ADAPTABILITY OF PACIFIC NORTH AMERICA'S SMALL-SCALE FISHERIES TO CLIMATE CHANGE

by

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Abstract

This thesis compares and contrasts the projected impacts of climate change on small- and large- scale fisheries and seeks to understand key characteristics of their vulnerability and adaptability to climate change using the Pacific North America region, including Alaska, Canada, USA West Coast and Mexico, as a case study. I undertake an interdisciplinary approach and use both quantitative and qualitative methodologies to examine the ecological and social-economic dimensions of vulnerabilities, impacts and adaptability of climate change on fisheries. I identify 312 exploited species that are important to small- or large- scale fisheries and apply the Dynamic Bioclimate Envelope Model to project changes in maximum catch potentials and their distributions separately for by small- and large- scale fisheries under the upper (RCP 8.5) and lower (RCP 2.6) greenhouse gas emission scenarios between year 2000 and 2080. Subsequently, I apply a vulnerability assessment framework to three case illustrations from the Pacific North America region: Alaska's cod fishery (USA), Monterey Bay's wetfish fishery (USA) and Sonora's cannonball jellyfish fishery (Mexico) to understand key commonalities and differences that would enable small-scale fisheries and large-scale fisheries to adapt to the climate-induced impacts.

The results indicate a projected increase in maximum catch potential for small-scale fisheries (RCP 2.6: +1.7%; RCP 8.5: +16.7%) compared to large-scale fisheries (RCP 2.6: -7.2%; RCP 8.5: -10.7%) across the region by 2080 relative to 2000, with varying patterns between different countries' waters. The increasing trend in catch potential is contributed by a few exploited species with significant projected gains such as California market squid (*Loligo opalescens*). The ability of fisheries and fishing communities to adapt to these ecological changes will determine their continued viability. Case illustrations suggest that having lower operational cost, flexibility in gear type, flexible management, clear regulations, strong social capital and well-educated communities tend to relate with lower vulnerability and stronger adaptive capacities to climate change.

Lay summary

This thesis seeks to understand the projected effects of climate change on small-scale fisheries compared to large-scale fisheries in Pacific North America. Based on these projections, it explores key characteristics that would enable fisheries to adapt to these climate-induced changes. By using quantitative and qualitative methods as well as incorporating ecological and social-economic considerations, this research provides an interdisciplinary perspective on the future scenarios and challenges that small-scale fisheries in the region may face under climate change. Ultimately, it is my hope that this research contributes to the ongoing efforts to elevate the profile of small-scale fisheries and adds to the discourse on adaptive fisheries management under climate change.

Preface

I conducted the analysis and wrote this thesis under the primary guidance of my supervisor, Dr. William Cheung. In addition to Dr. Cheung, my supervisory committee members, Dr. Rashid Sumaila and Dr. Ratana Chuenpagdee provided comments and suggestions through the process and on the final version of this thesis.

Chapter 2 incorporates the use of fisheries catch data from the Sea Around Us, current distribution maps through the Sea Around Us algorithm (Close et al. 2006) and future distributions and catches projected using the Dynamic Bioclimate Envelope Model (Cheung et al. 2008, 2009). The algorithms for the above two models were provided to me by Dr. Cheung, I was responsible for collecting life history and habitat parameters from online databases and literature sources, drawing species polygons and running the models. I performed the subsequent calculations and generated the figures and tables in this thesis, with comments and revisions from Dr. Cheung.

In Chapter 3, I identified the method, conducted the literature review and applied the vulnerability framework from Cinner et al. (2013).

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List of abbreviations

ADFG	Alaska Department of Fish and Game
DBEM	Dynamic bioclimate envelope model
DFO	Fisheries and Oceans Canada
EEZ	Exclusive Economic Zone
ENSO	El Niño Southern Oscillation
EOL	Encyclopedia of Life
ESM	Earth System Models
FAO	Food and Agricultural Organization
GFDL	Geophysical Fluid Dynamics Laboratory
IPCC	Intergovernmental Panel on Climate Change
IPSL	Institut Pierre Simon Laplace
LSF	Large-scale fisheries
NMFS	National Marine Fisheries Services
NOAA	National Oceanic and Atmospheric Administration
PDO	Pacific Decadal Oscillation
PNA	Pacific North America
RCP	Representative concentration pathway
SDM	Species distribution model
SSF	Small-scale fisheries
TAC	Total allowable catch
WDFW	Washington Department of Fish and Wildlife

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1. Introduction

1.1 Introduction

Climate change will have large implications for marine ecosystems and fisheries due to alterations in key oceanic drivers such as temperatures, salinity, circulation, pH, oxygen and nutrient availability (Doney et al. 2012; Pörtner et al. 2014). As these oceanic drivers impact the fundamental physiological performance of organisms, it has widespread implications on biodiversity, community composition and ecosystem structure. Ultimately, this will have direct and indirect impacts on marine fisheries distributions and productivity (Blanchard et al. 2012; Cheung et al. 2010; Perry et al. 2014; Pörtner et al. 2014; Poloczanska et al. 2013). Globally, marine fisheries supply 17% of the protein consumed by the world's human population (FAO 2014a), therefore changes to fisheries distribution and productivity can have substantial consequences for food security, economics and human livelihoods (Allison et al. 2009; Hollowed et al. 2013; Lam et al. 2016; Sumaila et al. 2011).

Particularly, within global marine fisheries, small-scale fisheries (SSF) have tremendous importance, accounting for 44% of all fishers in the primary production sector, 90% of employment in the fishing industry and 90% of global fishing vessels (Béné, 2006; Chuenpagdee et al. 2006; Teh & Sumaila, 2013). Studies have demonstrated that SSF have greater positive implications for society and economic viability than its large-scale fisheries (LSF) counterparts (Schuhbauer and Sumaila 2016). However, many SSF communities are often marginalized and rely heavily on marine resources (Pauly 2006; Jacquet and Pauly 2008). Hence, the impacts of climate change can add additional stress on the resilience of these communities that are already facing environmental, economic and social challenges (Khattabi and Jobbins 2011).

Understanding and projecting changes of fisheries catch potentials on SSF is crucial towards developing successful adaption strategies.

Current approaches on understanding the impacts of climate change on marine fisheries either assess the aggregated effects on all fisheries or focus on a specific fishing sector (SSF or LSF) (Ainsworth et al. 2011; Haigh et al. 2015; Lluch-Cota et al. 2018). Although SSF and LSF have distinctive characteristics, most existing studies are not sufficiently resolved to elucidate the differences in risk, vulnerability and responses between SSF and LSF to climate change. In contrast, a comparative approach between SSF and LSF such as in Berkes et al. (2001), Jacquet & Pauly (2008) and Sumaila et al. (2001) can illuminate potential differences in patterns that might otherwise be masked in a cumulative study.

As fisheries represents an interaction between marine resources and human exploitation, this thesis takes an interdisciplinary approach of understanding both the ecological and social-economic components. By integrating quantitative projections of climate change on fisheries catch potentials with qualitative vulnerability assessments of the social-economic dimensions, we can achieve a more holistic understanding of the challenges and adaptation strategies facing marine fisheries and their communities under climate change.

This chapter introduces the theoretical and methodological frameworks for this thesis. Firstly, I provide an overview of the marine social-ecological systems of Pacific North America (PNA) and existing knowledge about the projected climate change impacts on PNA marine ecosystems. I then review current understanding about SSF in PNA. Thirdly, I introduce the use of species distribution models to assess climate change impacts on fisheries resources, and existing frameworks used for climate vulnerability assessment. Finally, I explain the objectives and structure of this thesis.

1.2 Background

This thesis examines PNA as a case study region because of its biological and social-economic importance — it is identified as one of the fourteen ecologically significant regions by the Commission for Environmental Cooperation (Morgan et al. 2005). PNA includes four different Exclusive Economic Zones (EEZs): Alaska Sub-Arctic, Canada Pacific, United States Pacific and Mexico Pacific (Figure 1.1), and encompasses a total area of 6,928,449 km^2 within the EEZs of which shelf area and Inshore Fishing Area consists of 153,926 km^2 and 58,939 km^2, respectively (Zeller and Pauly 2015; extracted from www.seaaroundus.org). The three countries in the PNA are social-economically developed, with the Human Development Index ranking from “very high” (Canada and USA) to “high” (Mexico) (United Nations Development Program 2018).

The PNA is a region of diverse habitats and ecosystems including the temperate ecosystems of Alaska to California, tropical zones in southern Mexico and a semi-enclosed sea in the Sea of Cortez/Gulf of California (Wilkinson et al. 2009). There is considerable influence from upwellings, downwellings and currents in the PNA region, most notably the California and Alaska currents (Huyer 1983; Johnson 2016). Regions are also characterized by their transitionary states between these upwellings and downwellings such as in Canada and Mexico (Wilkinson et al. 2009). These areas have their own unique attributes and systems which adds to the diversity of flora and fauna in the PNA region. Furthermore, habitats across the PNA region are diverse ranging from estuaries, coral reefs, kelp forests, mangroves, seagrass beds, rocky shores and coastal lagoons (Morgan et al. 2005; Wilkinson et al. 2009).

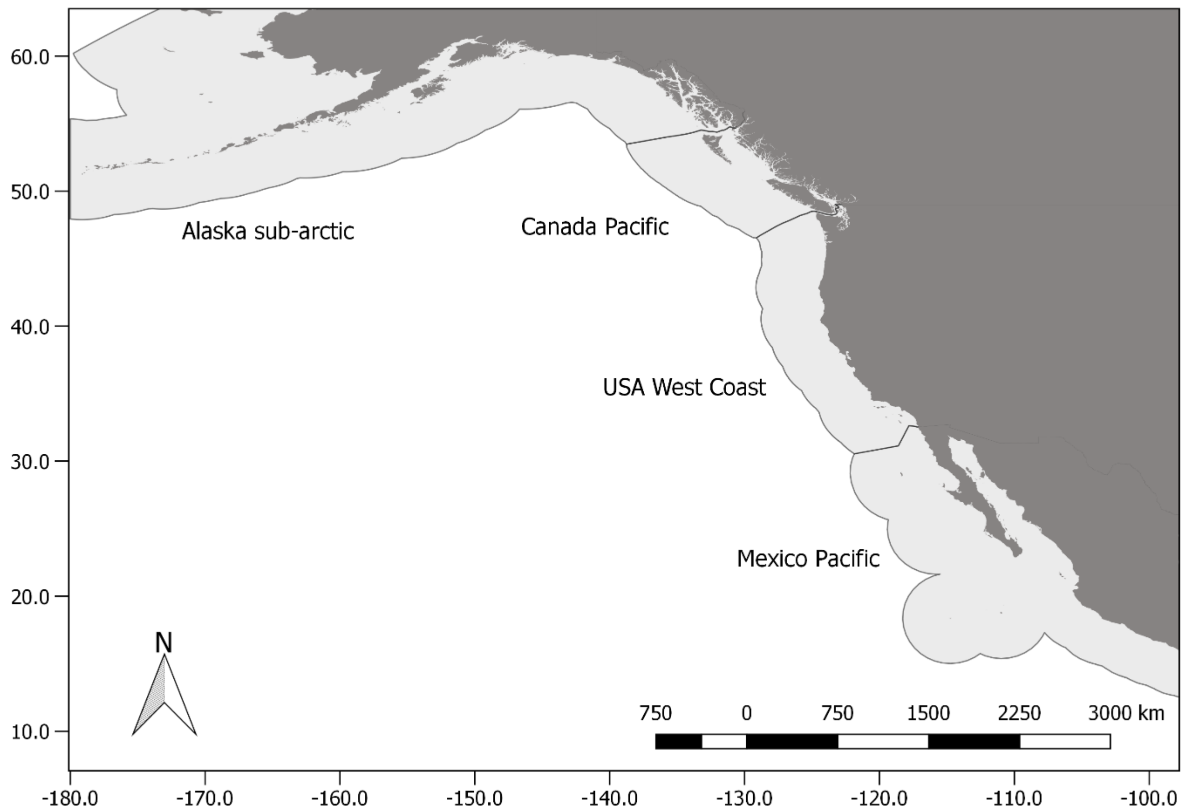


Figure 1.1: Map of the study area, Pacific North America, with its 200 nm Exclusive Economic Zone (EEZ).

1.3 Projected impacts of climate change on PNA's marine ecosystems

Generally, the waters of the PNA have been warming since the 20th century. A study by Rosenthal et al. (2013) documented the North Pacific waters to be approximately 0.65°C warmer at the time of the study compared to past decades, with the current rate of warming at the highest it has been in the past 10,000 years. Furthermore, historical data in recent decades for the North Pacific region shows an average pH decrease of about 0.02 units per decade (Feely et al. 2008) and average oxygen loss of 30 mol m^{-2} per decade (Schmidtko et al. 2017). The North Pacific region accounts for one of the largest portion of global oxygen loss (Schmidtko et al. 2017).

Ainsworth et al. (2011) modelled the effect of several climate drivers on PNA marine ecosystem and found strong evidence for synergistic effects which exacerbates the effects of climate change. Overall, these changes in ocean conditions result in a poleward redistribution of species and catch potentials in the region (Perry et al. 2014; Doney et al. 2012; Cheung et al. 2009; Pinsky and Fogarty 2012). However, as the PNA region spans over 45 degrees of latitude and encompass a variety of ecosystems, studies have revealed significant variation in climate change impacts between and within EEZs as well as seasonally and inter-annually (Ainsworth et al. 2011; Okey et al. 2014; Pörtner et al. 2014).

The PNA region is known for its climate variability from the El Nino Southern Oscillation (ENSO), the North Pacific Gyre Oscillation and the Pacific Decadal Oscillation (PDO). These transitionary phenomena can shift from warm to cool phases and fluctuate water temperatures tremendously. ENSO cycles typically last a few months, while the PDO shifts can last for decades (Mantua and Hare 2002). Climate variability is relatively short-term, while climate change is long-term, occurring over decades to millennia. Research by Overland & Wang (2007) projects the same decadal variability for Pacific waters into the future, with an additional upward trend from anthropogenic climate change.

1.3.1 Alaska Sub-arctic

Over the last 60 years, average temperatures in Alaska have risen 3.4°F, highlighting the progressive warming trend of the region (Johnson 2016). However, most of the changes in temperature was initiated by the 1976 regime shift and climate variability, which transitioned the Pacific ecosystem from a cool to a warm phase (Stewart et al. 2013).

Ocean warming is driving changes in salinity and currents, manifesting from changes in precipitation and further exacerbated by sea ice melts in the Gulf of Alaska. In particular, in the winter, precipitation is projected to shift from snow to rain (Johnson 2016). As this freshwater drains immediately into the ocean rather than gradually through snow melt in the spring months, this has implication for changing the timing of river discharge cycles (Chapin et al. 2014). Furthermore, warming leads to sea ice and glacial melt which increases freshwater influx to the marine ecosystem. As a result of the increases in influx of freshwater into the ocean, the density differences between fresh and salty water in the North Pacific promotes vertical and density stratification (Wang and Overland 2012; Pörtner et al. 2014). Enhanced stratification prevents nutrients from the deeper waters reaching the surface, ultimately limiting phytoplankton growth and causing a decrease in the net primary and upper trophic level productivity of the area (Doney et al. 2012).

Ocean acidification is also more prevalent at higher latitudes compared to tropical regions as colder waters are able to absorb more carbon dioxide. The highest concentrations of carbon dioxide have been measured in the Arctic waters (Johnson 2016; Chapin et al. 2014). This makes polar habitats, such as the Alaska sub-arctic, especially prone to declines in calcium carbonate which is required to build and maintain shells. A study projects that by 2044, Alaska's Bering Sea will no longer have enough calcium carbonate for key species to build their shells (Mathis et al. 2015).

1.3.2 Canada (Pacific)

The Canadian Pacific coast, bordering the province of British Columbia, is an ecologically diverse sub-region as it is a transition zone between the California Current upwelling system and Alaska Coastal downwelling system (Okey et al. 2013). The average seasonal sea surface temperature in British Columbia is projected to increase between 0.5 to 2.0°C by 2065 to 2078, compared to the average of 1995 to 2008 values (Foreman et al. 2014). There is presently already a strong contrast in sea surface temperatures between northern and southern boundaries of the EEZ (Amos et al. 2014), with future projections indicating large-scale ecological changes for the area and limited climate refuges or tolerable habitats that would reduce disturbances on species (Ban et al. 2016).

Similar to Alaska, warming increases glacial and mountain snow melt which alters freshwater discharges into the ocean. Additionally, precipitation is projected to increase in the winter and decrease in the summer months, prompting seasonal changes in salinity and ultimately, increasing stratification and reducing nutrient availability for primary and fisheries production (Morrison et al. 2014).

The British Columbian coast has notable seasonal upwelling and stronger winds, resulting in larger eddies and currents such as in Haida Gwaii and west coast of Vancouver Island (Crawford and Thomson 1991; Foreman et al. 2014). This brings nutrient rich waters to the shelf and surface waters, prompting increases in productivity in certain areas.

Ocean acidification and deoxygenation is a major threat facing Canada Pacific's ecosystem (Haigh et al. 2015). The Pacific North region is recorded as an area with the most acidic waters globally (Okey et al. 2015). Projections of increased ocean acidification comes at substantial economic cost to British Columbia's fish and shellfish sectors (Haigh et al. 2015). Oxygen levels along the coast is highly variable, however there are strong declines projected, specifically for the Strait of Georgia, with levels approaching thresholds for biological tolerances (Johannessen et al. 2014).

1.3.3 USA (West Coast)

USA West Coast's marine ecosystem is largely characterized by the California current system, which is among the world's most productive large marine ecosystem (Huyer 1983). The current, largely wind-driven, brings cooler water from the Gulf of Alaska (Snyder et al. 2003), as well as transport deep nutrient-rich waters to the surface. There is also considerable difference in intensity and circulation patterns between seasons; it tends to be the strongest in spring and summer months (King et al. 2011). This variation and uncertainty with the California upwelling system makes forecasting their impacts under climate change especially challenging. Overall, projections suggest substantial increases in the intensity of upwelling and changes in the seasonality as a result of changing wind patterns from climate changes (Bakun 1990; Snyder et al. 2003). While this is projected to increase food availability, the increased thermal stratification from warming ocean temperatures could also restrict the nutrients from reaching the surface (Roemmich and McGowan 1995). These contradictory effects reinforce the uncertainty in projections within this ecosystem.

Similar to the other EEZs, ocean acidification and deoxygenation are also considerable threats to marine ecosystems. Feely et al. (2008) documented the upwelling of acidified water (pH < 7.75) reaching California's inshore, surface waters. These changes in ocean chemistry had not been predicted to occur until after 2050 (Feely et al. 2008; Kelly and Caldwell 2012). A study by Cooley & Doney (2009) projects significant loss to the US shellfish industry, an economically important operation to the region, within the next 50 years under climate change. Some of the biggest losses for USA West Coast are projected for the Dungeness crab fisheries, which was worth about $113 million USD in 2011 (California Department of Fish and Game 2011). This acidification is projected to continue, with summer upwelling pH declining by 0.2-unit in 2063 compared to 2013 (Marshall et al. 2017). Furthermore, Chan et al. (2008) describe the emergence of extreme oxygen deficits and oxygen minimum zones along USA West Coast's coastal waters, limiting their productivity and altering the biochemistry of the water. The appearances of oxygen minimum zones are projected to increase with climate change, as rising temperatures decreases oxygen solubility in water (Breitburg et al. 2018). This oxygen limitation has been linked to the decline of the region's mesopelagic, deepwater fishes (Koslow et al. 2011), in addition to other species.

1.3.4 Mexico (Pacific)

There is high seasonal and inter-annual variability in salinity and temperature off Baja California due to the differences in wind patterns and currents (Durazo, 2009; Lluch-Cota et al. 2018). However, generally, Mexico's marine ecosystem is projected to see increased temperatures of 2 to 4°C and decreased precipitation by 5 to 8% by mid-century (Wilder et al. 2010). This prompts thermal stratification which reduces the nutrient availability and limits productivity (Doney et al. 2012). The increased temperature has also been linked to the whitening and loss of corals habitat. Mid-century projections also suggest a 0.5 unit reduction in pH and an expansion of minimum oxygen zones (Escobar-Briones, 2017). This leads to decalcification and prolonged hypoxia events which destroys viable fish habitats. As some of Mexico's main fisheries are associated with coral reefs, such as the red snapper and spiny lobster fisheries, the projected loss of habitat can lead to declines in catches (Martíinez Arroyo et al. 2011).

1.4 Understanding fisheries in Pacific North America

1.4.1 Catch contributions by EEZ

Fisheries production varies between different PNA EEZs and sectors, with highest catches estimated for Alaska, followed by Mexico and USA West Coast (Zeller & Pauly, 2015; www.seaaroundus.org; see Chapter 2). Canada is estimated to have the smallest contribution amongst the EEZ in the PNA region. LSF are classified as commercial and industrial vessels, usually capable of exploiting farther from shore using highly mechanized equipment (Berkes et al. 2001). Overall in PNA, average annual catches between 1990 and 2010 shows that LSF catches are higher than SSF's catches. LSF catches are mostly attributed to Alaska, while the majority (43%) of the SSF catches in PNA are caught by Mexico (Figure 1.2). As more data collection and research have been on LSF than SSF, management tools tend to focus on LSF (Berkes et al. 2001). However, SSF play an important role in employment, livelihoods and food security, despite the relatively lower contribution of SSF in terms of catch amounts (Berkes et al. 2001).

