
* Using atmospheric CO2 as a proxy (Table A1), a 1% increase in CO2 decreases live coral coverage by 0.61%

*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.

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 causes extensive reef mortality (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, and water and electricity supply disruption (Weatherdon et al. 2016). Also important and not included is the confounding effect of local stressors such as pollution and illegal and destructive fishing which negatively impact tourism values. Furthermore, the poleward movement of corals are not accounted for in our projections (Price et al. 2019). All these additional climate change induced stressors and the confounding effect of local stressors impact local and national economies (Hoegh-Guldberg et al. 2018).

When only looking at SST in isolation as a factor driving changes in coral cover and coral reef tourism values, many countries in the subtropics will benefit from climate change while countries in the tropics will be negatively affected (results not shown). Ocean acidification, however, interacts with reef health and tourism values only in the negative direction. Combining 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 (Figure 3, Table A2).



**Figure 3.** Percent change in coral reef tourism values in 2050 (relative to 2019 values) for different climate projections. See Table A2 for country values.

For the high emission scenario of RCP 8.5, which is characterized by considerable increases in greenhouse gas emissions, coral cover is expected to be reduced by 7-28% and on-reef tourism values by 23-66% from 2019 to 2050 due to combined ocean warming and acidification. The reduction will be less severe under a stabilization scenario of RCP 4.5 with an expected reduction of 7-17% and 24-47% in coral cover and on-reef tourism values, respectively. Note that the reduction in coral cover is conservative as other factors such heatwaves, storms, and other climate stressors are not included in the model.

The top five countries with the highest coral reef tourism values are Egypt (~US$7 billion/year), Indonesia (~US$3.1 billion/year), Mexico (~US$3 billion/year), Thailand (~US$2.4 billion/year), and Australia (~US$2.2 billion/year). These five countries have 45-86% of their coral reef tourism values based on on-reef activities (e.g. snorkeling and diving), and climate change impacts (ocean warming + acidification) will reduce on-reef tourism values by 25-60% in 2050 for RCP 8.5 (27%-44% 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 depend on the emission pathways taken in the future, although any of the emission scenarios would still negatively impact reef tourism values.

When most of the countries’ coral reef tourism values come from reef-adjacent activities, climate change may not severely affect these countries. 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 in 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 (World Tourism Organization (UNWTO) 2016; Lenzen et al. 2018). In accounting for the improvements in tourism values due to increase in tourist arrivals, it should be noted that the tourism value is a hump shape or concave function of tourism arrivals. Increasing arrivals increases tourism values up to some point where the desirability of a place for tourism decreases as tourist numbers further increase.

4.3.3.2 *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 tourism such as the coastal glaciers in Illulissat Icefjord, Denmark, which is a UNESCO World Heritage site, and coastal cities like Venice (Moreno and Amelung 2009) or Alexandra (Scott et al. 2012) will also be heavily affected by climate change. Beach tourism in tropical and temperate areas is expected to be heavily 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 costs for the main five ocean tourism cities under a future 1m sea level rise scenario is US$330 million (Ruiz-Ramírez et al. 2019), and in the US, total beach nourishment for 2060 estimated costs for a 0.32m scenario amount to US$20.40 billion (Scott et al. 2012). The breaking of ice in the polar region also poses potential danger to cruise ships and navigation.

The impacts of climate change go beyond tourism. Massive infrastructure losses are expected from intensifying storms and sea level rise -- global annual flood costs from sea level rise under RCP 8.5 are estimated at US$14 trillion per year (Jevrejeva et al. 2018). Sea level rise also threatens not only the tourism of low-lying island nations such as Maldives, Marshall Islands, Tuvalu, and Nauru but their entire economy and population.

