3. The range of ocean influences of climate change

Anthropogenic climate change, driven by the exponential increase in emissions of greenhouse gasses (GHGs) since the industrial revolution, is altering ocean climate, chemistry, circulatory patterns, sea level, and ice distribution with critical impacts on habitats, biotic productivity, and community assemblages (Barange, 2018; Gattuso et al., 2015). Unprecedented changes are already occurring across all latitudes (Barange, 2018; Gattuso et al., 2015) with high risk of negative impacts to many ocean organisms, ecosystems, and services expected before the end of this century (Gattuso et al., 2015). These impacts are likely to have dramatic consequences for 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.

Throughout this paper, we rely on the Representative Concentration Pathways adopted by the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report (AR5) to describe potential greenhouse gas emission trajectories and associated climate futures. The scenarios are named according to the amount of radiative forcing experienced in 2100 of the projections (2.6, 4.5, 6.0, and 8.5 W/m2, respectively).

3.1 Altered ocean climate and disturbances

Climate change has already contributed to significant warming of the oceans over most of the globe, from the upper ocean (above 700 m), since the 1960s, down to deeper waters (700 -2000 m), where warming has accelerated since the 1980s (Cheng et al., 2017). Sea surface temperatures (SSTs) have increased by an average of 0.7 °C per century globally since 1900 (Barange, 2018). RCP scenarios suggest that these trends, which already exceed the range in natural seasonal variability in subtropical areas and the Arctic, will continue. Estimates for mean warming by the end of the twenty first century for the top 100 m range from 0.6 °C (RCP2.6) to 2 °C (RCP8.5), and from 0.3 °C (RCP2.6) to 0.6 °C (RCP8.5) for depths of 1,000 m (Barange, 2018; IPCC, 2014). 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 thermal environment within the current range of many marine species are expected to change leading to shifts in their distribution. In general, species that are able to move to cooler waters both at higher latitudes and greater depths, and have suitable habitats to move to, will do so (Barange, 2018; Doney et al., 2014; Gattuso et al., 2015). Significant habitat losses are predicted in many areas, especially in the Arctic and coral reef ecosystems, resulting in altered community assemblages, phenological mismatches, and local extinctions (Doney et al., 2014; Free et al., 2019; Gattuso et al., 2015; Holbrook, Schmitt, & Stephens, 1997). Consistently warmer waters, the spread of biotic diseases, and ocean acidification (discussed below), along with temporary ocean “heat waves,” 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 processes of community thermofilization, involving replacement of cold-affinity by warm-affinity species, have 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, 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 climate changes (Barange, 2018), with potentially important impacts on fishing, aquaculture, and tourism operations. River flows and flooding may also increase with increased snowmelt and land-based precipitation, reducing salinity, increasing sedimentation, and impacting productivity in nearshore waters (Loo, Billa, & Singh, 2015). Finally, ocean warming leads to increased stratification of the water column and reduced water circulation and mixing (Barange, 2018; FAO, 2018; Oschlies, Brandt, Stramma, & Schmidtko, 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 and carbonate ion concentrations, and increases the partial pressure of CO₂ and dissolved inorganic carbon. These changes can impact all aquatic life, but they are especially detrimental to corals and shell-forming marine species (Barange, 2018; FAO, 2018). Observed trends in lowered ocean pH, which already exceed the natural seasonal variability throughout most of the ocean, are expected to continue throughout this century, with the largest decreases occurring in surface waters of the warmer low- and mid-latitudes (Barange, 2018; Gattuso et al., 2015). In addition, increased levels of CO₂ exacerbate nearshore biogeochemical changes stemming from land-based nutrient inputs, sedimentation, aquaculture, and fishing (Gattuso et al., 2015).

Climate change is also impacting dissolved oxygen content in ocean systems across the globe. As the ocean warms, reduced solubility of oxygen and increased stratification of the water column (exacerbated by eutrophication from coastal pollution) reduce 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; Oschlies et al., 2018). This trend is expected to continue, with 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).

However, discrepancies between observations and modelled trends, with observed deoxygenation generally worse than modelled results, point to the need to improve our understanding of the processes driving deoxygenation in order to reduce 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 potentially stops, the global conveyor belt (Barange, 2018; Liu, Xie, Liu, & Zhu, 2017). The meridional overturning circulation (MOC) 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). 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 years (Barange, 2018; Liu et al., 2017).

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 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 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). 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, increasing 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 has increased by 1.2 – 1.8% over the same period (Barange, 2018). Glaciers and land-based ice sheets across the world have also shrunk (Barange, 2018) and are expected to outpace other sources of sea level rise 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, 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). Approximately 30.6 million people participated (full-time, part-time, or occasionally) in capture fisheries operated by an estimated 4.6 million fishing vessels. Fish and fish products are among the most traded 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 (USD$143 billion) of fish products exported in 2016 constitute a 245% increase relative to 1976 exports (USD$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 (citation).