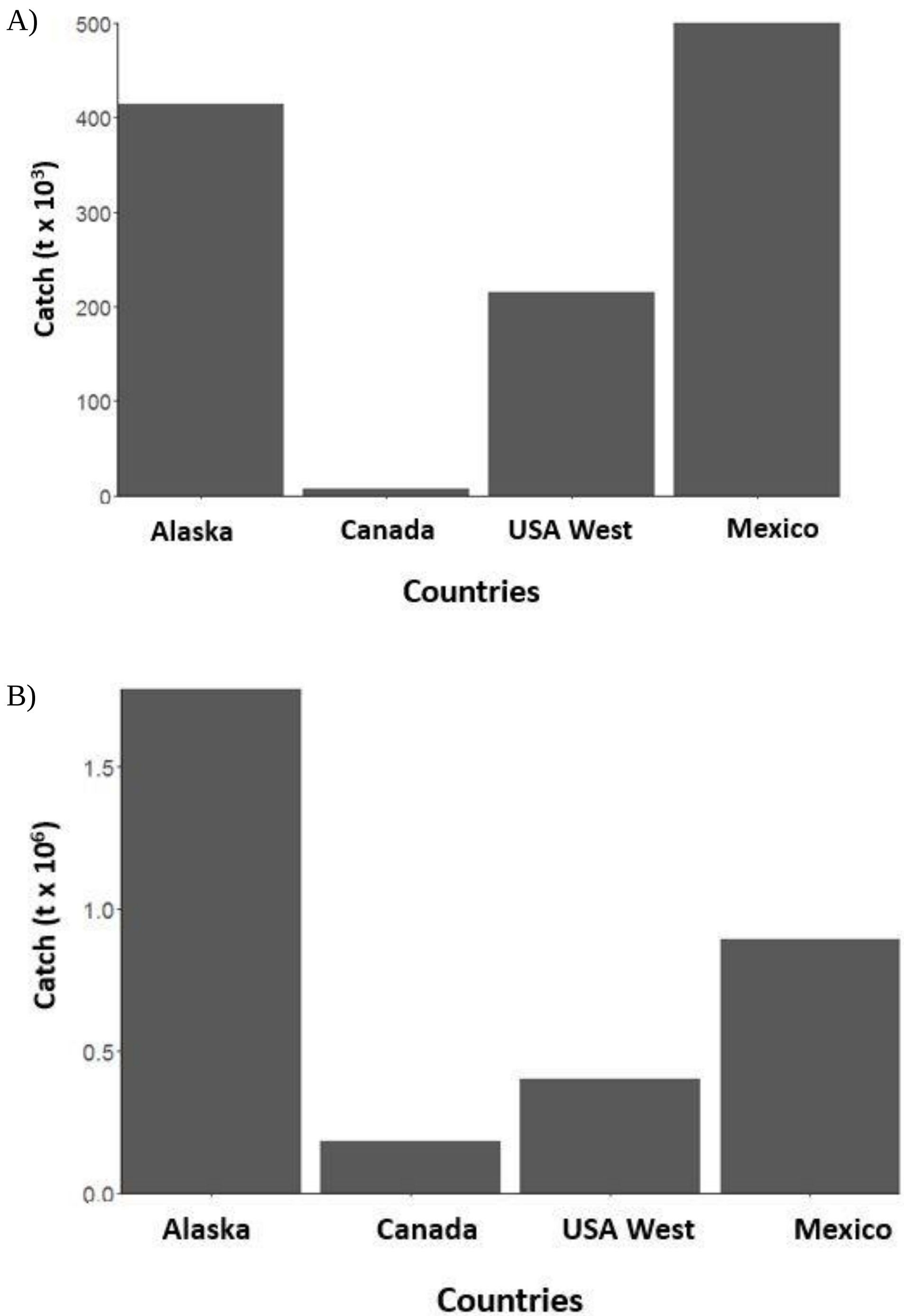


Figure 1.2: Average annual catches (years 1990 to 2010) from Pacific North America region for a) small-scale fisheries and b) large-scale fisheries in each Exclusive Economic Zone.

1.4.2 Defining small-scale fisheries

There have been several attempts to define SSF, however there is currently no universal definition for SSF (FAO 2012). Studies generally agree that common characteristics of SSF include multi-gear, multispecies, low capital, operation close to shore and labour intensive (Chuenpagdee et al. 2006; Salas et al. 2007), which invokes images of developing nations. Hence, studies often neglect to consider the presence and impact of SSF in the developed world, especially as the separation between SSF and LSF may not be as apparent as in developing countries.

Within the PNA region, there is a geographic and developmental diversity, and SSF tend to be located outside social and economic centres and/or involve participation of people that tend to be excluded from economic or political power (Charles 1991). Further, research by Gibson & Sumaila (2017) proposed a framework of determining the "small-scaleness" of British Columbia's fisheries through ranking of common SSF features. They demonstrate the prevalence of SSF in British Columbia, with Aboriginal Food, Social and Ceremonial fisheries considered to be the most small-scale. While First Nations fisheries are not considered separately within this study, rather as a component aggregated within SSF, I recognize that First Nations' fisheries have unique characteristics, governance and implications such as food sovereignty, traditional ecological knowledge and treaty rights. These are considered more thoroughly within the context of British Columbia's fisheries in Weatherdon et al. (2016).

There has been growing studies focussing on SSF, including research done by Too Big To Ignore, a global partnership to elevate the profile of SSF (www.toobigtoignore.net).

Additionally, in 2014, SSF gained international recognition and support of its importance through the FAO's Voluntary Guidelines for Securing Sustainable Small-scale Fisheries in the Context of Food Security and Poverty Eradication (the SSF Guidelines). This globally agreed upon instrument provides consensus on principles and guidelines on addressing SSF, illustrating an international priority on secure and sustainable SSF (FAO 2015).

1.5 Methodological framework

In this thesis, I use two approaches to characterize the potential impacts and vulnerabilities of climate change on PNA fisheries and compared them between SSF and LSF. For the first approach, I use a species distribution model which provides a quantitative understanding. Then, I employ the use of qualitative vulnerability assessments. The combination of methodologies provides an interdisciplinary perspective on PNA fisheries. The following section provides context and justification for their use in this thesis.

1.5.1 Species distribution models

Species distribution models (SDM) can be used to predict present and future spatial ranges and abundance of species. By inferring the existing relationship between species and the environment, species distribution models determine each species' bioclimatic envelope (or niche), which is a set of physical and biological conditions that fall within a species tolerance and preferences (Hutchinson 1957, Jones and Cheung 2010). Based on the estimated bioclimatic envelope and data on environmental conditions, SDM can be used to project potential distribution of species. Moreover, as environmental conditions change under climate change, SDM can also be applied to model shift in species distribution driven by changing environment.

There are a variety of species distribution models available with different model structures, assumptions, data requirement and uncertainties. Examples of SDMs that are commonly applied for marine species include Dynamic Bioclimate Envelope Model (DBEM), Maxent (Phillips et al. 2004) and Aquamaps (Kaschner et al. 2006).

For the purposes of this research, DBEM is used as it incorporates population dynamics and ecophysiology, and, can be used to project future fisheries production (Cheung et al. 2009; Fernandes et al. 2013; Tittensor et al. 2018). I recognize that there are variations and uncertainties between outputs of the SDMs (Robinson et al. 2017). However, multi-model comparisons by Jones & Cheung (2015) and Cheung et al. (2016) have shown that certain global variables (species invasion, local extinction and maximum catch potential) tend to be robust across SDMs or different structures of DBEM. However, I recognize the limitations from using a single model approach in this study. Jones et al. (2012) takes a multi-model approach in modelling commercial fish distributions, ultimately showing that as each SDM has a different methodology and algorithm, it is challenging to pick the "best" approach. Instead, a multi-model approach is proposed. Therefore, future studies should encompass additional SDMs to robustness of the findings to the structural uncertainties of the models (Marshall et al. 2014; L.M. Robinson et al. 2011; N.M. Robinson et al. 2017).

1.5.2 Vulnerability Frameworks

Vulnerability is defined as the state of susceptibility to harm from stresses (Adger 2006) or specifically in this case, the degree to which the fishery is susceptible to, or unable to cope with the adverse socio-ecological effects of climate change (Islam et al. 2014, adapted from

IPCC 2007). Vulnerability assessments are important tools used to understand the key components that contribute to the level of impact of climate change on a system and can help inform adaptation strategies to cope with these impacts. Vulnerability is a function of three components: exposure, sensitivity and adaptive capacity, as further discussed in Chapter 3. Overall, the countries in the PNA have a low national vulnerabilities to climate change (Allison et al. 2009). By applying a vulnerability framework, we can understand the capacity and characteristics of each component and recognize the relationships and interactions within the system.

Chapter 3 employs the use of vulnerability frameworks to understand the socio-ecological components of a fisheries, specifically in its impact on adaptive capacity. Originally, vulnerability frameworks tend to be considered as isolated ecological and social systems. In this thesis, we used a modified version of the Intergovernmental Panel on Climate Change (IPCC 2014)'s framework on vulnerability so that it accounts for the link between the ecological and social-economic dimensions. This integrated version has been applied in Cinner et al. (2013) and Marshall et al. (2010) (Figure 1.3), and further discussed in Chapter 3.

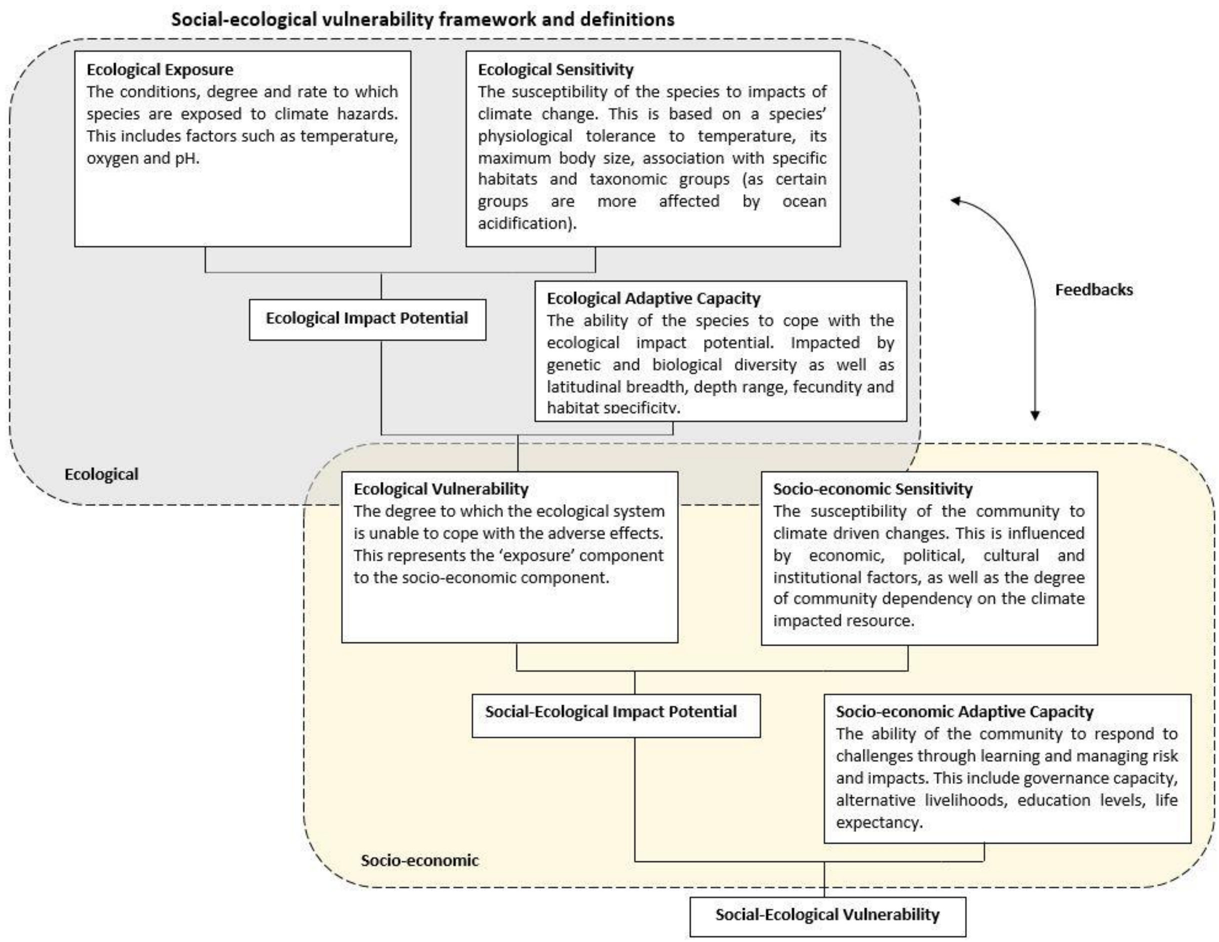


Figure 1.3: Social-ecological vulnerability framework with associated definitions. Framework and definitions adapted from Cinner et al. (2013), Marshall et al. (2010), Jones and Cheung (2018) and Fenton et al. (2007), discussed further in Chapter 3.

1.6 Thesis structure and objectives

The objective of the thesis is to answer these two research questions:

1. What are the projected impacts of alternative scenarios of climate change on the catch potential and species composition of SSF compared to LSF in the PNA region?

2. What are the commonalities and differences between SSF and LSF in their adaptive capacity to climate change impacts on fisheries catch potential and species composition?

In chapter 2, I apply the DBEM to project changes in catch potentials and distributions for PNA exploited species separated by SSF and LSF, for the upper (RCP 8.5) and lower (RCP 2.6) greenhouse gas emission scenarios, as defined in the IPCC. This chapter also improves upon taxonomic resolution of fisheries catches in climate projections by disaggregating groupings of family level or higher to species level using literature and expert sources. This resulted in projections for 312 species to year 2080.

Chapter 3 seeks to qualitatively understand which characteristics could enable fisheries to adapt to the projected ecological changes from Chapter 2. As fisheries compose of the ecological and social-economic components, this chapter takes an interdisciplinary focus by applying a vulnerability assessment framework (Cinner et al. 2013) to specific case illustrations from PNA in order to answer the research questions.

Using the vulnerability framework, the first aspect of the chapter examines the contributing factors to operational cost in Alaska's Pacific cod SSF and LSF. Operational cost is a key measure of adaptive capacity as it reflects the viability of a fisheries' profitability and continued operations.

The second aspect of the chapter seeks to understand key social-economic adaptive capacity characteristics needed, in order to capitalize on rapid ecological growth of exploited species. We apply the vulnerability framework to Monterey Bay's wetfish fishery (USA West Coast) and Sonora's jellyfish fishery (Mexico) to find common social-economic adaptive capacity traits.

2. Projecting impacts of climate change on Pacific North America's small-scale fisheries

2.1 Introduction

Climate change will have significant implications for global marine ecosystems and fisheries with multiple studies depicting shifts in species distributions and catch potentials (Doney et al. 2012; Cheung et al. 2010; Brierley and Kingsford 2009; Perry et al. 2014). While there is a tendency to take an aggregated approach in studying the effects of climate change on fisheries, understanding these climate-induced impacts on each fishing sector is essential. Specifically, small-scale fisheries (SSF) and large-scale fisheries (LSF) have distinctive characteristics that affect their vulnerability to climate change impacts. Comprehensive understanding of these fisheries sectors under climate change will contribute positively to resource management, and consequently, help inform policies on fisheries, livelihoods and food security.

Globally, SSF, encompassing the artisanal and subsistence sectors, accounts for 90% of employment in the fishing industry and composes 90% of fishing vessels (Béné 2006; Chuenpagdee et al. 2006). Studies have demonstrated that SSF have greater positive implications for society and economic viability than its large-scale fisheries (LSF) counterparts (Gibson and Sumaila 2017; Schuhbauer and Sumaila 2016). Yet, research and policies on SSF are often marginalized by efforts that largely focus on industrial operations (Pauly 2006; Jacquet and Pauly 2008; Schuhbauer and Sumaila 2016). Therefore, taking a comparative approach in analyzing each sector will illuminate any potential differences in patterns that might otherwise be masked in a cumulative study.

Pacific North America (PNA) is selected as the study region because of its biological and social-economic importance — it is identified as one of the fourteen ecologically significant regions by the Commission for Environmental Cooperation (Morgan et al. 2005). PNA includes four different Exclusive Economic Zones (EEZs): Alaska Sub-Arctic, Canada Pacific, United States Pacific and Mexico Pacific (refer to Figure 1.1). Majority of production occurs in the inshore areas where most fishing operations are shown to occur in the EEZs, which is the area of focus in this study (Froese et al. 2000). Further, as climate change is known to have a more profound effect across latitudes and as species migrate across national borders (Cheung et al. 2015), the three countries in the PNA (United States, Canada and Mexico) have an inherently linked ecosystem and hence, an integrated regional focus is necessary to assess overarching trends and effects (Morgan et al. 2005).

Within the PNA region, the definitions of SSF are highly varied as these countries and their fisheries have different historical developments and exploited species. Currently, there is no established global definition for small-scale fisheries, therefore what constitutes SSF in one country could be classified as LSF in another. International agreements like the SSF Guidelines (FAO 2014b) and State of the Fisheries and Aquaculture (SOFIA) (FAO 2014a) have provided general, guiding characteristics, including ascertaining which activities and operators are considered small-scale. It is up to each country to establish their own specific definition. As summarized in Chuenpagdee et al. (2006), the majority of nations have defined their SSF as follows (Table 2.1). While there are ongoing research and efforts towards identifying and establishing common SSF attributes within and across nations (Gibson and Sumaila 2017, Gibson 2017, FAO 2014), for the purposes of this research, the country-specific definitions, in relation to their estimated catches, as established in the *Sea Around Us* – a research initiative aiming to re-estimate global fisheries catches (Zeller and Pauly 2015; Doherty et al. 2015a; Ainsworth 2015; Doherty et al. 2015b; Cisneros-Montemayor et al. 2013) – was used in this study (Table 2.2). Generally, small-scale fisheries constitute the artisanal (small-scale commercial) and subsistence (small-scale non-commercial) sectors, while large-scale sector composes of the industrial sector (Zeller et al. 2016).

Table 2.1: Summary of common definitions of small-scale fisheries, extracted from (Chuenpagdee et al. 2006)

Key features	**Common definitions**
Boat size	Between 5-7m; less than 10, 12 or 15m
Boat gross registered tonnage	Less than 10 gross registered tonnage
Size of engine	Less than 60 HP
Boat type	Canoe, dinghy, non-motorized boat, wooden boat, boat with no deck, traditional boat
Gear type	Coastal gathering, fishing on foot, beach seine, small ring net, handline, dive, traps
Distance from shore	Between 5-9m, within 13km, up to 22 km
Water depth	Less than 10, 50 or 100m depth
Nature of activity	Subsistence, traditional, local, artisanal
Number of crew	2-3; 5-6
Travel time	2-3 hours from landing site

Table 2.2: Definition of SSF in each EEZ within PNA as identified by *Sea Around Us* reconstruction reports by Doherty et al. (2015a), Ainsworth (2015), Doherty et al. (2015b) and Cisneros-Montemayor et al. (2013).

Region	Definition
Alaska	SSF are defined by gear type, with small-scale fisheries having non-towed gear, while large-scale fisheries uses towed gear.
Canada Pacific	SSF are defined by species based on data reported by the Department of Fisheries and Oceans Canada (DFO) through the Pacific Regional Data Unit, creel and logbook surveys.
USA West Coast	Within SSF, subsistence is defined by National Marine Fisheries Services (NMFS) and Washington Department of Fish and Wildlife (WDFW) data and artisanal is split from large-scale commercial catches based on the Sea Around Us definition of a maximum of 50 km from the coast or 200 m depth, whichever comes first. Data is calculated separately by state.
Mexico Pacific	SSF is defined at species-level as reported in Cisneros-Montemayor et al. (2013).

Further, within the PNA region, catch amount varies significantly between EEZs with the total *Sea Around Us* reconstructed catch from the year 2000 depicted in Figure 1.2. This figure illustrates the varying magnitudes that each countries' fisheries contribute to the region. Majority of catches in the PNA region are caught by the LSF. In Mexico, SSF compose 38% of catches and in USA West, SSF compose 34% of catches. Alaska and Canada have the smallest portion of SSF relative to LSF with 19% and ~1%, respectively. Across the PNA region, majority of SSF catches are attributed to Mexico and Alaska, while LSF are predominately active within Alaska's EEZ.

Climate change is projected to have significant and varied impacts to PNA's ecosystems. Overall, the increased greenhouse gases will affect several key drivers of climate change such as increased atmospheric CO_2, increased sea surface temperatures, sea level rise, sea ice melt, declines in salinity and changes to ocean circulation (Scavia et al. 2002; Doney et al. 2012). Further, deoxygenation and ocean acidification is a particularly high threat along the PNA coast as the waters have a naturally low pH (Haigh et al. 2015). While the above description captures general trends of marine ecosystems applying for the PNA region, the specific region analyzed within this chapter spans over 45 degrees of latitude and composes a diverse range of ecosystems. There are specific localized effects and variability within sub-regions. For instance, in USA West, climate change is projected to increase seasonal winds and promote the upwelling of nutrient-rich, productive waters, while in Alaska, there are generally more freshwater outputs from river discharges arising from glacier and mountain snowpack melts, leading to declines in salinity. It is important to consider that these drivers of climate change can further intensify other existing stressors on marine ecosystems such as pollution or natural disasters (Scavia et al. 2002).

As species have specific environmental preferences and tolerances, these projected changes to ocean conditions, as driven by climate change, will prompt shifts from their current range as they seek new habitat that continues to meet their physical requirements. Species distribution models (SDM) can be used to understand and project these shift. By capturing the existing relationship between species and the environment, species distribution models determine each species' habitat suitability and can infer the implications of shifting environmental conditions on biomass, range and distributions. There are a variety of species distribution models available, such as Dynamic Bioclimate Envelope Model (DBEM), Maxent and Aquamaps. However, for the purposes of this research, DBEM is implemented as this model includes population dynamics and ecophysiology, and hence, can be used to project fisheries production (Cheung et al. 2009; Fernandes et al. 2013; Tittensor et al. 2018).

By taking a species distribution modelling approach, this chapter seeks to quantitatively understand the projected impacts of alternative scenarios of climate change on the catch potential and species composition of SSF compared to LSF in the PNA region. More specifically, the objectives include:

(a) What are the projected impacts of climate change on SSF and LSF in the PNA?
(b) Are there latitudinal patterns of change in maximum catch potential and species richness across the different countries in the PNA?
(c) Which exploited species are projected to be positively or negatively impacted by climate change?
(d) What are the implications of these ecological projections for PNA's SSF and LSF?

Such comparative approach can illuminate otherwise hidden trends of projected shifts in catch potential and species diversity from SSF. A methodological challenge to undertake fine-scale projection of climate change impacts on fisheries was the taxonomic aggregation of catches that may result in exclusion of less commercially valuable species – some of these species may be relatively more important for SSF than LSF. Thus, this chapter also attempts to address this potential bias by improving the taxonomic resolution for species-specific climate impact projections. The results will allow for a more comprehensive understanding of climate change impacts on SSF in the region and inform management decisions.

2.2 Materials and methods

The methodology described below details the steps taken to project future changes in maximum catch potential and species richness for the majority of SSF and LSF exploited species in the PNA region. Beginning with *Sea Around Us* reconstructed catch for the region, we use literature, national information and recognized databases such as FishBase and Encyclopedia of Life (EOL) to improve species taxonomic resolution, map current distributions and project future changes through a species distribution model for four EEZs in Pacific North America. The projections are implemented for two climate emission scenarios and under two Earth System Models to account for intermodal variability. The projections derived are by 0.5^{o} latitude x 0.5^{o} longitude grid cells and projected to year 2090.

2.2.1 Historical catch data from the Sea Around Us

Historical marine fisheries catch data for 1990-2010 by sectors were obtained for the four EEZs in the PNA region from the *Sea Around Us* databases (www.seaaroundus.org). As globally reported fisheries catch to the Food and Agricultural Organization (FAO) does not account for illegal, unreported catches and discards, *Sea Around Us* reconstructed catches were utilized for a more comprehensive source of marine fisheries catches. The methodology for the reconstruction of this fisheries data can be accessed in the following reports (Doherty et al. 2015a; Ainsworth 2015; Doherty et al. 2015b; Cisneros-Montemayor et al. 2013). As this study focuses on catch potential, by-catch and discards, where available, were included in the study, however they were accumulated and analyzed alongside landings data. This includes catches of marine finfish and invertebrates.