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

#### 4.3.4 Solutions

**1. Enhancing coral reef resilience to climate change.** Reducing the negative effects of climate change and associated ocean disturbances to coastal economies requires improving the resiliency of marine and coastal ecosystems to climate change (Gattuso et al. 2018; James et al. 2019; Weatherdon et al. 2016). Establishing marine protected areas (MPAs), improving fisheries management, and promoting ecosystem-based tourism can help improve the ecological resilience of coral reefs. MPAs protect marine ecosystems from environmental uncertainties and can also help minimize the footprint of fishing. MPAs help ensure that coral reefs and associated species that are important draws for tourism are protected. Protection should prioritize 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 favor some components (e.g. removing mangroves to access sandy beach) (e.g. Cabral and Aliño 2011), it is important to recognize the huge role played by the different ecosystems in maintaining coastal integrity.

**2. Natural habitats protection and regeneration.** Preservation and restoration of natural coastal habitats such as coral reefs, beaches, or mangroves increases the resilience of coastal areas to climate change (James et al. 2019), providing an alternative to tourism hard infrastructure that allows for wave attenuation and shoreline stabilization (James et al. 2019; Gattuso et al. 2018), as well as for storm surge and excess flooding (Ruiz-Ramírez et al. 2019). Traditional infrastructures for tourism such as urbanized beach fronts are expected to suffer shoreline erosion (coastal squeeze) due to climate change (Toimil et al. 2018; Scott et al. 2012). In this case, coastal natural habitats can allow for landward retreat, but otherwise beach nourishment will be required to maintain tourism in heavily urbanized 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. Policy diversified 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. Pressures and drivers to reef health are often associated with governance and 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 in order to reduce climate change impacts to local and national economies. For the case of coral reef tourism, this requires implementing local policies that promote healthy reef ecosystems. These policies should target drivers and pressures that contribute to the degradation of coral reefs. 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 proper siting of tourism infrastructure and investments that account for potential future coastal and ocean changes. Management plans should explicitly address the role of natural habitats that function as buffers to climate change on tourism (Ruiz-Ramírez et al. 2019).

**4. Proper waste disposal and waste treatment facilities for coastal tourism infrastructure.** Local nutrient influx exacerbates ocean acidification. Controlling nutrient input from coastal and terrestrial activities will help reduce the impact of climate change to coral reef tourism. Overfishing and pollution that degrades coral reefs caused the Caribbean to lose US$95-140 million/year in net revenue from coral reef-associated fisheries, US$100-300 million/year in reduced tourism revenue, and US$140-420 million/year in reduced coastal protection (Burke et al. 2011).

**5. Reducing the environmental footprint of tourism.** While CC will inevitably affect tourism, tourism is also a major contributor of greenhouse gas (GHG) emissions (Scott et al. 2012). It is estimated that tourism contributes 8% of the global GHG emissions, with transport, shopping, and food as major contributors (Lenzen et al. 2018). With tourism expected to grow at 3-5% per year, it is important to ensure that the environmental footprint of tourism is minimized. Future increases in international arrivals do not necessarily translate to economic benefits for countries; hence, policies ensuring optimal benefits for national economies while reducing tourism’s footprint should be a priority.

### 4.4 Improving the Energy Efficiency of the Ocean Economy

### Improving the energy efficiency of ocean-related industries not discussed above, 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 by utilizing existing technologies (Allison and Bassett 2015; Ash and Scarbrough 2019). For example, switching international shipping to solar-generated green ammonia-based fuel would allow for significant reductions of greenhouse gas emissions (Ash and Scarbrough 2019). Fisheries and aquaculture are already relatively energy-efficient, especially in comparison to terrestrial production of animal protein (Allison and Bassett 2015), 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 fuel efficiency improvements and carbon offsets for various modes of travel to efficiency improvements being made by hotels and other tourism destinations around the world (Allison and Bassett 2015).

## 5. 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.

### 5.1 Conservation and Expansion of 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, having already sequestered nearly 1/3 of all atmospheric CO2 emissions since the early 1700s (Gattuso et al. 2015). Through a process known as the “biological pump”, marine organisms convert CO₂ into biomass through photosynthesis, a portion of which 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 (Serrano et al. 2019; Vaughan and Lenton 2011). Marine carbon fixation 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.