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., changing habitat availability, 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 section 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.

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

Observed changes: Climate change has already 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 (Beaugrand *et al.* 2003; Clausen *et al.* 2017), while matches have reduced mortality rates (MacKenzie and Köster 2004). Finally, recruitment of juveniles is often more strongly driven by environmental factors than by spawner biomass (Szuwalski *et al.* 2014; 2019), and has declined as a result of environmental change and overfishing (Britten *et al.* 2016 but see Szuwalski 2016).

Forecasted changes:Fish growth rates and body sizes are expected to decline further under continued warming and deoxygenation, with consequences for catch potential (Cheung 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 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: Fisheries stock assessments will increasingly have to account for environmentally-driven, time-varying natural mortality, growth rates, and recruitment.

**Marine fish and invertebrates are shifting distributions to track their preferred temperatures. Transboundary agreements will be necessary to ensure that management remains both effective and equitable as species shift in and out of management jurisdictions.**

Observed changes: As the oceans warm 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 global 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 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 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: Establishing or strengthening transboundary fisheries management institutions will be necessary to ensure that management remains both effective and equitable as fish stocks shift into new management jurisdictions.

**Although the net global impacts of climate change on fisheries productivity (catch potential) are modest, regional impacts are strong, with pronounced winners and losers. Vulnerable regions must focus on management reform and adaptation. Resilience to climate change can be enhanced by preventing overfishing, rebuilding overfished stocks, and accounting for shifting productivity in assessment and management.**

Observed changes: Over the past eighty years, 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 (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, preventing overfishing and rebuilding overfished stocks will enhance resilience to climate change. Second, fisheries stock assessments and management procedures will need to account for shifting productivity (a.k.a., non-stationary or time-varying population dynamics). This will involve one of many strategies (Pinsky and Mantua 2014) including: (1) using assessments with time-varying productivity; (2) restricting assessments to the current environmental regime; and/or (3) using climate-adaptive harvest control rules.

4.1.3 Ability for management to mitigate the impacts of climate change

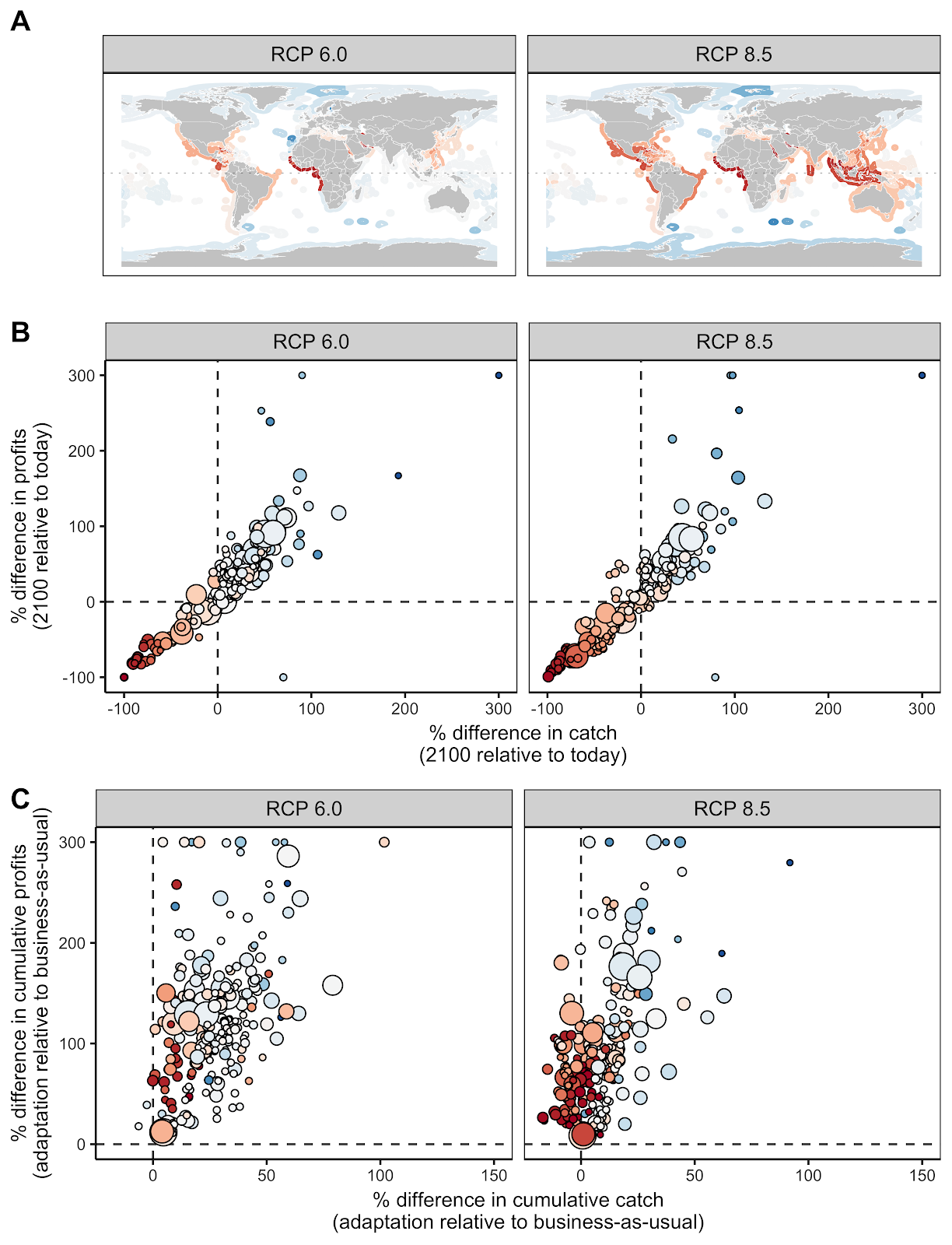
Most forecasts of the impacts of climate change on fisheries compare the maximum biological potential for food production today with that in the future (Cheung *et al.* 2010; Lam *et al.* 2016). While this is useful for understanding the biological limits of the ocean under change, it fails to consider 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).