I recognize that small-scale fisheries in different regions of the world may constitute a variety of vessel types and capacities, *Sea Around Us* methodology states that each countries' definition is used where possible. When a country's definition is unavailable, the reports used the *Sea Around Us* definition of operations in domestic waters, within an EEZ with a maximum of 50 km off the coast or 200 m depth (whichever comes first) (Zeller et al. 2016). More specifically, the distinction and approaches used to disaggregate SSF and LSF catches for each EEZ in the PNA region is summarized in Table 2.2.

2.2.3 Disaggregation of catch to species level

The fisheries data from the *Sea Around Us* are reported with taxonomic grouping. Certain catches were already reported to species level (n = 109), however there are classifications that are often reported at higher levels such as at family or genus level. For example, a large portion of the catch is reported as "Miscellaneous marine fishes" or "Perciformes." These larger classifications are refined to species level using information from literature and databases such as FishBase (www.fishbase.org) and SeaLifeBase (www.sealifebase.org). This disaggregation was done separately for each EEZ and sector as catch composition and species exploited can vary between countries. For each EEZ, local sources were prioritized and FishBase or SeaLifeBase were used to confirm commercial or subsistence exploitation. Subsequently, catches in higher taxonomic groupings were disaggregated equally between species.

After disaggregation, there were 417 unique species identified in the PNA region. For the purposes of this study, the species composing the top 70% of catches in each EEZ and sector were selected for subsequent analysis. These 312 species – comprising of marine fin fishes and invertebrates are summarized in Appendix A. This analysis is not intended to be a complete account of all species exploited by the large-scale and small-scale fisheries in the region, instead this represents a summary of key exploited species in the region to illustrate regional and temporal trends.

2.2.4 Current distributions of species

Knowledge of current species distributions are required to project future changes. Of the 312 species to analyze, 115 species had known distribution ranges previously developed with the detailed algorithm in Close et al. (2006), as updated in Palomares et al. (2016). The remaining 198 species were modelled following the same methodology of Close et al. (2006) and Palomares et al. (2016). Briefly, this algorithm estimated species distributions by applying a set of filters: 1. FAO area; 2. latitude range; 3. range-limiting polygons; 4. depth range; 5. habitat preferences; 6. equatorial submergence. Range-limiting polygons were drawn in QGIS (version 2.18.9) based on habitat information and ranges from IUCN Red List of Threatened Species (IUCN 2018). The species and habitat parameters for input into the algorithm are summarized in Appendix B with input parameters including species depth, latitudinal range limits and habitat association factors. Based on these input, the algorithm created a map of relative abundance on a 0.5^o latitude x 0.5^o longitude grid map for each species. Data for these filters were obtained primarily from FishBase, SeaLifeBase, Encyclopedia of Life (2018) and Ocean Biogeographic Information System (2018). For species with limited available parameters, data from other species within the same family group or genus were substituted.

2.2.5 Future distributions using the Dynamic Bioclimate Envelope Model

The DBEM is a SDM that connects habitat suitability to spatial and temporal populations (Cheung et al. 2016). In this study, it was used to project future changes in maximum catch potential and spatial distributions for the 312 studied species. Maximum catch potential is defined as the maximum exploitable catch of a given species assuming that current geographic range and fisheries selectivity are unchanged (Cheung et al. 2010). The detailed algorithm and methodology can be found in Cheung et al. 2008b; Cheung et al. 2009; Cheung et al. 2016.

In summary, the model involves seven steps as summarized below:

1. The current (1970-2000) distribution of commercially exploited species were produced using the *Sea Around Us* algorithm by (Close et al. 2006). The algorithm predicts the abundance and maximum catch potential of each of the 312 species on a 0.5^{o} latitude x 0.5^{o} longitude grid based on its known FAO statistical area, latitudinal range, species' depth range and expert-drawn polygons encompassing their known occurrences. It is further refined by habitat parameters (Appendix B), such as affinity for certain habitats like coral or shelf (inner and outer).
2. An index of habitat suitability for each species in each spatial cell from temperature, bathymetry, specific habitats, salinity and sea ice with 30-years average from 1971 to 2000. Then, DBEM estimated temperature preference profile or the thermal physiological performance of a species, by overlaying species distribution with seawater temperature. This resulted in a calculation of the relative abundance for each year from 1971 to 2000 and a TPP for each species.

3. The population carrying capacity is a function of the unfished biomass of the population, the habitat suitability and the net primary production. The top ten annual catches calculated to maximum sustainable yield (MSY).
4. DBEM calculates the average mass of the individual of a population in a given spatial cell. The model simulated changes in temperature and oxygen content that would affect growth and body size of the individual using a sub-model derived from a generalized von Bertalanffy growth function.
5. DBEM simulated changes in relative abundance and biomass based on population carrying capacity, intrinsic population growth and the advection-diffusion of adults and larvae of the population driven by ocean conditions. Movement and dispersal of adult and larvae modelled through advection-diffusion-reaction equation for larvae and adult stages. Larval movement is determined by the predicted pelagic larval duration. Population growth was represented by a logistic function.
6. By implementing a fishing mortality rate required to achieve MSY for each species, we can then predict a maximum catch potential.

Changes in annual maximum catch potential for each species on a 0.5^o latitudinal and 0.5^o longitudinal grid cell. The model does not include trophic interactions, varying fishing mortalities and dynamic fishing responses.

2.2.5.2 Representative Concentration Pathways

The DBEM was modelled under the two Representative Concentration Pathways (RCP) scenarios; RCP 8.5 (‘business-as-usual’ high emission scenario) and RCP 2.6 (‘strong mitigation' low emission scenario). These RCP scenarios represent the range of projected carbon emission scenarios developed for the Intergovernmental Panel on Climate Change (Moss et al. 2010), thus encompassing a range of potential climate change scenarios that are widely used in climate change impact assessments. These RCP scenarios captures the uncertainty associated with future climate projections due to variability in greenhouse gas emissions. The RCP 2.6 is a lower emission 'strong mitigation' scenario in which the radiative forcing trajectory peaked at $3W \cdot m^{-2}$ before 2100, followed by a decline to $2.6W \cdot m^{-2}$ by 2100. The RCP 8.5 is a high emission 'business-as-usual' scenario with rising radiative forcing pathway leading to $8.5W \cdot m^{-2}$ by 2100.

2.2.5.3 Climate Data from Earth System Models

In order to assess the sensitivity of the analysis to uncertainties of projecting environmental conditions and to explore intermodal uncertainty, each RCP scenario is computed using two different Earth System Models (ESM). These models represent variations in responses to climate forcing factors, such as aerosols, solar irradiance and mixing of gases (Randall et al. 2007). One model developed at Geophysical Fluid Dynamics Laboratory (GFDL; Dunne et al. 2014): GFDL ESM 2G and the other at Institut Pierre Simon Laplace (IPSL; Dufresne et al. 2013): IPSL-CM5-MR. The model outputs were interpolated onto a 0.5º latitude x 0.5º longitude grid using bilinear interpolation method (Cheung et al. 2016) The two models' outputs for changes in surface and bottom sea water temperature, oxygen concentration, salinity, net primary production, surface advection and sea ice concentration under the two RCP scenarios, as discussed above, were applied to explore the uncertainty associated with variations in the climate data.

2.2.6 Projections to species' maximum catch potentials and species richness

The disaggregated species-level *Sea Around Us* catch (from 2.2.3) is applied to the projected changes in maximum catch potential from DBEM (2.2.5) for years 2000 to 2090. The analyses, performed in R (version 1.0.136), were done separately for each type of fishery (large-scale and small-scale), climate models (GFDL and IPSL) and RCP scenarios (8.5 and 2.6), resulting in a spatial projections of future maximum catch potential and species distributions (on 0.5^o x 0.5^o grid of ocean). To focus on the long-term mean changes and reduce in influences of possible inter-annual and decadal variability (Mantua and Hare 2002; Chavez et al. 2018), a 20-year moving span was averaged, resulting in a time period ranging from 2000 (average between 1991-2010) to 2080 (average between 2071-2090).

Using the above processed maximum catch potentials, catch potentials in each EEZ, for each RCP scenario, earth system model and LSF/SSF were plotted in a map to visualize the percentage changes in maximum catch potential between year 2080 and 2000. The top 10 exploited species were also isolated and analyzed separately to observe catch trends.

Subsequently, changes in species diversity (richness) were analyzed for the PNA region. On an individual species basis, the spatial results from above were used to project presence of species ('1') and absence of species ('0'). Presence and absence in each 0.5^o x 0.5^o grid in each year were indicated by projected abundance of the species being greater than 0 and equal to 0, respectively. The difference between future and present time was taken to illustrate the changes in species occurrence in each spatial cell. The results were summed for all species to show the changes in species richness within the PNA region.

2.3 Results

The following results are presented first for the overall PNA region, and subsequently for each EEZ. The results are expressed as a mean between the GFDL and IPSL ESM. The GFDL model produces results on the upper range of the change in maximum catch potential in the 21st century under climate change while IPSL results in lower, more negative values.

2.3.1 Changes in maximum catch potentials in the PNA region

Overall across the PNA region, the relative maximum catch potential for 2080 relative to 2000 (20-year averages), was projected to decrease for LSF (RCP 2.6: -7.2% [-14.2% to -0.1%]; RCP 8.5: -10.7% [-29.6% to 8.3%]) and increase for SSF (RCP 2.6: +1.7% [0.9% to 2.4%]; RCP 8.5: +16.7% [14.3% to 19.0%]). Comparison of projection ranges, indicating intermodal variability of ESM, between SSF and LSF reveal larger variability for LSF.

IPSL consistently yields lower change in maximum catch potentials relative to GFDL (Appendix C). Ultimately, this suggests that species exploited by the LSF are more prone to variation in projections of ocean variables between ESM.

Further, there is a strong positive correlation between change in maximum catch potential and latitudes for both SSF and LSF in the high emission scenario, RCP 8.5. The relationship is less apparent in the low emission scenario of RCP 2.6 (Appendix D).

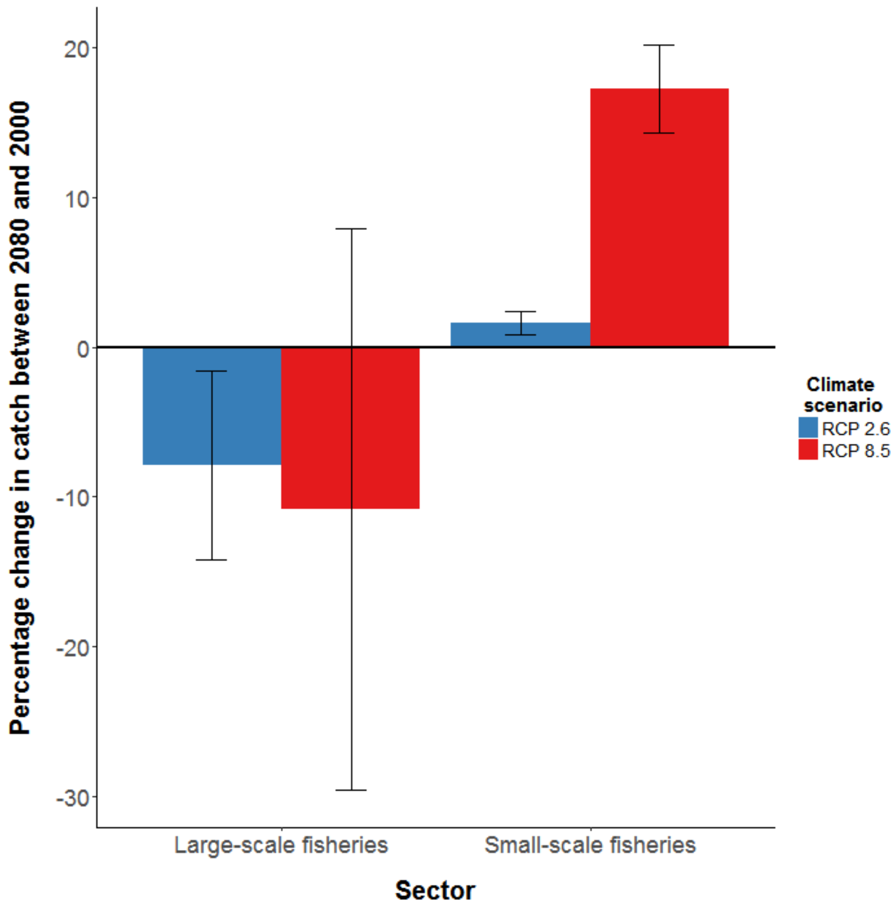


Figure 2.1: Percentage change in maximum catch potential in Pacific North America between 2080 and 2000 for large-scale fisheries and small-scale fisheries under Representative Concentration Pathways (RCP) 2.6 and 8.5.

The majority of exploited species by the SSF have projected decrease in their maximum catch potential between 2000 and 2080 (RCP 2.6: 48.4% to 86.4%; RCP 8.5: 45.0% to 79.8%). (Appendix E) Likewise, maximum catch potential of the majority of LSF species are projected to decreases (RCP 2.6: 28.0% to 80.5%; RCP 8.5: 36.6% to 76.1%) (Appendix F).

Despite these general decreases in maximum catch potentials observed across the majority of exploited species in the PNA region, it is important to note that the results are largely dominated by a few key species in both sectors that constitutes a high proportion of the catch

(Figure 2.2). The SSF sector is largely dominated by catches of California market squid (*Loligo opalescens*; 20.3% of catch), Pacific cod (*Gadus macrocephalus*; 19.4%) and pink salmon (*Oncorhynchus gorbuscha*; 11.0%), while the LSF species are mainly composed of Alaska pollock (*Theragra chalcogramma*; 46.8%), North Pacific hake (*Merluccius productus*; 11.1%) and Pacific cod (*Gadus macrocephalus*; 4.38%). This explains the contrasting increase in maximum catch potentials seen in the SSF, which is largely attributed to drastic increases in California market squid (*Loligo opalescens*) and cannonball jellyfish (*Stomolophus meleagris*).

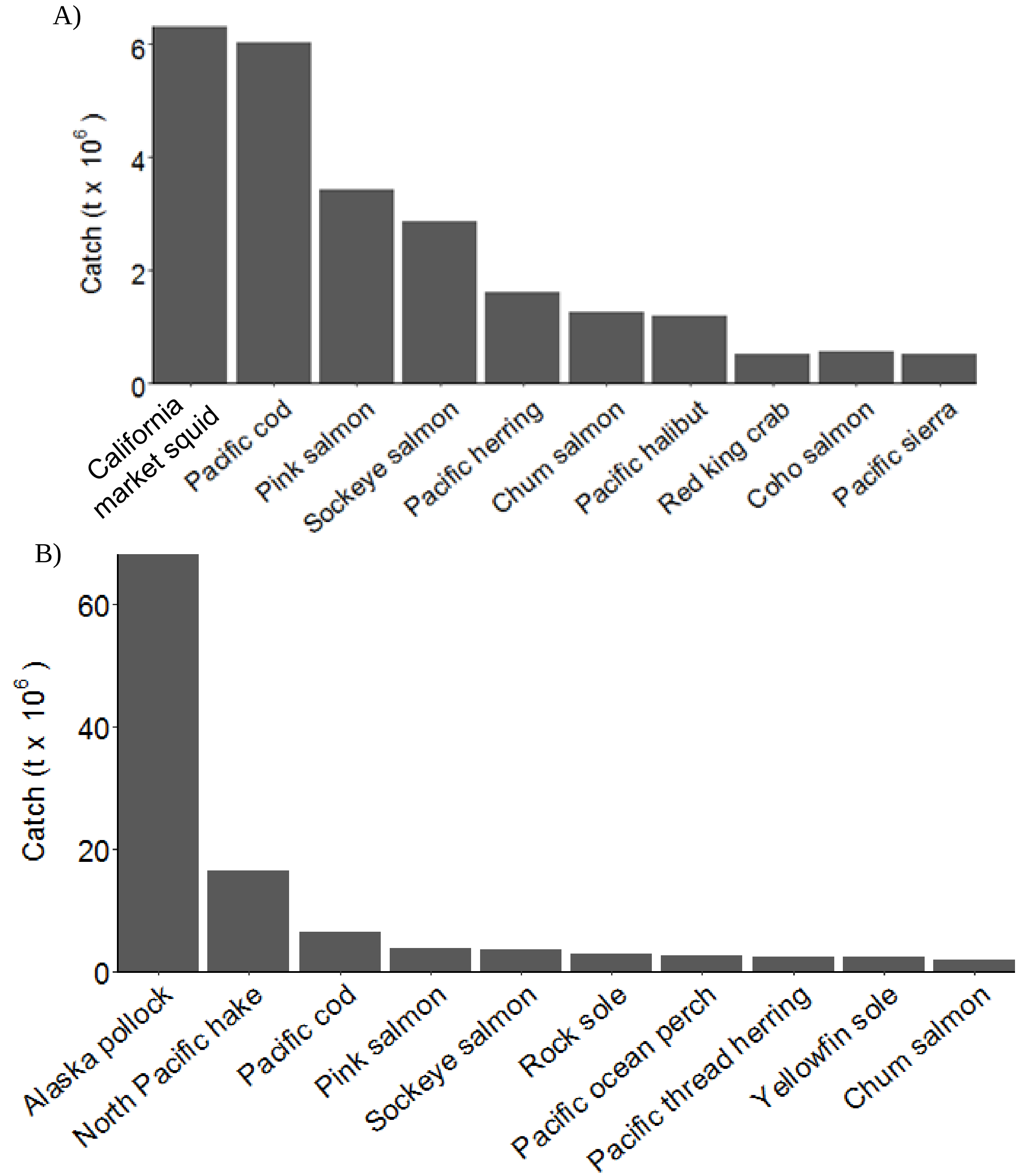


Figure 2.2: Top 10 species exploited in Pacific North America's EEZ by (a) small-scale fisheries; and (b) large-scale fisheries within the years 2080 and 2000.

The accumulated increases in projected maximum catch potential for the SSF was largely attributed to the increase in maximum catch potential for California market squid by 2080 relative to 2000 (Table 2.3). Other top exploited species were projected decrease in maximum catch potentials, e.g., Pacific cod (*Gadus microcephalus*), pink salmon (*Oncorhynchus gorbuscha*) and sockeye salmon (*Oncorhynchus nerka*) (Table 2.3; Figure 2.3a).

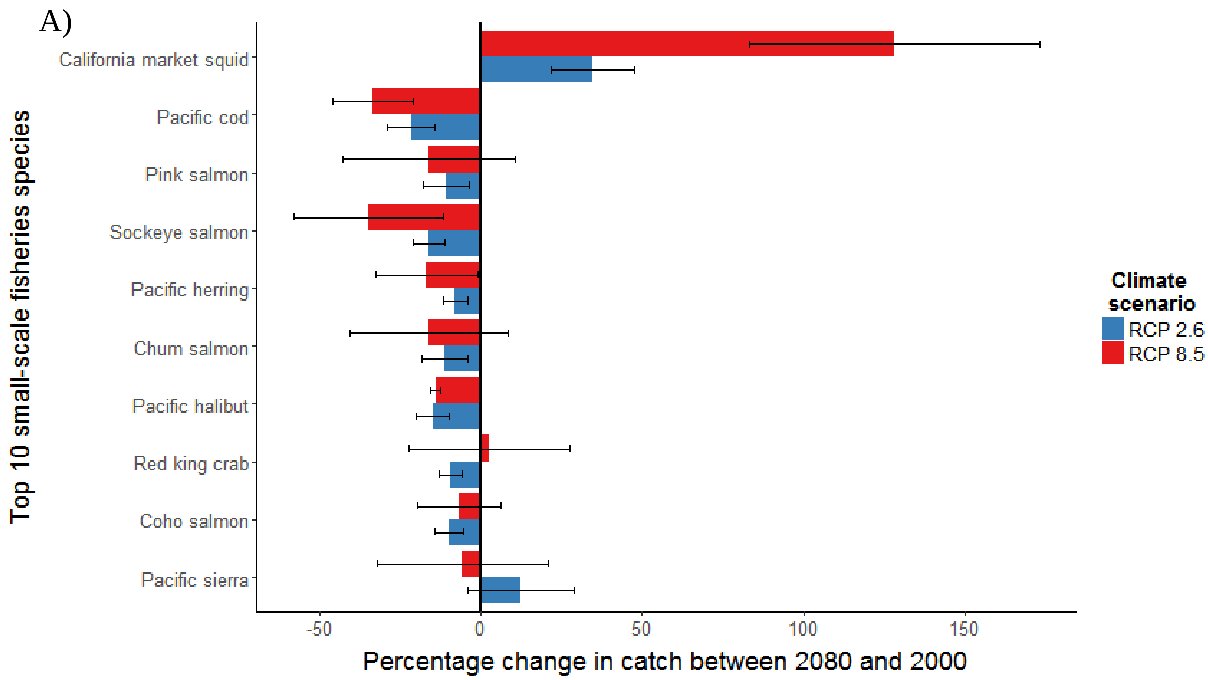
Table 2.3: Changes in maximum catch potentials between 2080 and 2000 for top species in Pacific North America's small-scale fisheries.

	RCP 2.6	RCP 8.5
California market squid	34.7% [21.7% to 47.8%]	128.2% [83.3% to 173.1%]
Pacific cod	-21.7% [-29.1% to -14.3%]	-33.4% [-45.8% to -21.0%]
Pink salmon	-10.7% [-17.9% to -3.6%]	-21.7% [-29.1% to -14.3%]
Sockeye salmon	-16.1% [-20.9% to -11.4%]	-34.9% [-58.1% to -11.6%]

Among the top 10 LSF exploited species, most were projected to experience a decrease in maximum catch potential between 2000 and 2080. While Pacific thread herring was expected to increase slightly, the following top LSF species were projected to decrease in maximum catch potential: Alaska pollock (*Theragra chalcogramma*); North Pacific hake (*Merluccius productus*) and Pacific cod (*Gadus microcephalus*) (Table 2.4; Figure 2.3b).

Table 2.4: Changes in maximum catch potentials between 2080 and 2000 for top species in Pacific North America's large-scale fisheries.