Vegetated coastal ecosystems – primarily seagrasses, mangrove forests, and tidal marshes – occupy only 0.2% of the global ocean surface, but have an exceptional capacity for carbon sequestration, contributing up to 50% of carbon burial in marine sediments (Duarte 2017; Duarte et al. 2013; Serrano et al. 2019), far outpacing the capacity per unit area of terrestrial habitats (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 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). These ecosystems are among the most threatened habitats on Earth, and their current and projected loss not only reduces global CO₂ 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; Serrano et al. 2019). There may be significant 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 also 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 feces, 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 would theoretically increase input of organic matter (including carbon) to the biological pump. 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 CO2 fixation (Aumont et al. 2018).

### 5.2 Expansion of 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). 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 (ORED) (Boehlert and Gill 2010). As these technologies expand, they will impact the oceans both above and below the water’s surface through 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 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 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. Construction, servicing, and decommissioning of structures brings additional risks 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 behavior of marine species that use natural electric and/ or magnetic fields for a variety of behaviors. 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: Energy removal from the water can change local water movement (for example 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 vs. far-reaching, and short- vs. long-term impacts). The cumulative impacts of multiple adjacent developments must also be understood (Boehlert and Gill 2010).

### 5.3 Expansion of 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. 2018). Mining contracts for deep-sea resources including rare earths have been awarded to a number of countries and companies (Miller et al. 2018). In addition to the usual risks associated with mining and other extractive industries in the ocean (including potential for release of toxic elements, contamination from dredge spoils, increased noise, heat and light pollution, and loss of biodiversity), these deep-sea mining operations will carry additional 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 recognized as vulnerable (Miller et al. 2018). Furthermore, impacts may extend many kilometers 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. 2018).

### 5.4 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; fertilization of patches of the ocean with limiting nutrients (iron, nitrogen, or phosphorus) to enhance primary productivity and sequestration of carbon (see blue carbon discussion above); induction of upwelling to do the same; induction of downwelling to increase the sinking of CO2 rich waters; and “enhanced weathering,” wherein materials such as carbonate or silicate are added to the water to increase alkalinity, thereby stimulating removal of CO2 from the atmosphere (Allison and Bassett 2015; Vaughan and Lenton 2011).

While the costs of implementing any of these techniques are currently prohibitive, and the carbon-balance effects are highly uncertain (Burke et al. 2011; 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 fertilization could lead to increased deoxygenation and eutrophication, and 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 only address global temperature changes, without reducing other impacts, such as ocean acidification (Gattuso et al. 2015; Vaughan and Lenton 2011). 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).

## 6. Conclusions and recommendations

The ocean is critically important to the global economy. Collectively, ocean-based industries contribute approximately US$31 trillion (2.5% of the global economy) and more than 31 million jobs annually (OECD 2016). In this paper, we reviewed the impact of climate change on the three key components of the ocean ecosystem economy -- fisheries, aquaculture, and coral reef tourism -- and the opportunities for effective institutions and markets to reduce these impacts.

Building on existing work, we developed three new models to forecast 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 catch 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 sustainable management. 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 helps lessen the economic impacts.

Since climate change impacts differ by country and sector, possible solutions will be context-specific. By exploring climate change impacts at the country-level for fisheries, aquaculture, and reef tourism provided 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.

### Capture Fisheries

This [interactive web interface](https://sfg-ucsb.shinyapps.io/fishcast2/) summarizes 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. It illustrates how the health of fisheries and the catch 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 “primary 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 positive impacts of climate change) should account for shifting productivity in fisheries stock assessments and management procedures (see Pinsky and Mantua 2014) to capitalize on the positive effects of climate change and mitigate the negative effects.
3. All countries will derive benefits from international cooperation to ensure that management does not degrade as stocks shift distributions and to ensure fairness and equity in fisheries outcomes under climate change.