***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 up to 2100 under two IPCC Representative Concentration Pathways (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 3**). 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 3**). Climate-adaptive fisheries management results in greater cumulative profits than business-as-usual management for 99% of countries under both 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 seven key recommendations for implementing such reforms.



**Figure 3.** 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

1. **Eliminate illegal, unreported, and unregulated (IUU) fishing:** IUU fishing is a widespread problem that undermines the effectiveness of fisheries management and reduces climate resilience by promoting overfishing (Agnew *et al.* 2009). By eliminating IUU fishing, countries can rebuild fisheries and increase climate resilience without incurring the short-term reductions in food and income associated with typical reforms (Cabral *et al.* 2018).
2. **Implement best practices in fisheries management:** Best practices in fisheries management, such as science-based harvest control rules and the protection of essential habitat, even when not explicitly climate-adaptive, confer climate resilience through two mechanisms: (1) well-managed fisheries are the most resilient to negative climate impacts (Free *et al.* 2019), and preventing overfishing and rebuilding overfished stocks will enhance climate resilience; and (2) a portfolio of well-managed fisheries buffers fishers against declines in a subset of targeted stocks.
3. **Build resilience by implementing forward-looking, variability-responsive, and adaptive science and management:** Climate change is likely to lead to drastic transformation and high variability and uncertainty in most fishery systems. Management strategies must therefore be adequately responsive to changes in productivities, abundances, and mixes of species, and must expect and prepare for uncertainty and system shocks. In order to design and implement such climate-adaptive management systems:
   1. Management targets and reference points must be revised to be realistic relative to expected future conditions, as historic baselines will no longer be appropriate (Busch *et al.* 2016). 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, highly precautionary and adaptive management strategies should be implemented to account for uncertainty and allow for near-real-time responsiveness to variability.
   2. Fisheries management plans and governing policies should be expanded to promote flexibility and diversification in access to target species, protect “weak stocks,” facilitate the precautionary management of emerging stocks, and to conserve or restore species and functional diversity throughout the system.
   3. Ensure fishery access and allocation systems can accommodate changes in species mix and abundance, as well as socio-ecological change.
4. **Establish and strengthen transboundary institutions and agreements to better manage stocks shifting between 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 tradeable across political boundaries to foster dynamic catch allocations.
5. **Use marine protected areas (MPAs) to foster transitions and to buffer against transboundary growing pains:** Networks of MPAs could assist the redistribution of species in response to rapid environmental changes. Furthermore,MPAs placed along country borders could buffer against the degradation of management as stocks shift into new management jurisdictions. The protection offered by MPAs may provide more time for the development of the transboundary institutions and climate-adaptive management methods required to properly manage stocks under climate change.
6. **Build and enhance flexible, polycentric and nested, participatory co-management systems:** Similarly to the way in which best-practice fisheries management can build climate-resilience even when not explicitly climate-focused, implementing “best-practice” co-management and governance systems can build system resilience to undesirable socio-ecological shifts and climate-driven inequities. Representative participatory decision-making systems help to ensure all impacted groups are considered in management thereby reducing drivers of inequity, and flexible, polycentric and nested co-management governance systems help to ensure management decisions match the scale of management challenges (CITE (Ostrom and others)).
7. **Actively address disparities in the distribution of climate impacts that can cause or exacerbate inequity:** Identify existing issues of social vulnerability and differentiated access to power, knowledge and resources, and assess how they might change as the climate changes. Account for vulnerable groups’ need for a change of circumstance to avoid imbalances of power into the future. Prioritize the values and needs of dependent communities in fishery management decision-making, especially around allocation and access to resources.