	RCP 2.6	RCP 8.5
Pacific thread herring	10.8% [3.3% to 18.4%]	-8.5% [-18.6% to 1.7%]
Alaska pollock	-9.69% [-18.9% to -0.5%]	-15.3% [-45.2% to 14.6%]
North Pacific hake	-9.0% [-14.6% to -3.4%]	-13.6 [-14.8% to -12.5%]
Pacific cod	-19.4% [-29.1% to -9.8%]	-31.4% [-45.8% to -16.9%]



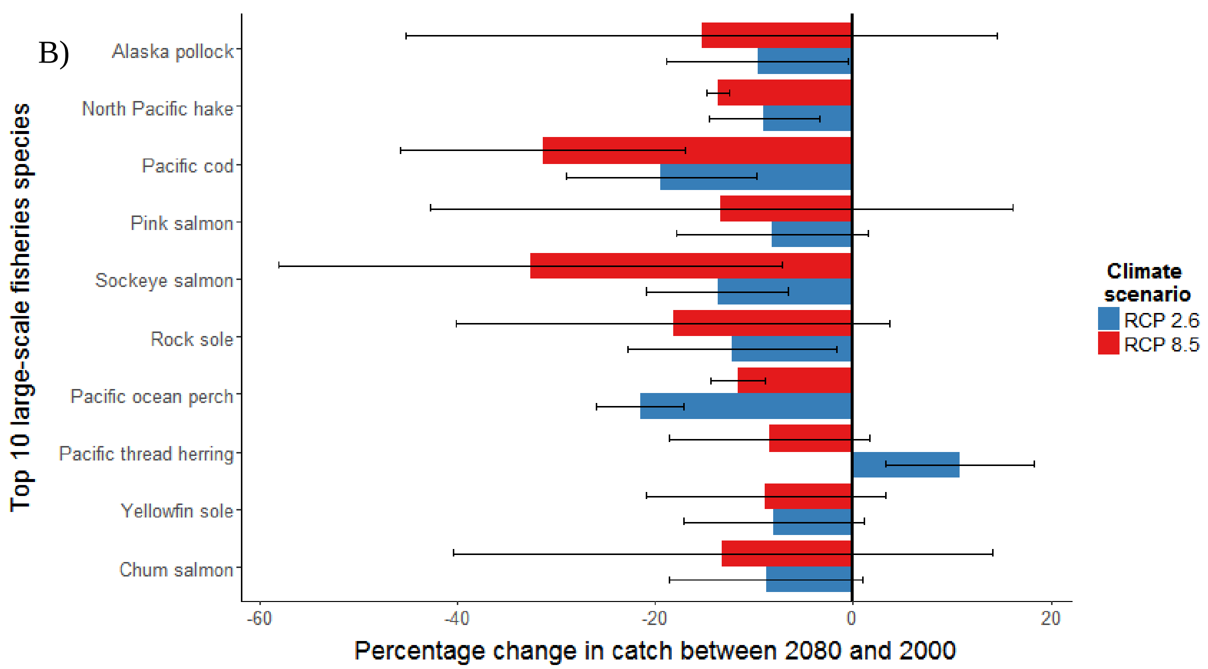


Figure 2.3: Percentage change in the maximum catch potential of top exploited species in Pacific North America's EEZ between 2080 and 2000 by (a) small-scale fisheries; and (b) large-scale fisheries. Species ranked in order of their catch amount with the species composing the majority of the catch at the top.

There was high overlap (241 species; 77.0% of all the exploited species) in species composition between LSF and SSF in the PNA region as both fisheries operated within the same fishing area. Overall in the PNA region, LSF had 38 unique species composing 6.9% of the total LSF catch, while SSF had 34 unique species composing 1.35% of the total SSF catch. Therefore, the resulting differences we observed in maximum catch potentials between SSF and LSF were attributed to the varying catch amount and relative composition of exploited species in each sector rather than differences in species composition.

Changes in maximum catch potential across time series in PNA

Regionally, while the model projected fluctuations in maximum catch potentials in the 21st century, maximum catch potential was projected to increase generally relative to the present levels for SSF and decrease relative to present levels for LSF (Figure 2.4). The model projected increases in maximum catch potential for SSF in the first half of the 21st century under both RCP 2.6 and RCP 8.5. However, changes in maximum catch potential was projected to diverge drastically from 2070 onward with RCP 8.5 surpassing RCP 2.6 around 2068. For LSF, maximum catch potential was projected to drop from 1.7 million tonnes in the 2060s to around 1.6 million tonnes by 2080 under RCP 2.6. In contrast, RCP 8.5 was projected to increase from 1.7 million in the 1960s to 1.73 million by the end of the 21st century.

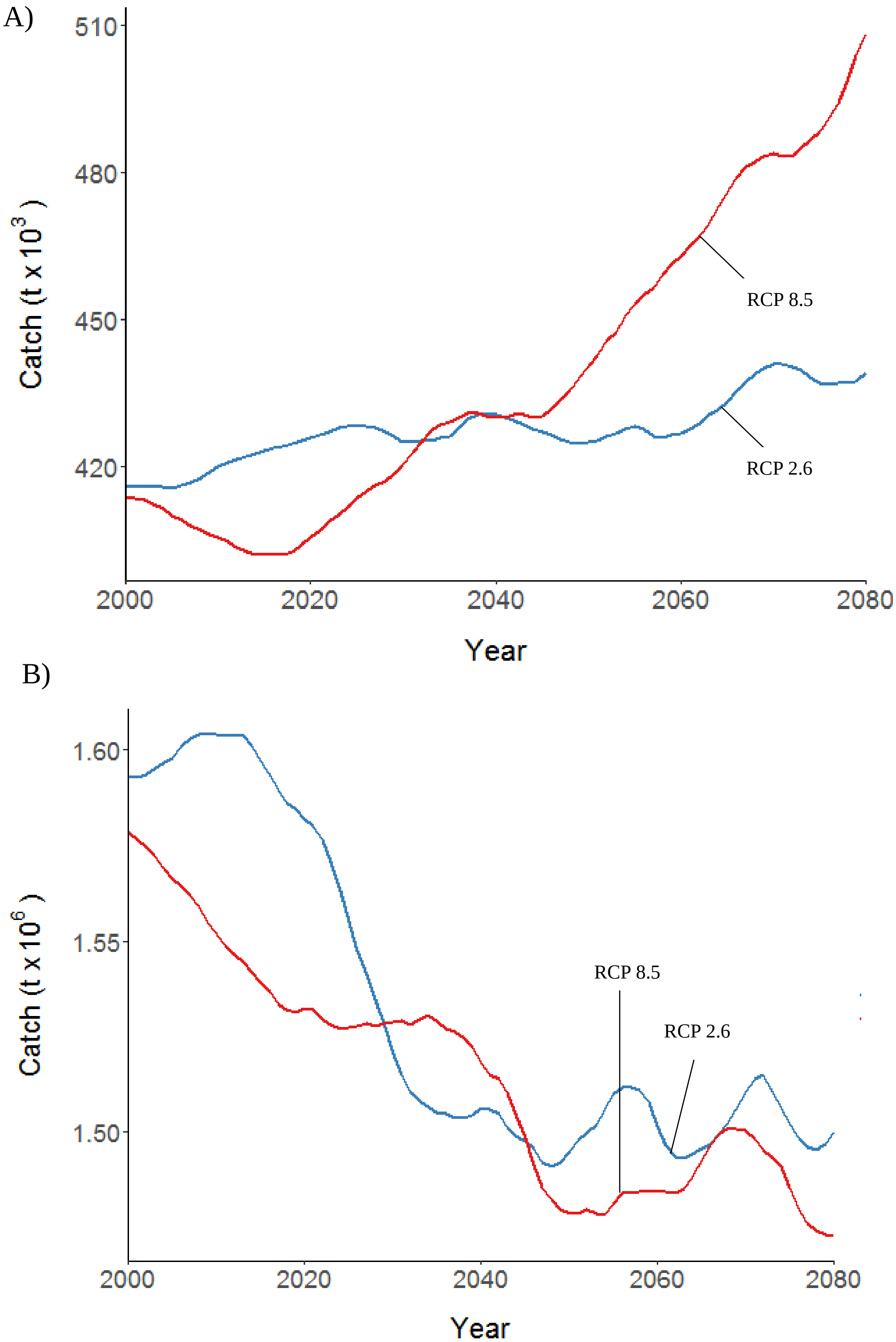


Figure 2.4: Time series changes (%) in maximum catch potential 2080 relative to 2000 for Pacific North America region under low (RCP 2.6; blue) and high (RCP 8.5; red) climate change scenario for (a) small-scale fisheries and (b) large-scale fisheries.

Overall, the contribution of SSF's catches to the total regional catch are projected to steadily increase through the time period. Under RCP 2.6, SSF catches contribute 20.7% to the PNA region in 2000 and are projected to reach 22.6% by 2080. Under RCP 8.5, SSF catches similarly contribute 20.7% in 2000 and are projected to surpass RCP 2.6, reaching 25.7% to the total regional catch by 2080 (Figure 2.5).

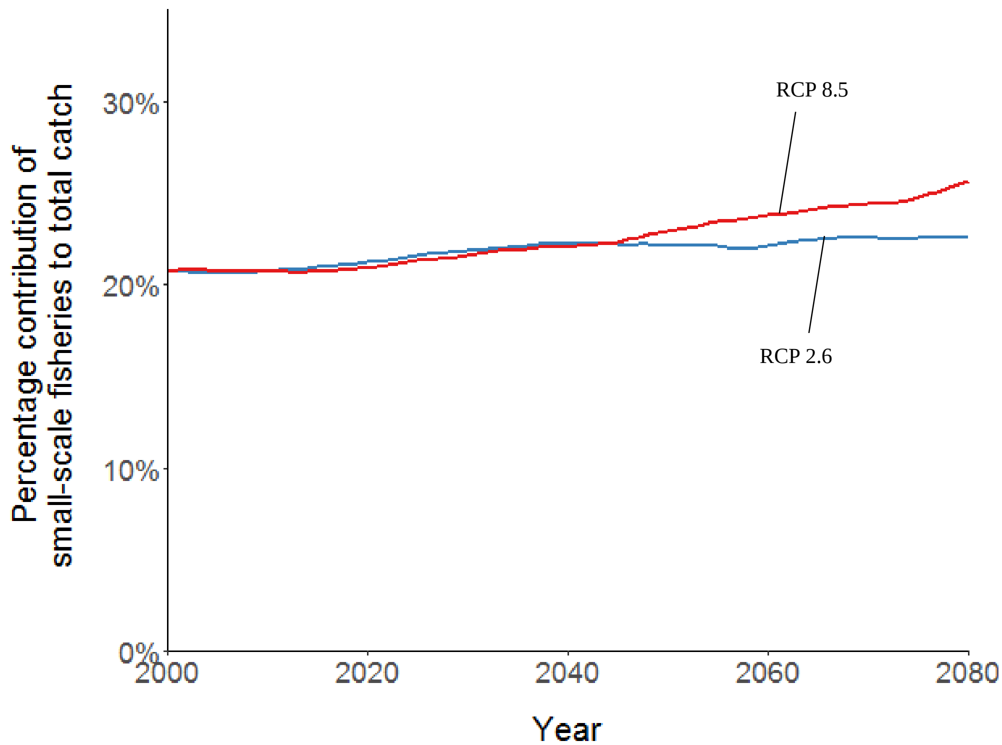


Figure 2.5: Proportion of small-scale fisheries catches to Pacific North America's regional total across the time period (2000-2080) under RCP 2.6 (blue) and RCP 8.5 (red).

2.3.2 Alaska Sub-arctic

Changes in maximum catch potentials in Alaska were projected to have large variability between sectors, climate scenarios and earth system models (Figure 2.6). For SSF in Alaska, maximum catch potential was projected to increase substantially under RCP 8.5 by 2080 relative to 2000 (19.5% [7.6% to 30.7%]) while maximum catch potential was projected to decrease for

RCP 2.6 in the same time period (RCP 2.6 = -11.5% [-14.1% to -9.5%]). LSF yield negative maximum catch potentials in both RCP scenarios, with large variability between ESM (GFDL and IPSL) under RCP 8.5 (RCP 2.6: -7.9% [-14.6% to -1.2%]; RCP 8.5: 9.6% [-35.2% to 16.1%]).

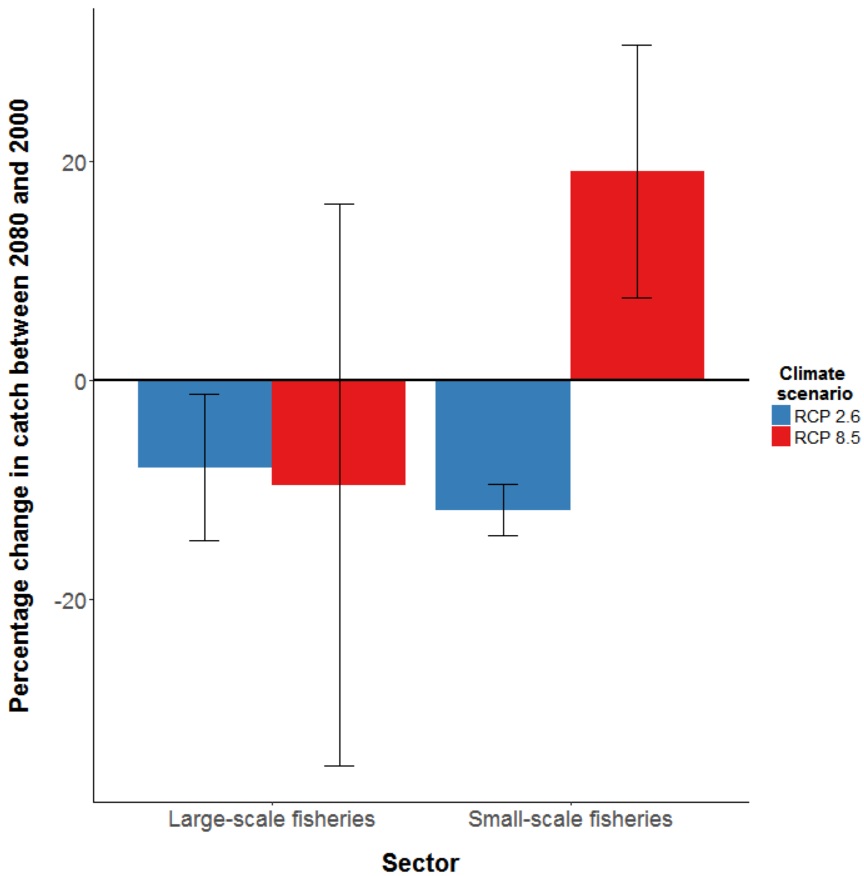


Figure 2.6: Percentage change in maximum catch potential in Alaska between 2080 and 2000 for large-scale fisheries and small-scale fisheries under Representative Concentration Pathways (RCP) 2.6 and 8.5.

The majority of LSF species in Alaska was projected to decrease in maximum catch potential (RCP 2.6: 78.4 – 85.8% of species; RCP 8.5, 65.8 – 81.8% of species). Likewise, maximum catch potential was projected to decrease for the majority (85.6 – 90.0%) of SSF species under RCP 2.6, while 70.3 – 83.0% of the species were projected to decrease under RCP 8.5.

Catches in the SSF and LSF within Alaska were dominated by a few species as shown in (Figure 2.7). The top exploited species by SSF were Pacific cod (*Gadus macrocephalus*; 27.2%), pink salmon (*Oncorhynchus gorbuscha*; 17.2%) and sockeye salmon (*Oncorhynchus nerka*; 16.0%) and the top exploited species by LSF were Alaska pollock (*Theragra chalcogramma*; 62.3%), Pacific cod (*Gadus macrocephalus*; 5.4%) and sockeye salmon (*Oncorhynchus nerka*; 3.5%).

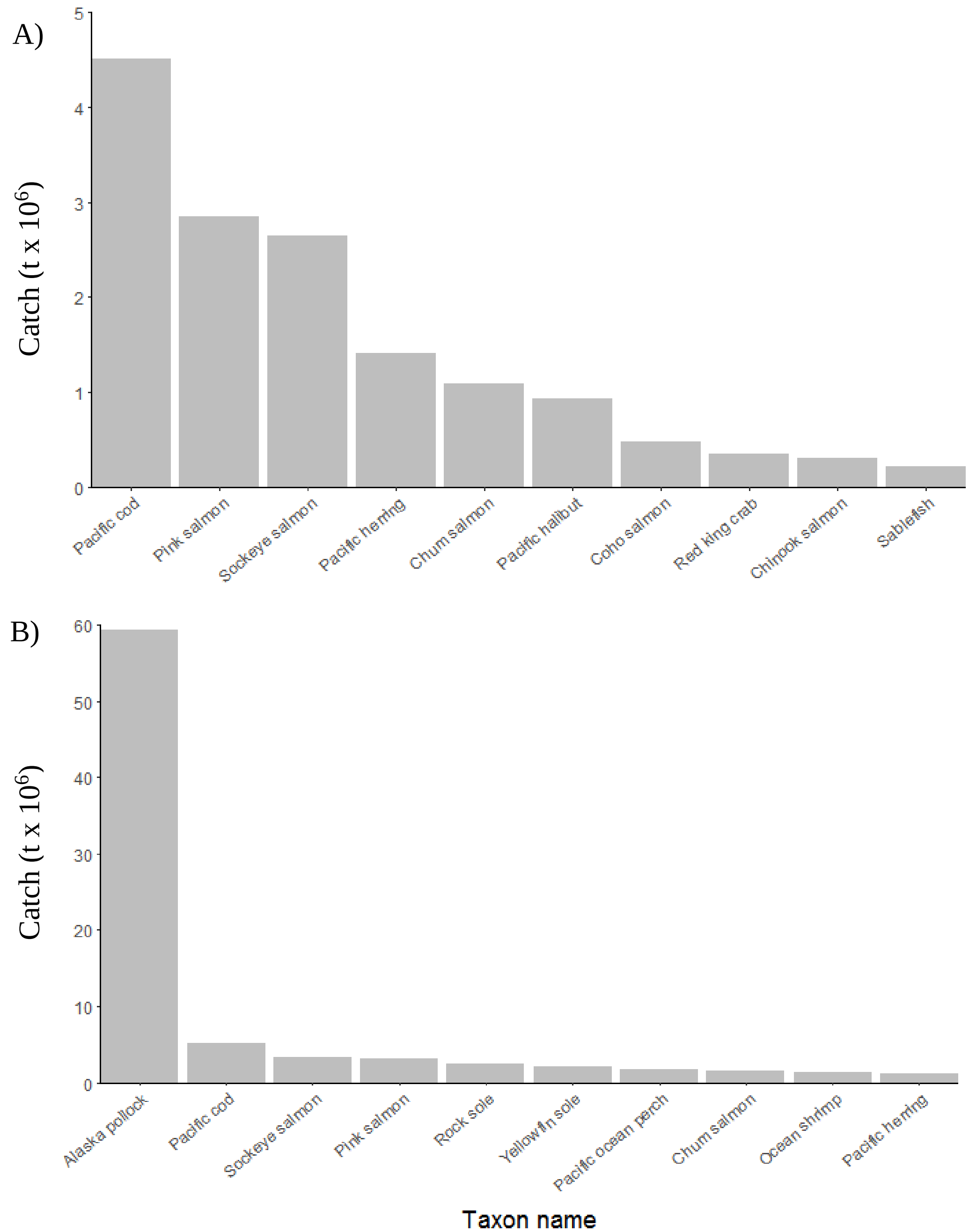


Figure 2.7: Aggregated catch within the years of 2080 and 2000 of the top species exploited in Alaska's EEZ by (a) small-scale fisheries; and (b) large-scale fisheries.

Amongst the top exploited species by SSF such as Pacific cod, pink salmon and sockeye salmon, there is a decrease in maximum catch potential by 2080 relative to 2000 for both RCP scenarios (Table 2.5; Figure 2.8a).

Table 2.5: Changes in maximum catch potentials between 2080 and 2000 for top species in Alaska's small-scale fisheries.

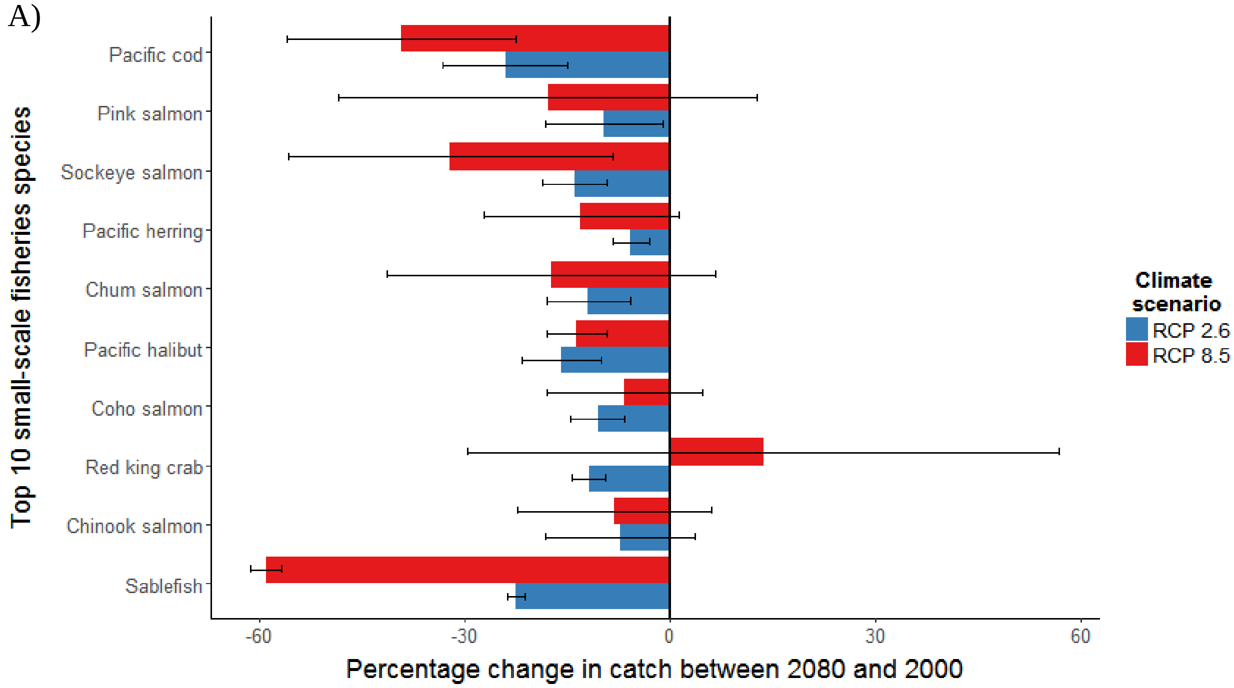
	RCP 2.6	RCP 8.5
Pacific cod	-24.1% [-33.1% to -15.0%]	-39.2% [-55.8% to -22.5%]
Pink salmon	-9.6% [-18.2% to -9.2%]	-17.8% [-48.3% to 12.7%]
Sockeye salmon	-13.9% [-18.7% to -9.2%]	-32.0% [-55.7% to -8.3%]

Likewise, for top species exploited by Alaska's LSF, maximum catch potential of Alaska pollock, Pacific cod and sockeye salmon were projected to decrease during the same time period (Table 2.6; Figure 2.8b).

Table 2.6: Changes in maximum catch potentials between 2080 and 2000 for top species in Alaska's large-scale fisheries.