### Aquaculture

1. In countries with underdeveloped mariculture potential (**Fig. 2**), the negative effects of climate change can be offset by developing sustainable mariculture infrastructure.
2. In countries with fully developed mariculture potential (**Fig. 2**), mariculture production can be maintained by selectively breeding for fast growth or heat tolerance or by shifting their portfolio 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 practice is sustainable mariculture.

### Ocean Tourism

Climate change will reduce the potential of ocean tourism to boost local economies of all coastal countries with coral reefs. The magnitude of the impact depends on the realized global emission 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. snorkeling and diving) will surely be more vulnerable than reef-adjacent tourism (e.g. sun bathing, white sand), it is well known that the latter will also be affected, although the magnitude of the impact is uncertain. Table A2 summarizes 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 the Maldives, Palau, and St. Barthelemy (i.e., over 40% of their GDP is from reef tourism), options include slowly diversifying to other industries such as developing capacity for capture fisheries and aquaculture, while at the same time improving the investments in the management and improvements of reef ecosystem and ocean tourism.
2. In countries with high reef-adjacent values and where ocean tourism is important, it is still recommended to improve and maintain coral reef health to secure the continuous provisioning 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 can enhance both the economic potential of coral reefs and can motivate more investments towards protecting reef health.
4. Coral reef tourism can be a viable industry in countries that are expected to lose from aquaculture and capture fisheries. Although climate change will affect countries from tapping the full potential of ocean tourism, it 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 enhance ocean tourism gain efficiency by prioritizing high economic gain activities while at the same time reducing the ecological footprint of ocean tourism activities.

It is imperative that countries explore the synergistic impacts of climate change across all three sectors and identify whether they are vulnerable to universally negative impacts versus having options to offset negative impacts in some sectors through adaptation or 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 economy 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 acts synergistically with other sectors, especially when the action is aimed at maintaining and enhancing ecosystem health. Our results will ultimately help guide new ocean investments and positive conservation actions by governments, NGOs, development agencies, philanthropies, and international communities.

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:

1. **Be forward looking:** The future of the ocean economy is expected to drastically change given climate change. It will no longer be appropriate (or possible) to set our sights 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 and anticipate changes, and make decisions aimed at improving ecosystem health. For wild-capture fisheries, looking forward will entail things like scenario planning and management strategy evaluation, while stock assessments, harvest controls, and allocation systems will all need to be more flexible, adaptive, and precautionary. Mariculture operations will need to invest in things like selective breeding and improvements to feed conversion ratios, and 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 but less ecological footprint.
2. **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 they are well-managed, and that the benefits are fairly distributed, during and after the transition. For mariculture, it will be critical to incorporate other marine uses and sectors in the planning and implementation of operations. Tourism too will benefit on whole-systems thinking to ensure the durability of this sector into the future as well as to take advantage of tourism opportunities for areas that will be suitable for tourism investments, i.e. for the case where new coral reefs will establish in subtropical areas. In addition, it will be critical to share lessons learned and tools applied across and between sectors to ensure lower-capacity regions will not fall behind in the implementation of new solutions.
3. **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, and inequity reduces resilience. Truly inclusive, representative, participatory decision-making processes can help to address these concerns in all sectors.

## Appendix

**Table A1.** Global atmospheric CO2 concentration (ppm) for different RCPs using CMIP51.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 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 |

1 Data from:<http://climexp.knmi.nl/getindices.cgi?WMO=CDIACData/RCP45_CO2&STATION=RCP45_CO2&TYPE=i&id=someone@somewhere&NPERYEAR=1>