	RCP 2.6	RCP 8.5
Alaska pollock	-8.3% [-18.0% to 1.5%]	-14.3% [-47.7% to 18.7%]
Pacific cod	-21.8% [-33.1% to -10.5%]	-37.2% [-55.8% to -18.6%]
Sockeye salmon	-11.5% [-18.7% to -4.3%]	-29.8% [-55.7% to -3.8%]

A)



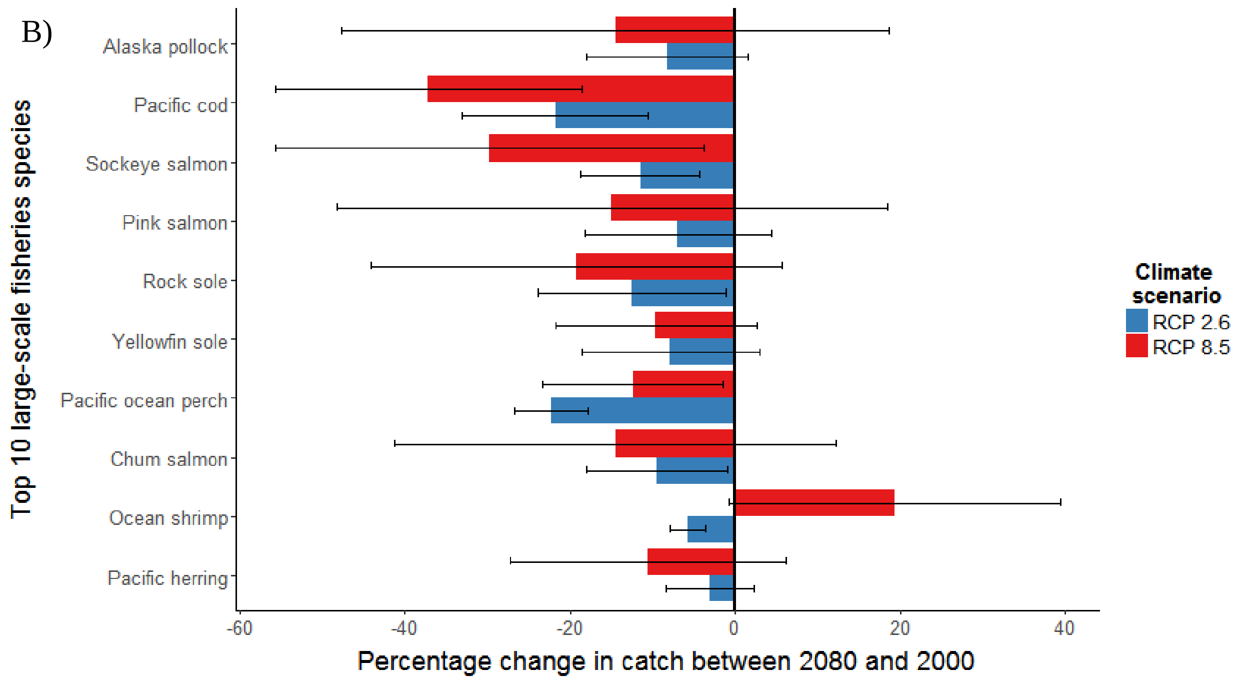


Figure 2.8: Percentage change in the maximum catch potential of top exploited species in Alaska between 2080 and 2000 by (a) small-scale fisheries; and (b) large-scale fisheries. Species displayed in descending order of total amount of reported catches.

Similar to species composition at the regional level, species composition overlapped largely between LSF and SSF in Alaska (110 species; 94.7% of total exploited species). The top 10 exploited species in SSF and LSF exclusively consisted of common species found in the catch portfolio of both sectors. LSF consisted of 19 unique species that contributed 4.9% of the total LSF catch, while SSF included 13 unique species contributing to only 0.4% of their catch. The most important species that were unique to SSF were red sea urchin (*Strongylocentrotus franciscanus*; 0.3% of catch) and giant Pacific octopus (*Enteroctopus dofleini*; < 0.1% of catch). In contrast, unique species that contributed most to LSF catch were shortraker rockfish (*Sebastes borealis*; 0.5%), tiger rockfish (*Sebastes nigrocinctus;* 0.5%) and China rockfish (*Sebastes nebulosus*; 0.5%).

Projected changes in maximum catch potentials diverged significantly between RCP 2.6 and RCP 8.5 starting in the late 2060s to early 2070s for SSF (Figure 2.9a). Contrastingly, LSF catches fluctuates through the time period but converge by 2060s (Figure 2.9b).

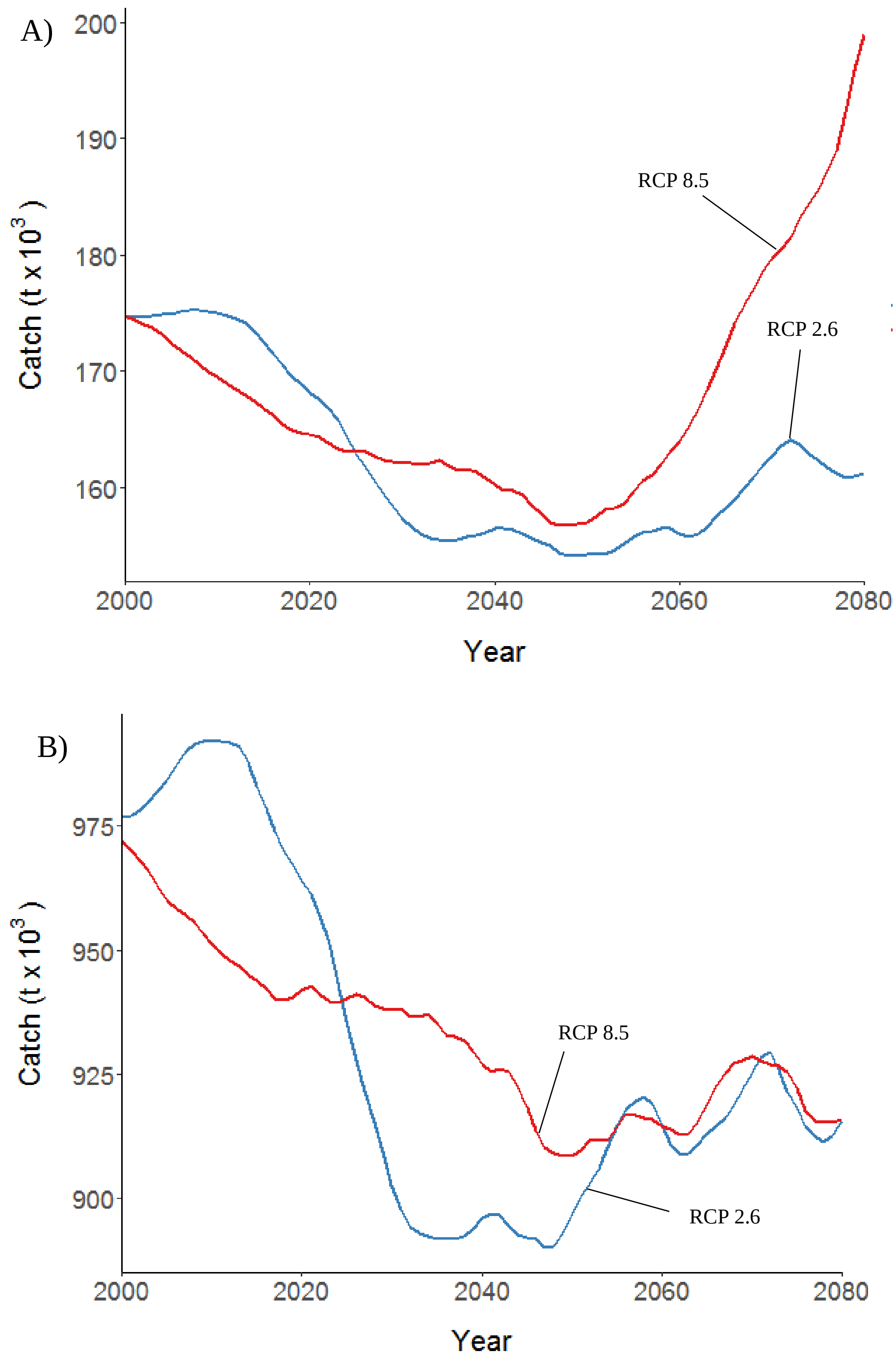


Figure 2.9: Projected maximum catch potential (t) from 2000 to 2080 for Alaska under RCP 2.6 (blue) and RCP 8.5 (red) for (a) small-scale fisheries; and (b) large-scale fisheries.

2.3.3 Canada Pacific

In Pacific Canada, maximum catch potential was projected to increase for SSF under both climate change scenarios by 2080 relative to 2000 (RCP 2.6: +49.7% [31.6% to 67.9%]; RCP 8.5: +193.6% [188.6% to 198%]), while slight decreases were projected for LSF (RCP 2.6: -14.8% [-22.9% to -6.7%]; RCP 8.5: -13.2% [-31.3% to 5.0%]) (Figure 2.10).

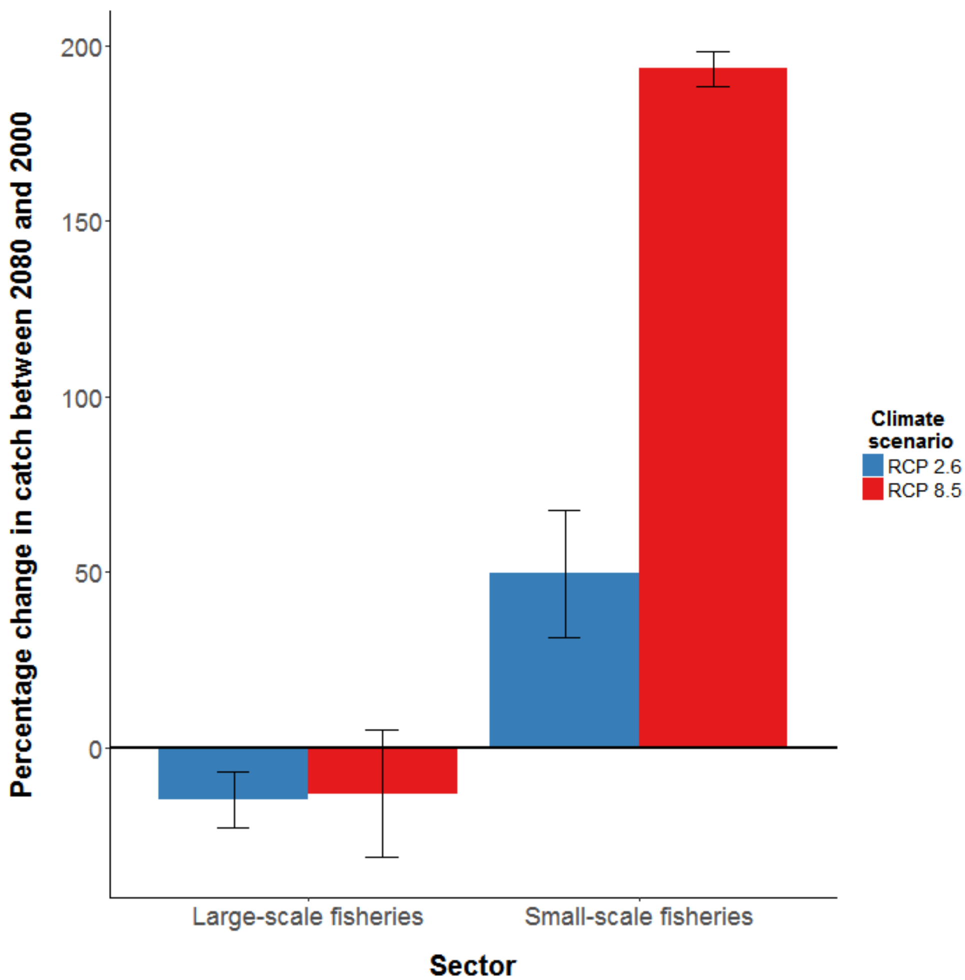
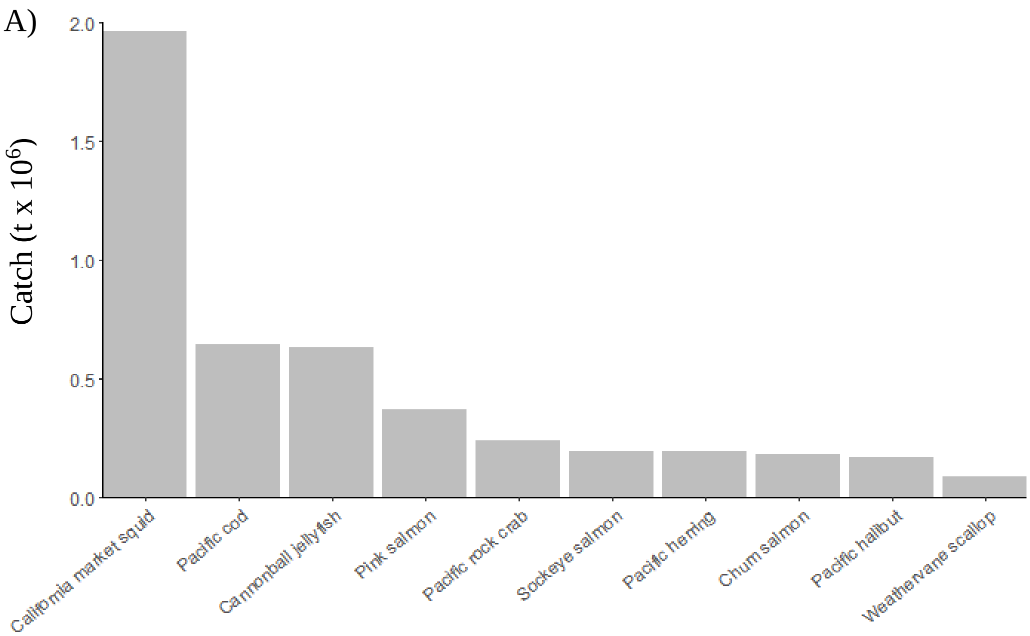


Figure 2.10: Percentage change in maximum catch potential in Pacific Canada between 2080 and 2000 for large-scale fisheries and small-scale fisheries under Representative Concentration Pathways (RCP) 2.6 and 8.5.

Amongst the studied species, 74.3 – 91.0% and 60.4 – 83.0% of species caught by SSF were projected to increase in maximum catch potential under RCP 2.6 and RCP 8.5, respectively. In contrast, 66.3 – 85.8% and 57.8 – 81.8% of species exploited by LSF were projected to decrease in maximum catch potential under RCP 2.6 and RCP 8.5, respectively. Integrating over the projected time period (2000 – 2080), the most important species in maximum catch potential were California market squid (*Loligo opalescens*; 34.7% of catch), Pacific cod (*Gadus macrocephalus*; 11.3%) and cannonball jellyfish (*Stomolophus meleagris*; 11.1%) for SSF and Alaska pollock (*Theragra chalcogramma*; 40.9%), North Pacific hake (*Merluccius productus*; 6.20%) and Pacific cod (*Gadus macrocephalus*; 4.07%) for LSF across RCP 2.6 and 8.5 (Figure 2.11).

A)



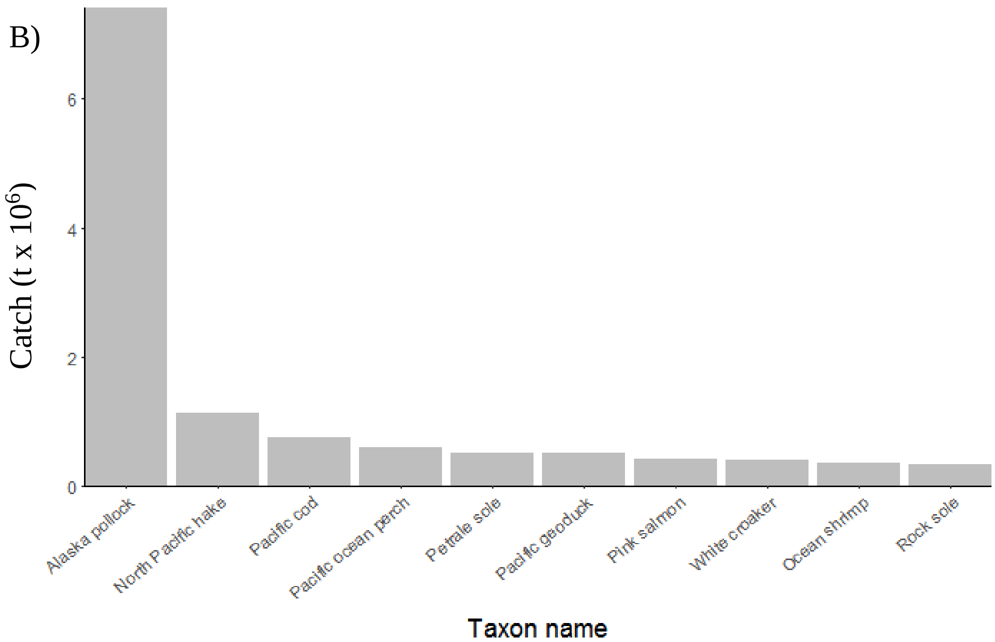


Figure 2.11: Aggregated catch within the years of 2080 and 2000 of the top species exploited in Canada's EEZ by (a) small-scale fisheries and (b) large-scale fisheries.

The increase in maximum catch potential of SSF exploited species by 2080 relative to 2000 was mainly attributed to the projected increase for a few species while the projected changes had less variation between species for maximum catch potential of LSF. Particularly, California market squid and cannonball jellyfish were projected to increase drastically in maximum catch potential of SSF, up to 100 times by 2080 relative to 2000 (Table 2.7; Figure 2.12a)

Table 2.7: Changes in maximum catch potentials between 2080 and 2000 for top species in Canada's small-scale fisheries.

	RCP 2.6	**RCP 8.5**
California market squid	206.7% [172.3% to 241.0%]	750.0% [720.0 % to 771.0%]
Pacific cod	26.0% [20.1% to 31.8%]	32.5% [27.3% to 37.6%]
Cannonball jellyfish	257.9% [281.0% to 234.8%]	1005.1% [270.2% to 1720%.0]

For LSF, amongst the top species, the biggest contrast in projected changes in maximum catch potential were between Alaska pollock, north Pacific hake and Pacific cod (Table 2.8; Figure 2.12b).

Table 2.8: Changes in maximum catch potentials between 2080 and 2000 for top species in Canada's large-scale fisheries.

	RCP 2.6	**RCP 8.5**
Alaska pollock	-24.4% [-34.6% to -14.4%]	-31.7% [-52.3% to -11.1%]
North Pacific hake	7.3% [3.3% to 11.3%]	12.3% [9.6% to 15.0%]
Pacific cod	-23.0% [-34.1% to -12.0%]	-32.5% [-49.8% to -15.3%]

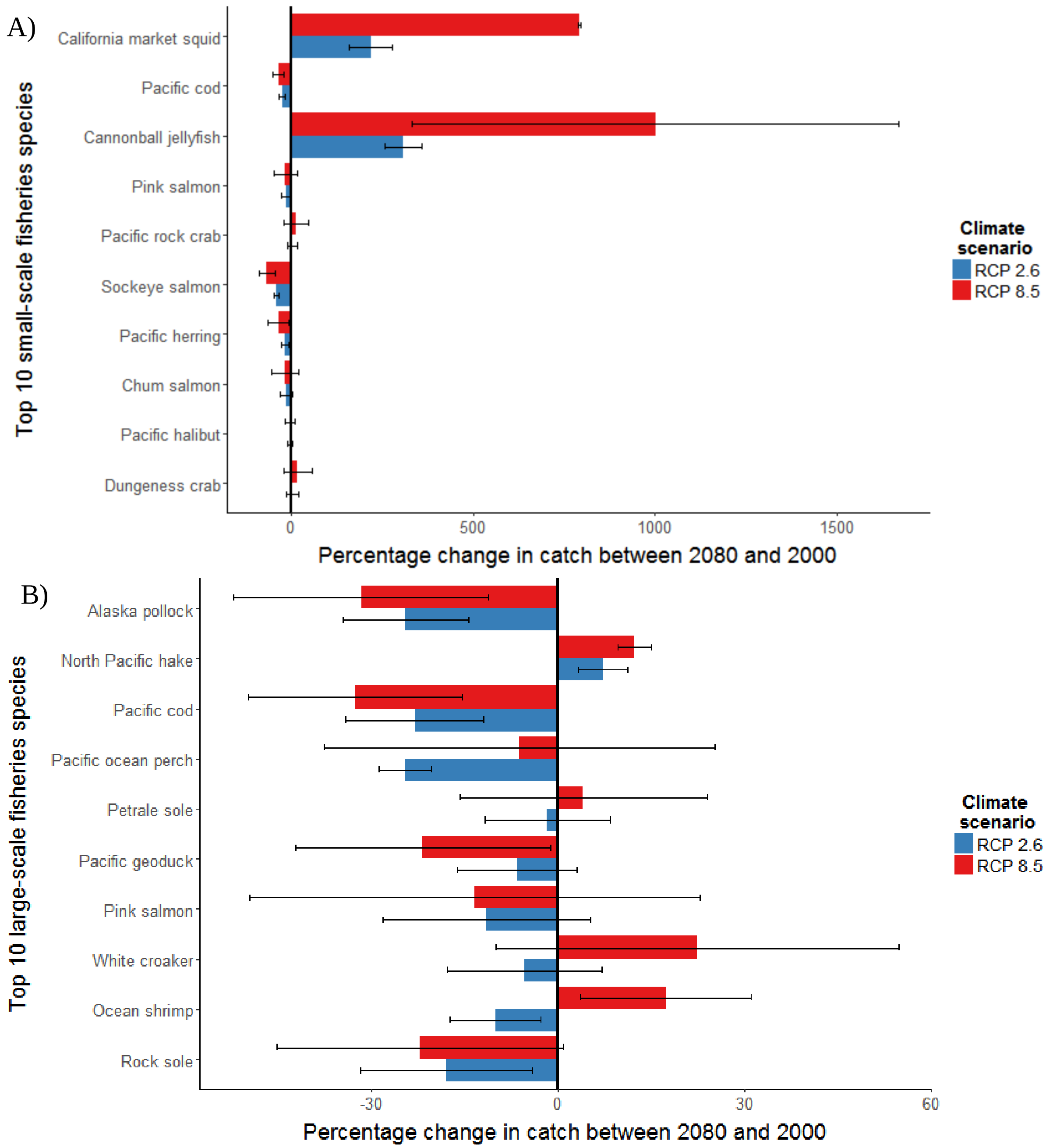


Figure 2.12: Percentage change in the maximum catch potential of top exploited species in Canada Pacific between 2080 and 2000 by (a) small-scale fisheries and (b) large-scale fisheries. Species displayed in descending order of total amount of reported catches.

Species composition of catch overlapped substantially between LSF and SSF in Pacific Canada (124 species; 92.3% of total exploited species). Twenty-one species were unique to LSF, composing 7.3% of the total LSF catch. The most important unique species for LSF were Pacific spiny dogfish (Squalus suckleyi; 1.4% of catch), China rockfish (*Sebastes nebulosus*; 0.7% of catch) and copper rockfish (*Sebastes caurinus*; 0.7% of catch). For SSF, 15 species were unique to the fisheries, composing 0.3% of the total SSF catch. The most important unique species to the SSF were red sea urchin (*Strongylocentrotus franciscanus*; 0.2% of catch), giant Pacific octopus (*Enteroctopus dofleini*; <0.1% of catch) and olympia oyster (*Ostrea lurida*; <0.1% of catch).

Figure 2.13a depicts the variation across the time period for SSF which begins to diverge significantly in the mid-2040s. LSF catches in Canada fluctuates through the time period with RCP 2.6 producing more positive maximum catch potentials compared to RCP 8.5 until the late 2070s (Figure 2.13b).

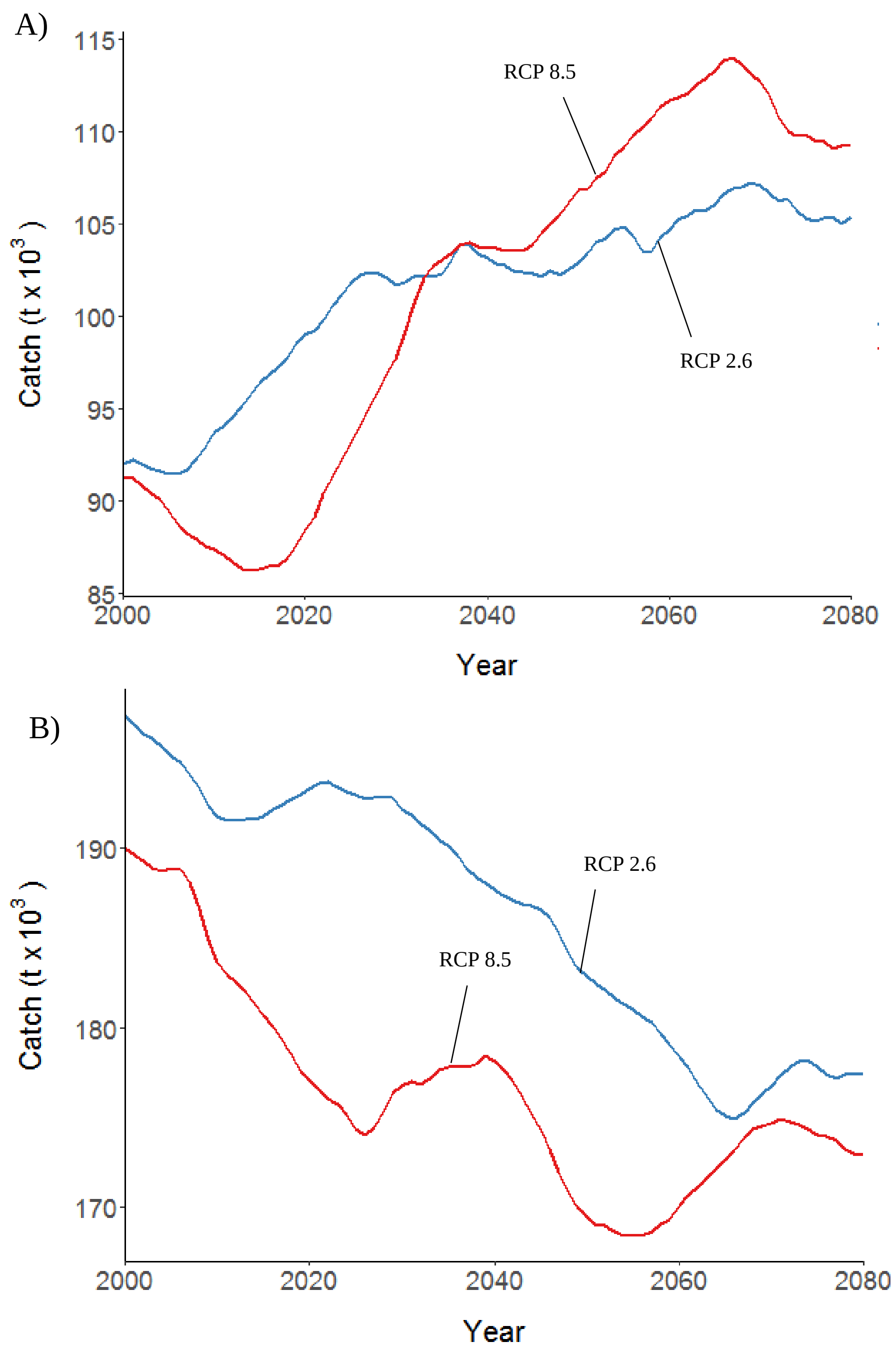


Figure 2.13: Time series plot illustrating changes in maximum catch potential (t) from 2000 to 2080 for Canada Pacific under RCP 2.6 (blue) and RCP 8.5 (red) for (a) small-scale fisheries and (b) large-scale fisheries.

2.3.4 USA West Coast

In USA West Coast's EEZ, maximum catch potential was projected to increase for SSF under both climate change scenarios by 2080 relative to 2000 (+11.2% (RCP 2.6: +8.0% [7.3% to 8.7%]; RCP 8.5: +14.4% [13.9% to 14.9%]), while it has projected declines for LSF (RCP 2.6: -10.2% [-10.4% to -10.1%]; RCP 8.5: -8.9% [-11.2% to -6.5%]) (Figure 2.14).

Amongst the studied species, 69.3 – 81.3% and 54.8 – 77.3% of species caught by SSF were projected to decrease in maximum catch potential under RCP 2.6 and RCP 8.5, respectively. Additionally, 57.8 – 78.6% and 52.6 – 66.8% of species exploited by LSF were projected to decrease in maximum catch potential under RCP 2.6 and RCP 8.5, respectively. Integrating over the projected time period (2000 – 2080), the most important species in maximum catch potential were California market squid (*Loligo opalescens*; 65.3% of catch), Pacific cod (*Gadus macrocephalus*; 9.74%) and Pink salmon (*Oncorhynchus gorbuscha*; 3.63%) for SSF and North Pacific hake (*Merluccius productus*; 41.3%), Alaska pollock (*Theragra chalcogramma*; 21.3%) and California anchovy (*Engraulis mordax*; 4.09%) for LSF across RCP 2.6 and 8.5 (Figure 2.15).

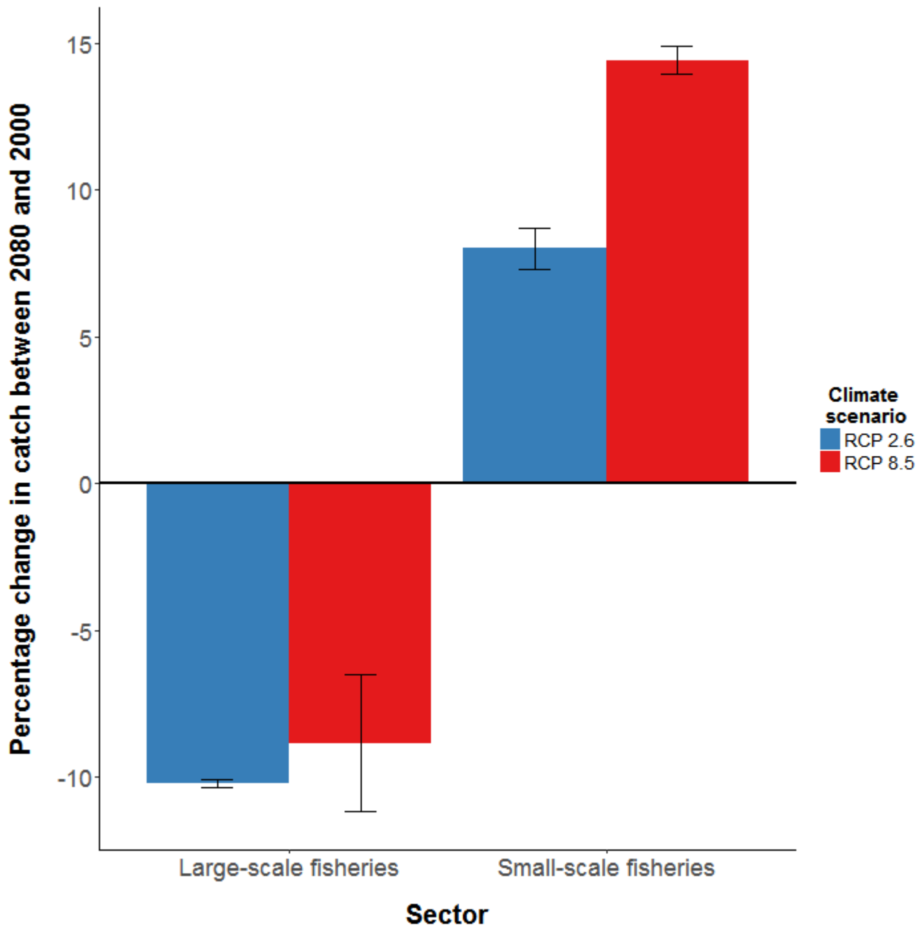


Figure 2.14: Percentage change in maximum catch potential in USA West Coast between 2080 and 2000 for large-scale fisheries and small-scale fisheries under Representative Concentration Pathways (RCP) 2.6 and 8.5.

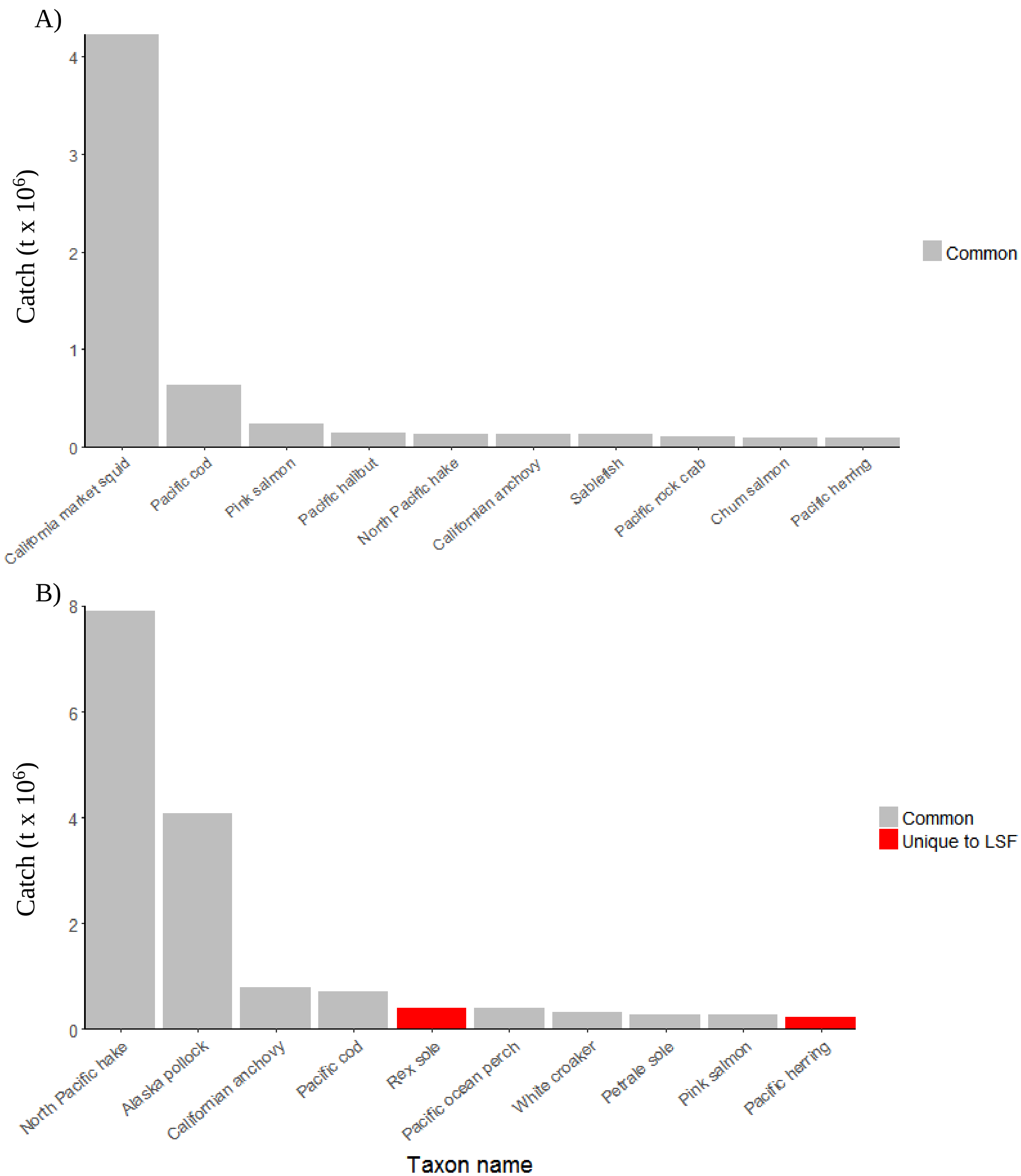


Figure 2.15: Aggregated catch within the years of 2080 and 2000 of the top species exploited in USA West Coast's EEZ by (a) small-scale fisheries and (b) large-scale fisheries, with red bars indicating species that are unique to the LSF.

The increase in maximum catch potential of SSF exploited species by 2080 relative to 2000 was mainly attributed to the projected increase for a few species while the projected changes had less variation and a general declining trend between species of LSF. Particularly, California market squid were projected to increase drastically in maximum catch potential of SSF by 2080 relative to 2000 (Table 2.9; Figure 2.16a).

Table 2.9: Changes in maximum catch potentials between 2080 and 2000 for top species in USA West Coast's small-scale fisheries.

	RCP 2.6	RCP 8.5
California market squid	+18.7% [17.2% to 20.2%]	+8.7% [-10.6% to 28.0%]
Pacific cod	-12.4% [-10.1% to -14.6%]	-15.4 [-14.8% to -15.9%]
Pink salmon	-19.0% [-12.8% to -25.1%]	-13.7% [-12.2% to -15.2%]

For LSF, amongst the top species, the declines in projected changes in maximum catch potential were attributed to North Pacific hake, Alaska pollock and Californian anchovy (Table 2.10; Figure 2.16b).

Table 2.10: Changes in maximum catch potentials between 2080 and 2000 for top species in USA West Coast's large-scale fisheries.

	RCP 2.6	RCP 8.5
North Pacific hake	-15.2% [-20.7% to -9.7%]	-12.0% [-21.5% to -2.5%]
Alaska pollock	-9.4% [-12.7% to -6.2%]	11.1% [-15.5% to -6.6%]
Californian anchovy	-5.3% [-16.4% to 5.8%]	-24.5% [-39.3% to -9.7%]

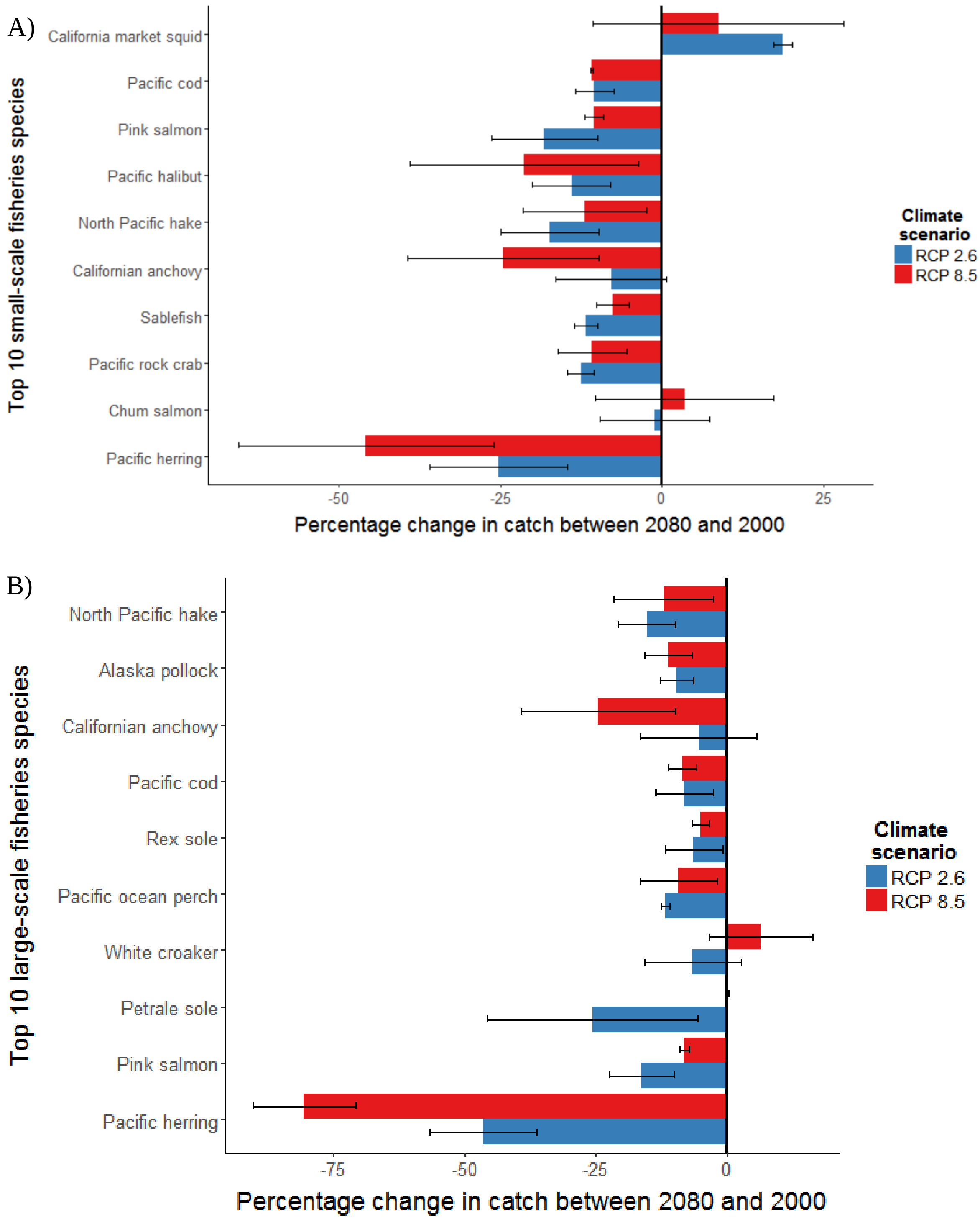


Figure 2.16: Percentage change in the maximum catch potential of top exploited species in USA West Coast's EEZ between 2080 and 2000 by (a) small-scale fisheries and (b) large-scale fisheries. Species displayed in descending order with top exploited species at the top.

Species composition of catch overlapped substantially between LSF and SSF in USA West Coast (100 species; 91.6% of total exploited species). Thirty species were unique to LSF, composing 7.2% of the total LSF catch. The most important unique species for LSF were Rex sole (*Errex zachirus*; 2.04%), Pacific spiny dogfish (*Squalus suckleyi*; 0.671%) and Longnose skate (*Raja rhina*; 0.563%). For SSF, 14 species were unique to the fisheries, composing 0.3% of the total SSF catch. The most important unique species to the SSF were red sea urchin (*Strongylocentrotus franciscanus*; 0.2% of catch), giant Pacific octopus (*Enteroctopus dofleini*; <0.1% of catch) and olympia oyster (*Ostrea lurida*; <0.1% of catch).

Figure 2.17a depicts the variation across the time period for SSF which begins to diverge significantly in the mid-2040s. LSF catches in RCP 8.5 for USA's West Coast fluctuates through the time period while RCP 2.6 produces more stable results. Eventually, both climate emission scenario producing negative changes in maximum catch potentials by the end of the time period (Figure 2.17b).

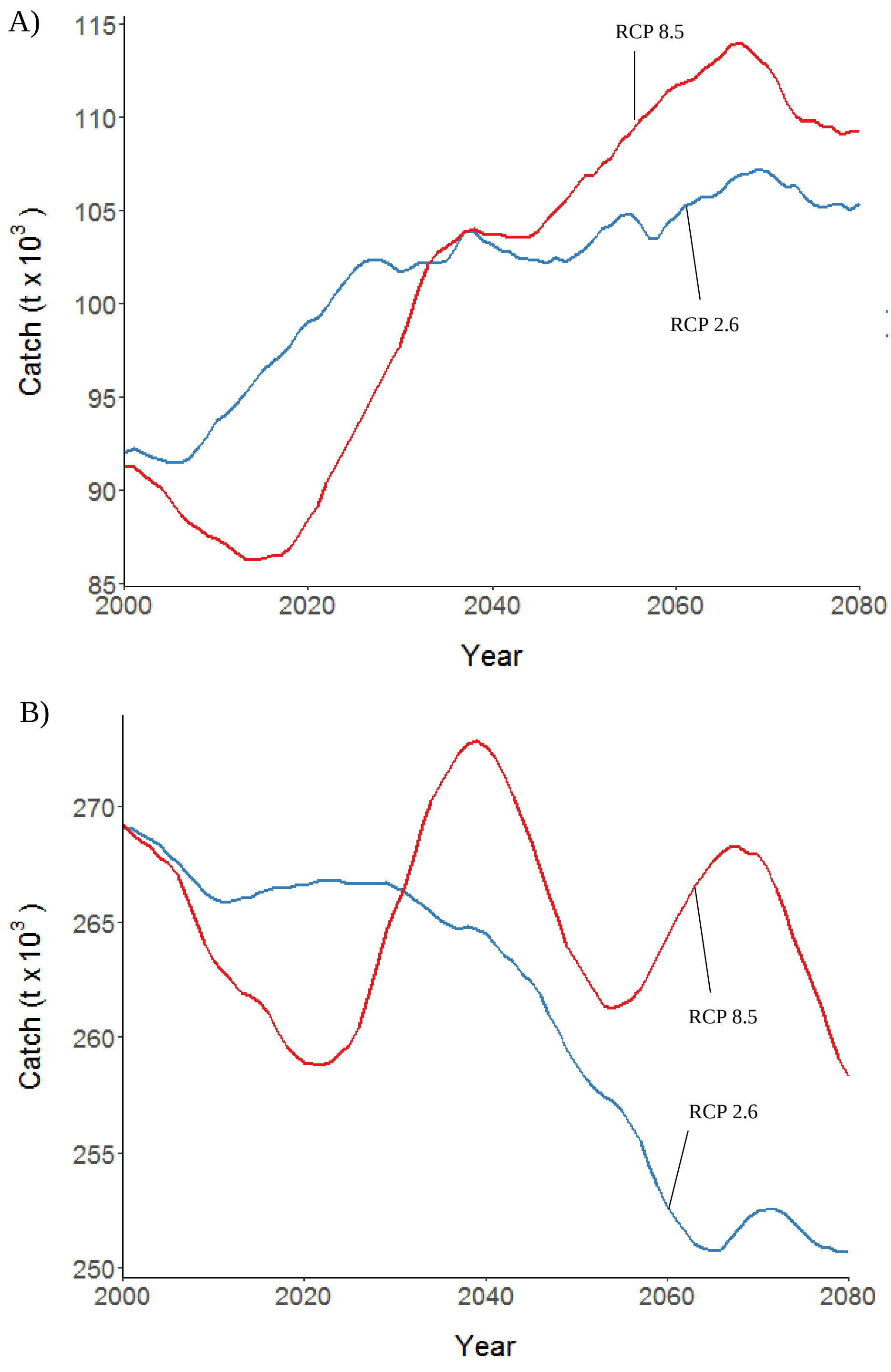


Figure 2.17: Time series plot illustrating changes in maximum catch potential (t) from 2000 to 2080 for USA West Coast under low (RCP 2.6; blue) and high (RCP 8.5; red) climate change scenario for (a) small-scale fisheries; and (b) large-scale fisheries.