**Table A2.** Climate change effect. Summary table for all countries and territories with >50km2 of reef and total reef-related expenditure >US$10 million/year (from Table A2 of Spalding *et al.* 2017). On-Reef Tourism value pertains to in-water activities such as diving, snorkeling, and glass-bottom boats. Adjacent Reef Tourism value captures a range of indirect benefits from coral reefs, including provision of sandy beaches, sheltered water, seafood, and attractive views. Country-level tourism values data provided by M. Spalding.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Country | Total Coral Reef Tourism Values (US$ 1000 per year) | Percent 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 | -8 | -26.6 | -12.5 | -38.6 |
| Indonesia | 3,097,453 | 64.3 | -15 | -44.2 | -23.7 | -60.2 |
| Mexico | 2,999,883 | 44.8 | -8.6 | -28.3 | -14 | -41.9 |
| Thailand | 2,410,154 | 44.8 | -14.8 | -43.7 | -24.3 | -61 |
| Australia | 2,176,084 | 78.3 | -8.4 | -27.8 | -14.4 | -42.8 |
| China | 1,871,814 | 15.3 | -9.4 | -30.5 | -15.9 | -46.2 |
| Philippines | 1,385,144 | 67.4 | -15.5 | -45.2 | -23.9 | -60.6 |
| Hawaii | 1,230,894 | 44.8 | -8.2 | -27.2 | -13.9 | -41.7 |
| Japan | 1,177,549 | 53.9 | -7.6 | -25.4 | -13.6 | -41 |
| Malaysia | 1,148,955 | 64.3 | -15.1 | -44.4 | -24 | -60.6 |
| Maldives | 1,085,273 | 84.4 | -16 | -46.4 | -24.9 | -62 |
| Puerto Rico | 648,867 | 21.3 | -16 | -46.2 | -25.2 | -62.5 |
| Brazil | 612,864 | 8.3 | -8.9 | -29.2 | -25 | -62.1 |
| Bahamas | 526,058 | 60.5 | -15.7 | -45.7 | -24.9 | -62 |
| Dominican Republic | 511,669 | 26.5 | -15.8 | -45.9 | -25.1 | -62.3 |
| India | 464,082 | 15.3 | -15.9 | -46.1 | -25.2 | -62.4 |
| Honduras | 446,628 | 85.8 | -15.7 | -45.7 | -25.2 | -62.4 |
| United Arab Emirates | 445,654 | 15.3 | -8.7 | -28.7 | -26.8 | -64.7 |
| Jamaica | 333,386 | 35.1 | -15.8 | -45.8 | -25.2 | -62.4 |
| Taiwan | 323,440 | 15.3 | -16 | -46.3 | -25 | -62.2 |
| Guam | 323,244 | 64.3 | -15.7 | -45.8 | -24.6 | -61.5 |
| Mauritius | 312,389 | 47.4 | -15.6 | -45.4 | -24.8 | -61.8 |
| Cayman Islands | 292,794 | 83.2 | -15.5 | -45.3 | -25.1 | -62.2 |
| Cuba | 283,290 | 35.1 | -15.6 | -45.4 | -25 | -62.2 |
| Venezuela | 281,865 | 35.1 | -15.9 | -46 | -24.7 | -61.7 |
| Virgin Islands of the United States | 276,056 | 53.9 | -16 | -46.3 | -25.2 | -62.4 |
| Saudi Arabia | 268,681 | 49.7 | -16.4 | -47 | -26.9 | -64.9 |
| Fiji | 234,676 | 65.4 | -15 | -44.1 | -23.7 | -60.2 |
| Bermuda | 223,639 | 69.2 | -8.2 | -27.3 | -14.1 | -42.2 |
| Oman | 221,164 | 35.1 | -16.4 | -47.1 | -25.6 | -63 |