2.3.5 Mexico Pacific

Generally, in Mexico's EEZ, RCP 8.5 tend to produce more positive catch potentials for RCP 2.6 and more negative catch potentials under RCP 8.5 for both LSF (RCP 2.6: -3.3% [-16.0% to 9.5%]; RCP 8.5: -17.8% [-26.1% to -9.5%]) and for SSF (RCP 2.6: +0.8% [-6.5% to 8.2%]; RCP 8.5: -17.1% [-26.0% to -8.2%]) (Figure 2.18). There is large variability for maximum catch potential between ESM (GFDL and IPSL).

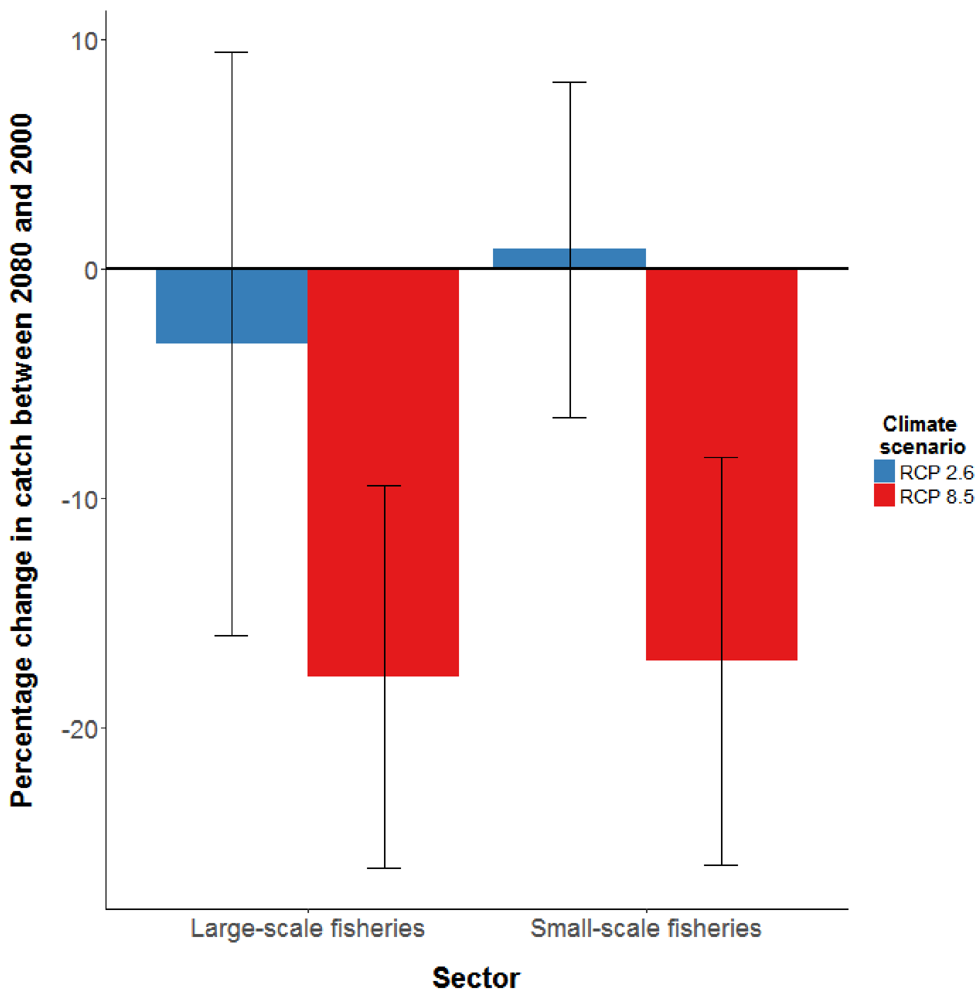
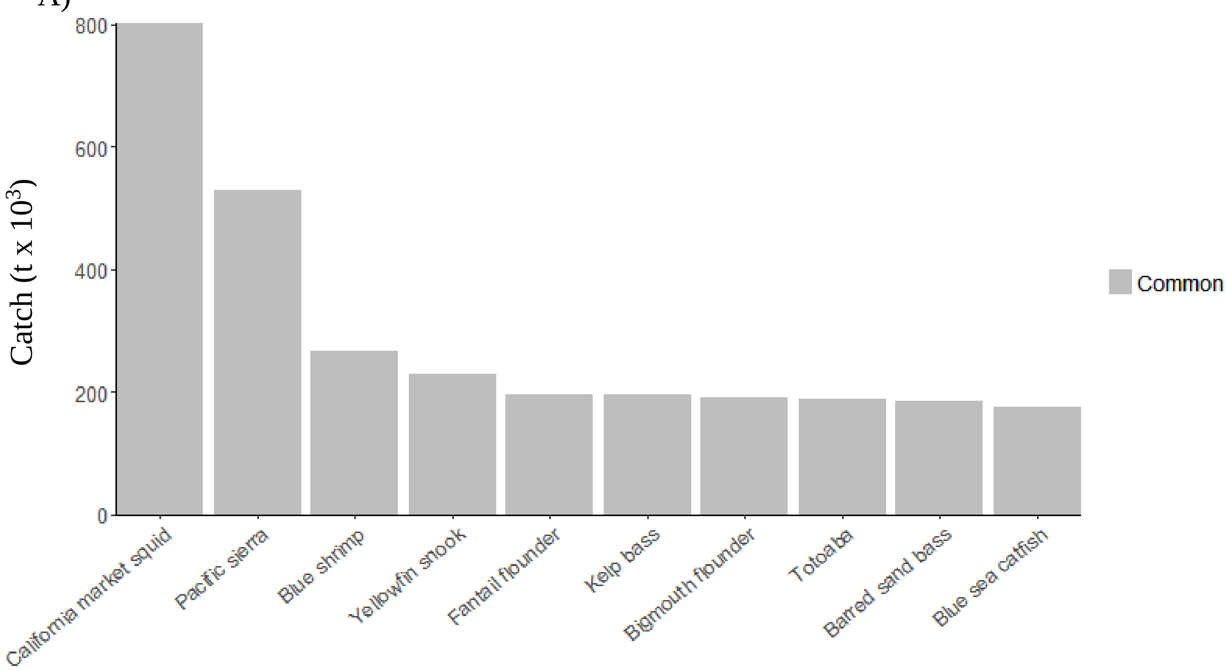


Figure 2.18: Percentage change in maximum catch potential in Mexico Pacific between 2080 and 2000 for large-scale fisheries and small-scale fisheries under Representative Concentration Pathways (RCP) 2.6 and 8.5.

Amongst the studied species, for SSF, we observe that majority of species will decline (RCP 2.6: 59.7 – 81.6%; RCP 8.5: 71.9 – 77.3%). Similarly, for LSF, there are projected decreases for a slight majority of exploited species under both RCP scenarios (RCP 2.6: 46.9 – 85.8%; RCP 8.5: 67.4 – 81.8%).

Integrating over the projected time period (2000 – 2080), the most important species in maximum catch potential were California market squid (*Loligo opalescens*; 9.40% of catch), Pacific sierra (*Scomberomorus sierra*; 6.22%) and blue shrimp (*Litopenaeus stylirostris*; 3.13%) for SSF and North Pacific hake (*Merluccius productus*; 57.8%), Pacific thread herring (*Opisthonema libertate*; 17.3%) and Pacific anchoveta (*Cetengraulis mysticetus*; 4.80%) for LSF (Figure 2.19).

A)



B)

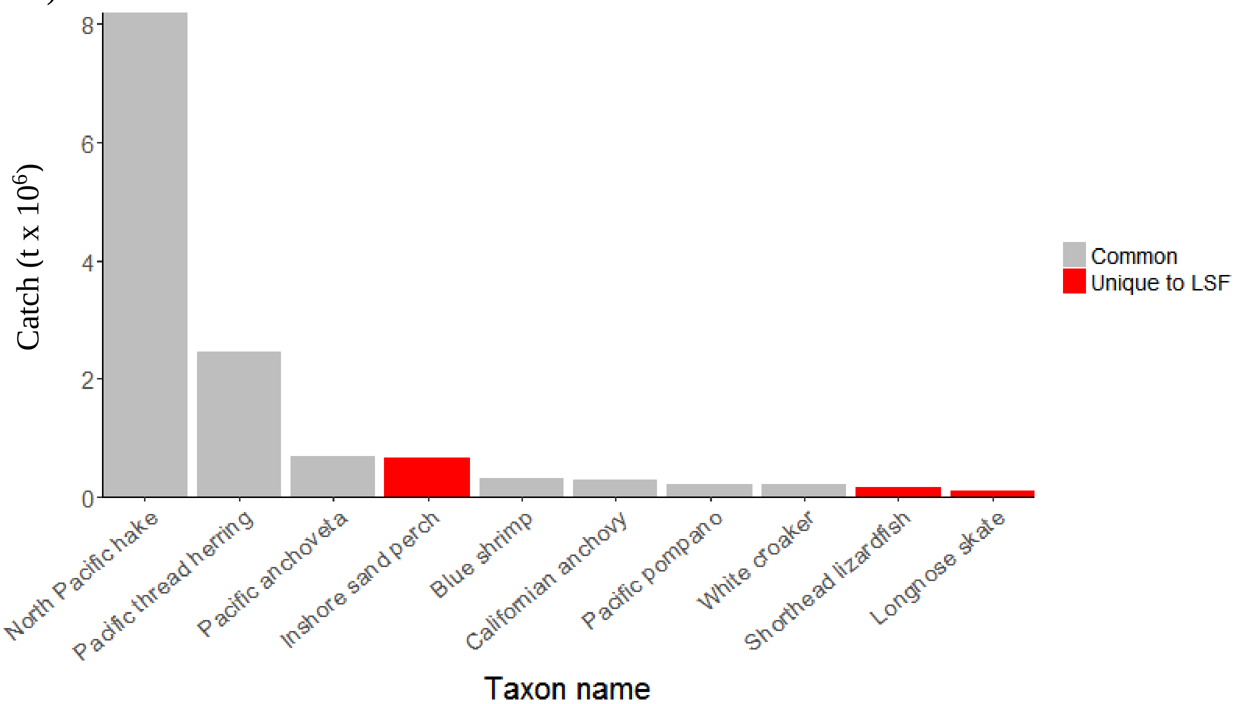


Figure 2.19: Aggregated catch within the years of 2080 and 2000 of the top species exploited in Mexico's EEZ by (a) small-scale fisheries; and (b) large-scale fisheries, with red bars indicating species that are unique to the LSF.

Within Mexico's EEZ, the top exploited species exhibit the following changes in maximum catch potential (Table 2.11; Figure 2.20). In SSF, declines are observed in California market squid, while the maximum catch potentials of Pacific sierra and blue shrimp are dependent on RCP scenarios.

Table 2.11: Changes in maximum catch potentials between 2080 and 2000 for top species in Mexico's small-scale fisheries.

	RCP 2.6	**RCP 8.5**
California market squid	-30.0% [-42.2% to -17.8%]	-75.4% [-80.0% to -70.7%]
Pacific sierra	12.4% [-4.0% to 28.9%]	-5.7% [-32.3% to 20.8%]
Blue shrimp	6.5% [-12.6% to 25.5%]	-3.0% [-16.5% to 10.5%]

In the LSF, most of the top exploited species have projected declines in the high emission scenario. North Pacific hake are projected to decline for both RCP scenarios, while Pacific thread herring and Pacific anchoveta show increases in maximum catch potentials only in the low emission scenario (Table 2.12; Figure 2.20).

Table 2.12: Changes in maximum catch potentials between 2080 and 2000 for top species in Mexico's large-scale fisheries.

	RCP 2.6	**RCP 8.5**
North Pacific hake	-8.6% [-24.5% to 7.4%]	-21.3% [-30.1% to -12.5%]
Pacific thread herring	10.8% [3.3% to 18.4%]	-8.4% [-18.6% to 1.7%]
Pacific anchoveta	2.8% [-12.0% to 17.6%]	-9.9% [-21.7% to 2.0%]

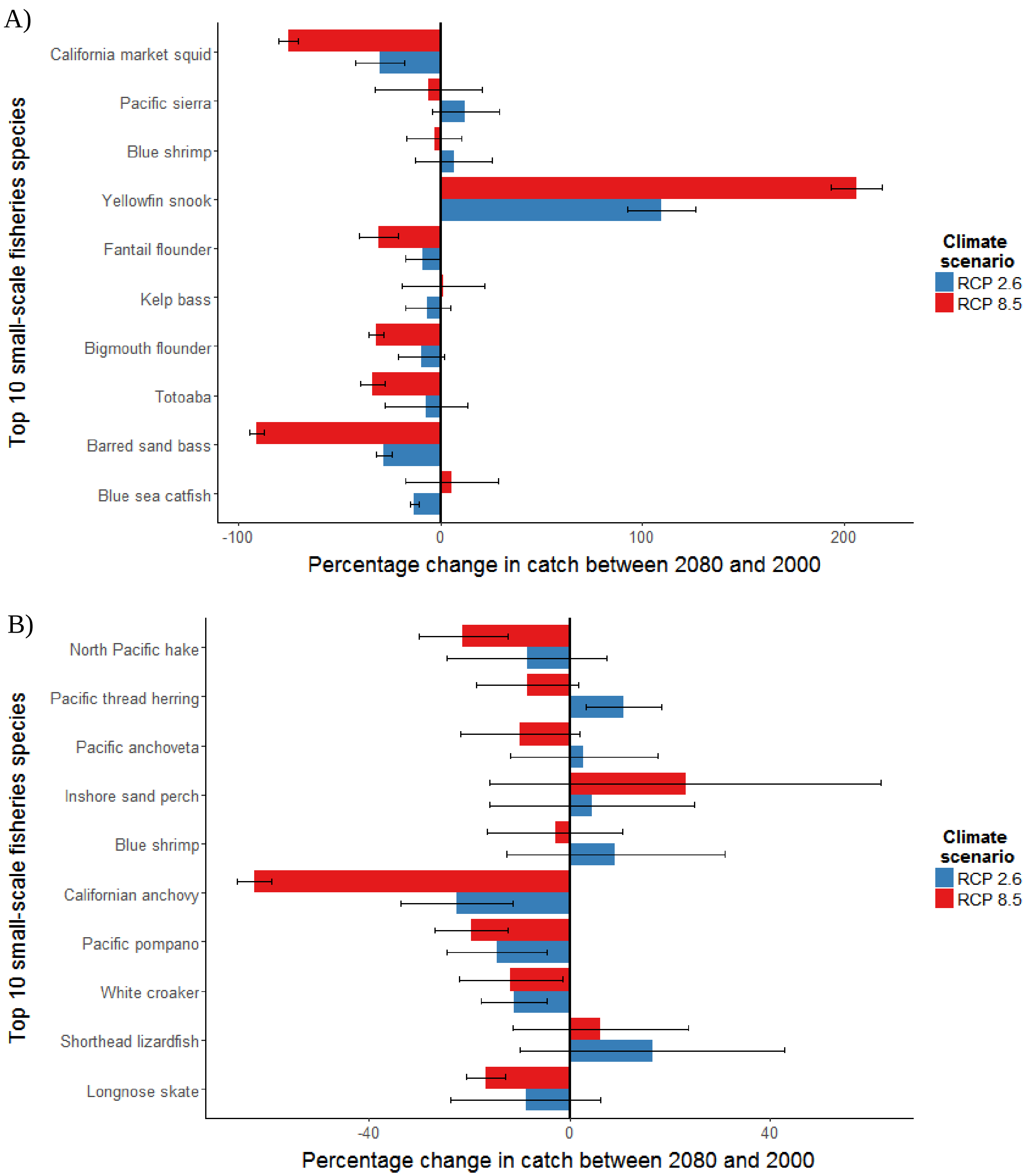


Figure 2.20: Percentage change in the maximum catch potential of top exploited species in Mexico's EEZ between 2080 and 2000 by (a) small-scale fisheries; and (b) large-scale fisheries. Species displayed in descending order with top exploited species at the top.

Species composition of catch overlapped substantially between LSF and SSF in Mexico (87 species; 91.2% of total exploited species). Sixteen species were unique to LSF, composing 8.7% of the total LSF catch. The most important unique species for LSF were inshore sand perch (*Diplectrum pacificum*; 4.74%), shorthead lizardfish (*Synodus scituliceps*; 1.14%) and longnose skate (*Raja rhina*; 0.83%). For SSF, 7 species were unique to the fisheries, composing 0.1% of the total SSF catch. The most important unique species to the SSF were giant Pacific octopus (*Enteroctopus dofleini*; 0.0399% of catch), Pacific calico scallop (*Argopecten ventricosus*; 0.0246% of catch) and snow crab (*Chionoecetes opilio*; 0.00910%).

Within Mexico's EEZ, the model projected fluctuations in maximum catch potentials starting in the 2030s. Maximum catch potential was projected to increase generally relative to the present levels for RCP 2.6 and decrease relative to present levels for RCP 8.5 (Figure 2.21). The model projected increases in maximum catch potential for both SSF and LSF until 2030s under both RCP 2.6 and RCP 8.5. However, changes in maximum catch potential was projected to diverge drastically from 2050 onward with RCP 8.5 declining past RCP 2.6.

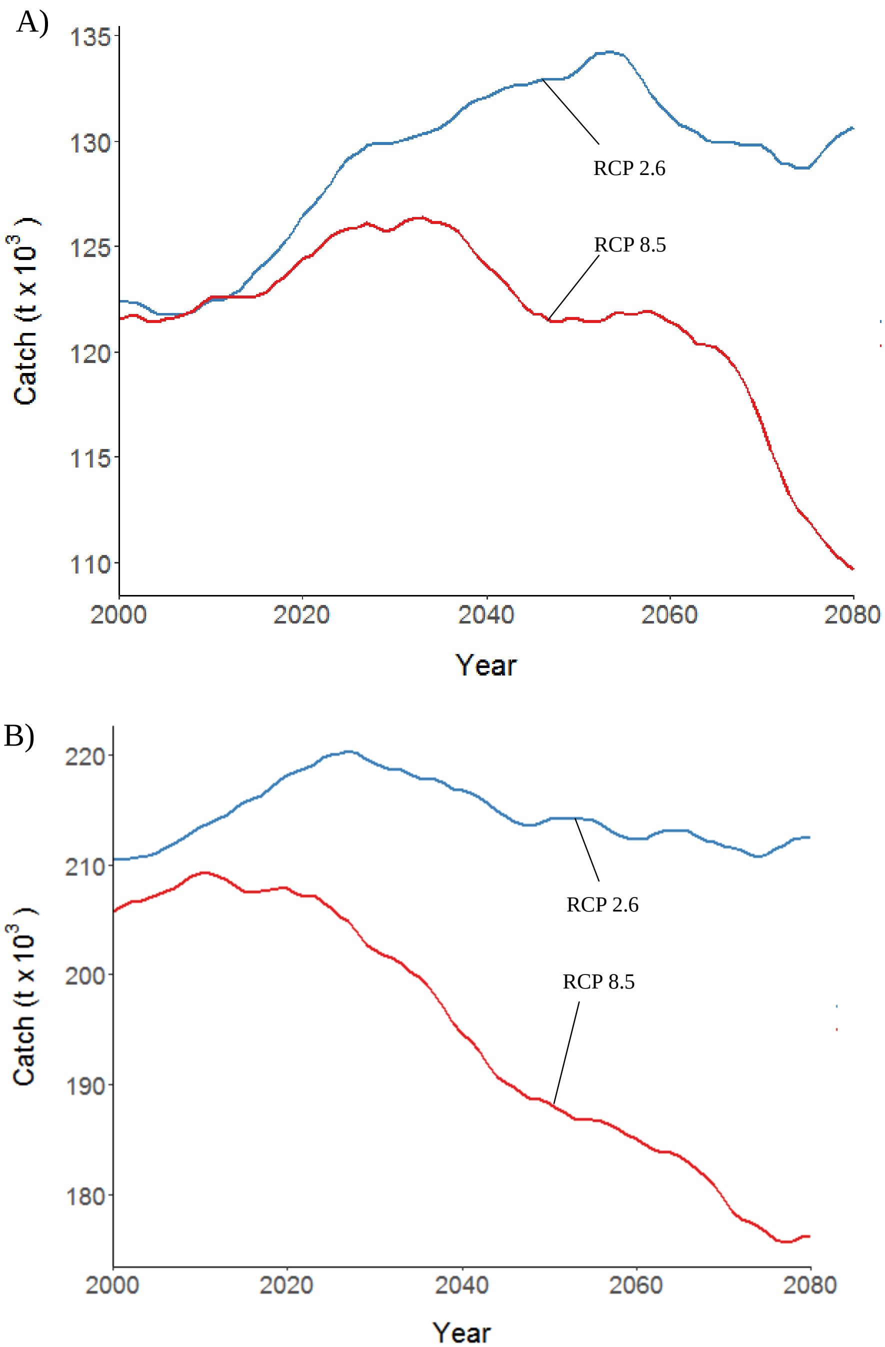


Figure 2.21: Time series plot illustrating changes in maximum catch potential (t) from 2000 to 2080 for Mexico under low (RCP 2.6; blue) and high (RCP 8.5; red) climate change scenario for (a) small-scale fisheries; and (b) large-scale fisheries.

2.3.6 Impacts to species richness and diversity

Species richness across the PNA region was projected to decrease by around 3% by 2080 relative to 2000 across RCP 2.6 and RCP 8.6 (Table 2.14). Specifically, the projected decrease in species richness range from -3.2% to -3.6% for LSF under RCP 2.6 and RCP 8.5, and -2.7% to -3.6% for SSF under RCP 8.5 and RCP 2.6, respectively.

The models projected substantial differences in changes in species richness between EEZs in the PNA region (Table 2.14). Under RCP 8.5, biodiversity was projected to increase in Alaska's EEZ (SSF: 4.4%; LSF: 3.8%) under RCP 8.5, but decrease slightly under RCP 2.6 (SSF: -2.8%; LSF: -1.1%). Biodiversity within Canada's EEZ was projected to increase under all RCPs and fishing sectors; in contrast, substantial decrease in species richness (9 – 13%) were projected for USA west coast across scenarios and sectors. Mexico was projected to have the biggest contrast in decrease in species richness between scenarios (~-4% for RCP 2.6 and ~-16% for RCP 8.5). Spatial projections of the changes in species richness illustrate significant losses in Mexico's EEZ and complementary gains in Alaska's EEZ in the RCP 8.5 scenario compared to the RCP 2.6 scenario. While less apparent visually, SSF (Figure 2.22a, b) generally tend to have more positive changes in species richness, especially in Canada's EEZ than LSF (Figure 22c, d).