| Aruba | 218,226 | 35.1 | -15.8 | -45.9 | -24.8 | -61.8 |
| Barbados | 180,082 | 38.7 | -15.9 | -46 | -24.9 | -62 |
| Costa Rica | 169,518 | 35.1 | -16.3 | -46.9 | -25.8 | -63.4 |
| Panama | 154,178 | 38.7 | -16.3 | -46.8 | -25.4 | -62.8 |
| Colombia | 147,202 | 35.1 | -16.4 | -47.2 | -25.7 | -63.1 |
| Vietnam | 137,445 | 15.3 | -15.4 | -45.1 | -24.3 | -61.1 |
| Tanzania | 131,076 | 49.7 | -16.3 | -46.9 | -25.4 | -62.7 |
| Kuwait | 117,236 | 35.1 | -11.2 | -35.3 | -13.1 | -40 |
| Bahrain | 115,837 | 21.3 | -7.1 | -24.1 | -6.8 | -23.2 |
| French Polynesia | 113,657 | 63.1 | -9.3 | -30.3 | -23.8 | -60.3 |
| Qatar | 108,066 | 8.3 | -15 | -44.1 | -27.8 | -66.1 |
| Turks and Caicos Islands | 97,587 | 69.2 | -15.9 | -46 | -25.3 | -62.5 |
| Palau | 92,503 | 86.3 | -15 | -44.2 | -23.7 | -60.2 |
| Guadeloupe | 90,463 | 38.7 | -16 | -46.2 | -25 | -62.1 |
| Martinique | 89,337 | 35.1 | -15.8 | -45.8 | -24.9 | -62 |
| Kenya | 84,152 | 31 | -16.4 | -47.2 | -25.7 | -63.2 |
| Sri Lanka | 82,371 | 8.3 | -15.9 | -46 | -24.8 | -61.8 |
| Belize | 80,611 | 70.8 | -15.7 | -45.7 | -24.9 | -61.9 |
| Seychelles | 73,141 | 47.4 | -16.2 | -46.7 | -25.3 | -62.6 |
| Mozambique | 68,356 | 80.9 | -16.3 | -47 | -25.2 | -62.4 |
| Northern Mariana Islands | 61,302 | 73 | -15.7 | -45.8 | -24.6 | -61.5 |
| Ecuador | 58,883 | 60.5 | -16.6 | -47.5 | -27.5 | -65.7 |
| Saint Lucia | 56,574 | 41.9 | -15.8 | -45.8 | -24.8 | -61.8 |
| Madagascar | 50,496 | 47.4 | -8.4 | -27.7 | -24.9 | -62 |
| Vanuatu | 49,991 | 59 | -14.8 | -43.7 | -23.9 | -60.5 |
| Papua New Guinea | 32,024 | 73 | -15.1 | -44.3 | -24.1 | -60.8 |
| Sudan | 28,480 | 85.8 | -16.1 | -46.5 | -27.1 | -65.1 |
| New Caledonia | 28,465 | 57.4 | -8.8 | -28.9 | -14.8 | -43.7 |
| Brunei | 28,259 | 26.5 | -15.1 | -44.4 | -23.8 | -60.4 |
| Grenada | 23,150 | 53.9 | -15.9 | -46.1 | -24.6 | -61.6 |
| Solomon Islands | 21,984 | 79.5 | -14.9 | -43.9 | -23.8 | -60.4 |
| Anguilla | 19,685 | 41.9 | -16.1 | -46.5 | -25.2 | -62.4 |
| Cook Islands | 19,106 | 41.9 | -15.1 | -44.4 | -23.9 | -60.5 |
| Cambodia | 18,285 | 15.3 | -15 | -44.3 | -24.6 | -61.5 |
| Micronesia | 18,108 | 86.3 | -15.2 | -44.6 | -24.2 | -61 |
| Haiti | 15,206 | 31 | -16 | -46.2 | -25.4 | -62.7 |
| Iran | 13,345 | 0 | -7.8 | -26.1 | -12.3 | -38.1 |
| Tonga | 13,291 | 71.6 | -8.9 | -29.3 | -15.5 | -45.3 |
| Samoa | 12,490 | 31 | -15 | -44.1 | -23.5 | -59.9 |
| Myanmar | 11,581 | 51.9 | -15.3 | -44.9 | -24.3 | -61.2 |
| Nicaragua | 10,975 | 41.9 | -15.8 | -45.9 | -25 | -62.2 |

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