Table 2.14: Projected changes (%) in species richness between 2080 and 2000 for LSF and SSF in PNA and its EEZs for lower (RCP 2.6) and upper (RCP 8.5) climate change scenarios.

	Large-scale fisheries		Small-scale fisheries	
	RCP 8.5	**RCP 2.6**	**RCP 8.5**	**RCP 2.6**
Pacific North America	-3.6 [-1.9 – -5.3]	-1.9 [-1.6 – -2.2]	-2.6 [-1.6 – -3.6]	-0.8 [-0.5 – -1.1]
Alaska	3.9 [3.4 – 4.3]	-0.9 [-0.1 – -1.7]	5.1 [3.8 – 6.4]	-0.9 [-2.7 – 1.0]
Canada	2.9 [1.1 – 4.7]	0.7 [0.6 – 0.8]	3.9 [2.2 – 5.6]	2.9 [2.4 – 3.3]
USA West Coast	-3.0 [-7.4 – 1.5]	-5.2 [-8.9 – -1.5]	-0.6 [-6.3 – 5.1]	-5.6 [-7.2 – 1.6]
Mexico	-23.4 [-28.4 – -18.3]	-3.4 [-5.3 – -1.4]	-23.2 [-27.7 – -18.7]	-3.7 [-5.3 – -2.1]

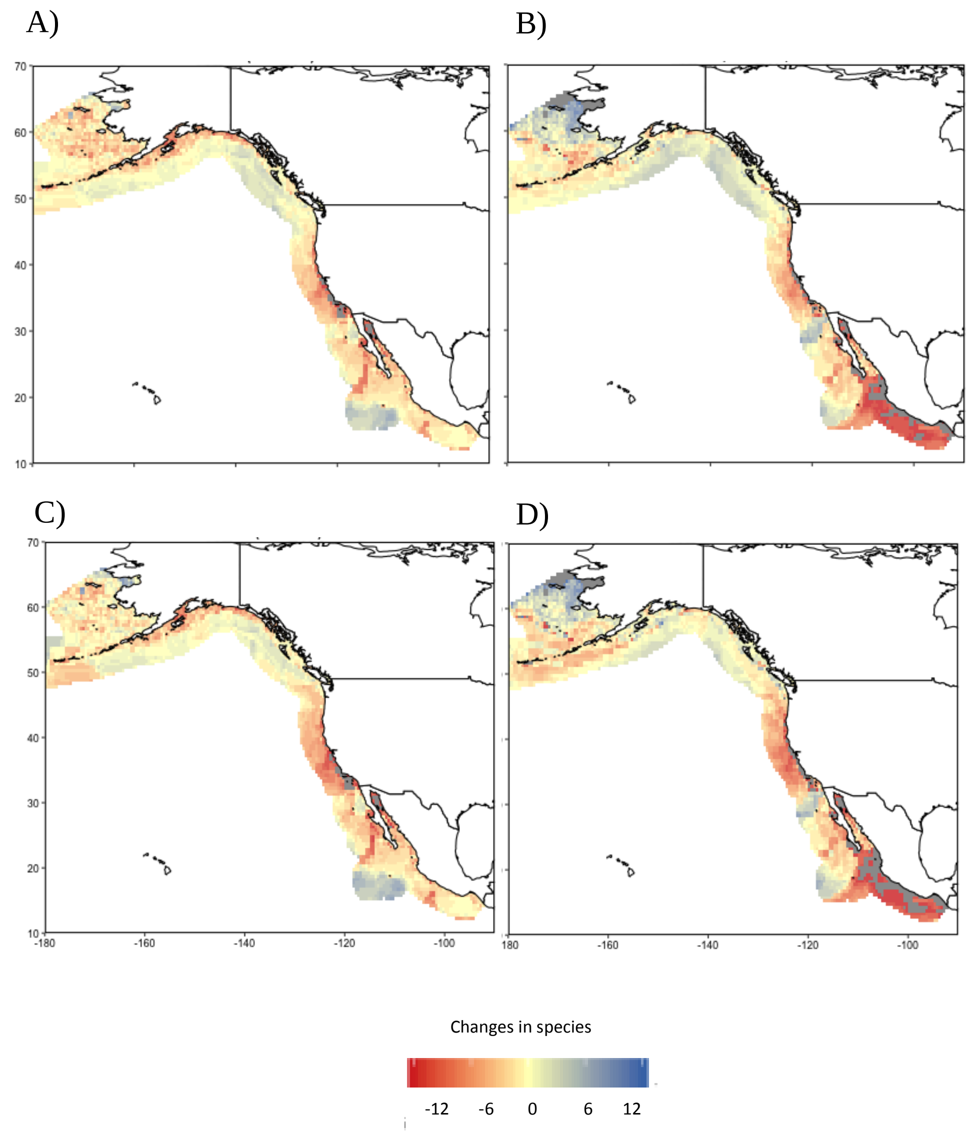


Figure 2.22: Maps of PNA region illustrating changes in number of species from 2080 relative to 2000 for (a) small-scale fisheries under low (RCP 2.6) greenhouse gas emission scenario; (b) small-scale fisheries under high (RCP 8.5) greenhouse gas emission scenario; (c) large-scale fisheries under low (RCP 2.6) greenhouse gas emission scenario; (d) large-scale fisheries under high (RCP 8.5) greenhouse gas emission scenario. High emission scenario exhibiting greater loss at lower latitudes and gains at higher latitudes compared to the low emission scenario.

2.4 Discussion

2.4.1 Implications to PNA fisheries

Across EEZs, the predominant difference in projected changes in maximum catch potential between EEZs is attributed to gradients of species richness and differences in oceanographic characteristics. Firstly, patterns of species richness from Mexico to Alaska follows the general latitudinal gradient, with decreasing number of species towards the pole (IPCC 2014). While ocean warming is projected to lead to poleward shifts of marine species along the coast of Northeast Pacific (Cheung et al. 2015), climate change is also predicted to lead to the replacement of productive temperate waters by warmer and less productive waters (Overland and Wang 2007). Further, increased upper ocean (between surface to 200 m depth) stratification under ocean warming is expected to lead to reduction in nutrient exchanges and, consequently, loss of productivity in tropical oceans within Mexico's EEZ (Capotondi et al. 2012). Such expansion of the oligotrophic "ocean deserts" and the local extinction of substantial number of species because of range shifts could explain the projected losses in maximum catch potentials and species richness in Mexico's water. Meanwhile, in Alaska, reduction in salinity because of the increased freshwater run offs from melting glaciers also intensified stratification, resulting in a reduction of ocean productivity (Rabalais et al. 2010). This decrease in productivity leads to an overall reduction in maximum catch potentials of existing exploited species and overall species richness in Alaska's EEZ, even after accounting for temperate species shifting into Alaskan waters under warming. In Canada, the general increases in maximum catch potentials could be attributed to the movement of adapted southern species seeking refuge in Canada's EEZ. With a predicted increase between 0.5 and 2.0°C by 2078 (Foreman et al. 2014b), this new temperature range expands the number of species that could inhabit within the area. The

USA Pacific Northeast is a productive ecosystem from the upwelling of the California Current System. Climate change is projected to intensify upwelling in the spring and weaken currents through the summer causing large seasonal variability (Brady et al. 2017). While stronger upwelling in the spring could increase food availability and promote growth, especially in species that require high energetic demands in the spring for spawning. Contrastingly, some top predators like pink salmon require high energy in the summer months and may be nutrient and prey limited with the decreased upwelling projections from climate change. Ultimately, the overall decrease in maximum catch potential and species richness may be due to significant commercially exploited species that have energetic requirements in the summer months.

The projected impacts are also affected by the characteristics of the fisheries, with relatively larger impacts of climate change on LSF relative to SSF in terms of changes in potential catches. As SSF and LSF were catching similar species, the differences in the impacts of climate change between SSF and LSF could largely be attributed to the relative levels of catch between exploited species in each sector. Compared to LSF in the PNA region, SSF was exploiting more species with a higher degree of positive changes in maximum catch potentials, and at greater relative amounts. Arguably, LSF do have the capacity to fish those species which large potential future catches, as they are presently already exploiting these species. Future studies exploring how SSF and LFS may modify their fishing behavior and preferences would help understand how the fisheries may adapt to climate change. SSF may not have the capacity to shift and keep pace with the redistribution of their target species, which could cause further complications as species move across countries boundaries (Song et al. 2017; Pinsky and Fogarty 2012).

The future changes in Alaska pollock is expected to contribute substantially to climate impacts of LSF in Alaska. Alaska Pollock is an important species for LSF but not for SSF. Alaska Pollock is also a key species in the region with multiple interactions and predator-prey relationships. Projected drastic increase in the maximum catch potential of this species is the attributing factor in the projected gains of LSF. It is a key prey of marine mammal and sea birds and consequently has been demonstrated to fluctuate with its population. As it consumes prey and crustaceans, dramatic increases in Alaska Pollock can directly compete with other fisheries in the region (A'mar et al. 2018). Other studies also suggested additional climatic factors not included in DBEM may also increase the productivity of Alaska Pollock. For example, higher precipitation in the Gulf of Alaska, which is projected to increase under climate change (Royer 1979), can cause more eddies which have positive implications for the survival of juveniles Pollock (Bailey et al. 2005)

The large influences of the expansion of squid and jellyfish distribution into Alaska waters could also explain the larger differences in impacts two sectors between SSF and LSF under the high emission scenario (RCP 8.5) compared to the low emission scenario (RCP 2.6). Particularly, in Alaska, under low emission scenario, many exploited species important to Alaska were projected to increase, the growth in new species such as squid and jellyfish was projected to decrease. The aggregation of catches in Alaska's EEZ depicts SSF to generate more positive maximum catch potentials than LSF in the high emission scenario. Potentially, the full extent of climate change's effects on maximum catch potentials are delayed in the lower emission scenario. The higher emission scenario creates environmental conditions for more species to strive in the habitats that are notably exploited by SSFs, that are able to adapt.

In Canada's and USA's EEZs, the substantially larger increase in SSF relative to LSF in maximum catch potentials in the future can be directly attributed to California market squid and Cannonball jellyfish, with the other top species ranking around a neutral or slight negative maximum catch potential. In contrast to Alaska EEZ, it was the decrease in maximum catch potential in Alaska Pollock that contributed to the lack of growth in maximum catch potentials of LSF in Canada' EEZs. In addition, in USA's waters, top LSF species such as North Pacific hake is projected to decrease but increase in neighbouring Canada's EEZ.

Lastly in Mexico's EEZ, LSF slightly outperforms SSF. However, the predominant variation in this EEZ is associated with the RCP scenarios, with RCP 2.6 deriving more positive maximum catch potentials compared to RCP 8.5. Further, regional comparisons illustrate the largest decline in species richness in Mexico's EEZs. Potentially in Mexico, the higher emission scenario creates an environment that is too extreme and beyond a species' habitat tolerances, prompting their movement towards higher latitudes to seek refuge.

Finally, because of large variations in the projected impacts and the characteristics of the fisheries between countries, the ability of fisheries to adapt to the changes in maximum catch potentials and species richness will be country-specific.

2.4.2 The projected expansion of California market squid and cannonball jellyfish

Projected increase in maximum catch potential of SSF in PNA is largely attributed to the tremendous growth of selected few species, notably California market squid and Cannonball jellyfish, even with the majority of species displaying declines in maximum catch potentials as reported in previous global species distribution studies (Cheung et al. 2016). California market squid is not an exploited species in Canada at present while it is a valuable fishery in Central and Southern California with a net value of over $41 million per year (California Department of Fish and Game 2001). Previous studies have shown that squids are highly temperature dependent species with a tendency to exhibit fast growth rate and thriving population sizes in cool waters (Reiss et al. 2004). As a fast growing species with a short lifespan of approximately 6 months, they are known to respond quickly to environmental and ecosystem changes (Reiss et al. 2004). For example, Sims et al. (2001) documented *Loligo* spp. to shift its range within the English Channel away from warm water temperatures. Moreover, squids are highly mobile and a quick shifting species with documented movement in distribution ranges and depth during El Nino cycles. In Monterrey Bay USA' west coast, abundance of California market has been fluctuating along with Pacific sardine (*Sardinops sagax*) and northern anchovy (*Engraulis mordax*) driven partly by the changing environmental conditions (Aguilera et al. 2015). Other climate projection studies in the Pacific have shown that related squid species such as the neon flying squid are highly sensitive to temperature changes and display pronounced northward habitat retreat (Alabia et al. 2018). As ocean temperatures are predicted to increase overall across the Pacific, Northward shifts in the distributional range of California market squid towards cooler, northern waters is not surprising. The projected increase in California market squid in the northern part of PNA such as Canada's EEZ is thus corroborated by known biological and oceanographic trends.

Evidence from California of fluctuating population sizes suggests that the squid fishery is relatively unstable and thus, shifting target catch or investments towards building this fishery should be considered with caution. In the 1990s, the market squid became the largest fishery in California by revenues and landings (Koslow and Allen 2011). While Canada's SSF does not presently exploited squid in such high amounts, the potential for expansion and development of this fishery as an adaptation strategy may be possible, especially with the notably declines that are projected for other currently exploited top species such as Pacific herring and salmon species. This warrants further analysis and community-based research, especially as these species in decline have cultural significance and provide ecosystem services. The results are in line with other climate change and species distributions studies in the region, that projects decline for Pacific herring, eulachon and salmon species in Canada (Weatherdon et al. 2016). However, these significant fisheries to First Nations communities in British Columbia, tend to be masked by larger exploitations of species in the region.

Likewise, increases in maximum catch potentials in cannonball jellyfish are also documented in Canada's EEZ. Jellyfish populations tend to benefit with climate change as they are known to thrive in harsh conditions such as warmer temperatures, eutrophication and salinity changes (Brotz et al. 2012). Jellyfish in the Mediterranean have been documented to live within a wide temperature range of 4°C to 30°C (Brotz and Pauly 2012). Such large thermal variations can be tolerated due to the transition between different life stages; polyp, cyst and medusae (Boero et al. 2016). Further, as a quick growing and adaptable species (cannonball jellyfish requires approximately 28 days to mature), they are able to thrive and outcompete other species, thereby making jellyfish blooms or sudden outburst more ubiquitous in a changing ocean. While this is largely a generalization as specific species have different environmental preference and tolerances, Boero et al. (2016) and Brotz et al. (2012) reports overall decrease in jellyfish diversity and increase abundances in certain populations. This could be the underlying mechanism behind the drastic increases in cannonball jellyfish that we observed in our results. Furthermore, as a sessile invertebrate, they are largely dependent on currents and ocean conditions to migrate, suggesting that the Alaska and California current system, which brings offshore waters towards the coast of British Columbia may be a huge factor in the predicted abundance of jellyfish in Canada's EEZ.

Largely catered towards an Asian market, the cannonball jellyfish's range has been noted to expand towards North American waters, generating almost 3.5 million US$ in revenue in Mexico and holds potential for expansion (Agencias 2013; Girón-Nava et al. 2015). While the market for jellyfish can be profitable, it presents a management challenge as they often interfere with fishing gear, destroy aquaculture and can affect tourism through beach and swimming closures. Often times, jellyfish blooms are associated as decadal oscillations, seen as periodic blooms followed by crashes. However, a global study by Brotz et al. (2012) examining Large Marine Ecosystems, reported that jellyfish populations are increasing in the majority of coastal ecosystems worldwide. Notably, the California Current and the Gulf of California have historical data indicating increased jellyfish populations over time. Therefore, the increased maximum catch potentials of cannonball jellyfish as shown in this study is corroborated with known information. At present, there is no operating cannonball jellyfish fishery in Canada and as there is high uncertainty associated with jellyfish populations, management plans to invest in this fishery should be considered carefully. For example, in 2012, upon a bloom of jellyfish in

Mexico's water, millions of dollars' worth of investment was made in fishing gear which was deemed to be worthless as the population disappear the subsequent year (Girón-Navam et al. 2015). Interestingly, while this study predicts an increase in Cannonball jellyfish populations specifically, as the model is a direct reflection of currently exploited catch, the environmentally conditions created are ideal for other jellyfish populations to thrive.

Overall, the projected large expansion of squid and jellyfish populations in PNA may suggest a diversion of targeted species towards these species as adaptation measures for SSF. However, this may eventually reduce the diversity of SSF's exploited species and focus on the more volatile and unreliable fisheries (Koslow and Allen 2011).

Coastal upwelling systems are extremely productive ecosystems, however their complex and interconnected nature often presents a challenge to isolate and predict their effects in a changing ocean. With this caveat in mind, studies have shown that the waters off the West coast of USA, spanning the California Current System, is projected to intensify in its upwelling in the Northern range, particularly during the Spring season under anthropogenic climate change (Brady et al. 2017). These upwelling forces are driven by strong offshore winds projected in a changing climate. Snyder et al. (2003) predict an increased regional productivity along the Northern portion of the USA's West coast, which could explain the relatively more positive changes in species richness as seen in Figure 2.22.

2.4.3 Uncertainties and assumptions

2.4.3.1 Fisheries data

The underlying assumptions of the distinguishing characteristics between SSF and LSF in each EEZ (Table 1) would have a drastic effect on the initial input data for SSF and LSF and hence, would alter its subsequent projections on maximum catch potentials and species richness. In majority of the EEZs, the disaggregation of SSF and LSF from a cumulated data source is based on fisheries characteristics (gear type, vessel type or fishing area) rather than an individual species approach and this would reflect the quality of the initial dataset.

The study encompasses the top 70% of fisheries catches in the PNA region including top commercially exploited species. The results, taken collectively, provide insights into the general trends and projected patterns in the region. However, there is a level of uncertainty associated with any individual species-level forecasts, especially as the method of the species disaggregation of higher taxonomic groupings to species level is performed on an equal proportion assumption. However, substantial efforts were undertaken to overcome this uncertainty by including as comprehensive list of species as possible through referencing with literature and database sources like FishBase and SeaLifeBase.

As the inclusion of species in the study is based on their relative catch amounts, it is important to recognize that the analysis may overlook culturally important or socially relevant species when they are not exploited in significant numbers. For instance, in Weatherdon et al. (2016), eulachon (*Thaleichthys pacificus*), a species of importance to First Nation fisheries, was shown to decline considerably. While the projections in this study concur, the impacts to these culturally important species, like eulachon, are masked by more heavily exploited species. Therefore, this study does not attempt to comment on any specific community or provide a complete account, rather it should be viewed as a quantitative approach towards analyzing the general effects of climate change on fisheries in the region.

2.4.3.2 Species distribution model

Uncertainties and assumptions associated with SDM studies are discussed in detail in Barry and Elith (2006), Robinson et al. (2017), Cheung et al. (2011) and outlined below. Key uncertainty includes equilibrium assumptions, biological assumptions on the correlation between oxygen, growth and maximum body size, biotic interactions between species and with human activities, evolutionary adaptation and dispersal ability (Pearson and Dawson 2003; Guisan and Thuiller 2005; Cheung et al. 2009). The implications of a complete regime shift, such as a major ecosystem or community restructure, are also not considered in the model.

Further, the study is based on the assumption that historical information on the species' current distributions and it represents an equilibrium of the species with the environment such that its current occurrences reflects the species' environmental preferences and tolerance. If the current distributions are conservative and well within a species thresholds, then the results may be an overestimation of the effects (Cheung et al. 2008). Further, historical fishing data is used as an indication of maximum catch potentials, therefore the assumption is that the current fishing pressure and level remains consistent into the future. Given that *Sea Around Us* data commences in 1950 and captures a 60-year time period, any fluctuations in fishing pressures and trends can arguably be said to have standardized in this study. Further, the initial *Sea Around Us* data encompassed discards and by-catch in order to account for the total maximum catch potentials.

Therefore, our results may be an over-estimation of the fisheries resources exploited and landed by fisheries.

To best provide a detailed account of exploited species through the species distribution models, assumptions were made to estimate parameters for species where data was unavailable. For instance, parameters from a closely related species within the same family or genus, and preferably one that occupied a similar range, was applied. This obstacle of the lack of available information predominately arose in species that were under-studied and generally not heavily exploited; often in species that compose a small proportion of the fisheries catch. Given this, the overall trends should be unaffected, although precaution should be taken when examining the less ubiquitous and sparsely exploited species.

Finally, the model projections in this study was based on two ESM; GFDL and IPSL, in order to account for variability in the physical and biogeochemical outputs. As the results generated is directly related to these outputs, future studies could encompass other climate models to enhance robustness. Further, a multi-model ensemble, combining other SDMs such as Maxent and AquaMaps with DBEM, as modelled in Cheung et al. (2016) could be introduced to account for variation between SDMs (Jones and Cheung 2015).

2.5 Conclusion

Taken cumulatively, our results predict an overall decline in maximum catch potentials and species richness across the PNA region. While there is an overall declining trend, this varies across the regions, exhibiting different patterns within each EEZ. It is apparent that this regional catch is dominated by a few exploited species. This suggests that while fisheries in the region may continue to further exploit certain species, the diversity in catch may be narrowed due to declining maximum catch potentials in other historically caught species. This prompts further investigation into operating fisheries by target species; will fisheries that exploit species that are projected for declines be able to adapt by shifting target species?

Importantly, the intention of this study is to better understand the impacts of climate change on SSF relative to LSF in the PNA region. To this regard, the study projects a trend of increasing relative maximum catch potential for SSF compared to LSF across the region under both low (RCP 2.6) and high (RCP 8.5) emission scenarios. However, species diversity is projected to decrease similarly for both SSF and LSF under the low and high emission scenarios. As there is high overlap in catch composition between top exploited SSF and LSF species, this suggest the existing potential for LSF to focus on exploiting these high maximum catch potential species at larger amounts and divert away from the species with declining maximum catch potential. An economic and management analysis assessing the change in revenue generated from switching between target species would be valuable in providing more context.

Finally, it is important to note that this study presents a quantitative assessment by top exploited species. Although there is an overall projected increase in SSF maximum catch potentials, the impacts on a localized scale is difficult to assess. The decline of certain species may have irreplaceable cultural or social importance to communities and shows the need for further research on a more localized scale into the adaptive capacity for fisheries to cope with these projected changes (Chapter 3).

3. Understanding socio-ecological vulnerability and adaptive capacity of small-scale fisheries to climate change: case illustrations from Pacific North America

3.1 Introduction

Significant changes in catch abundance and species distributions are projected for Pacific North America (PNA)'s fisheries in the coming decades (Chapter 2). From an ecological perspective, regional declines in the majority of exploited species' catch potentials and species richness are projected for both small-scale fisheries (SSF) and large-scale fisheries (LSF) (see Chapter 2). As SSF and LSF operate in the same fishing grounds within the Pacific North America region and are known to exploit a similar catch portfolio of species, the pattern of impacts differs between regions because of differing latitudes and ocean conditions. Climate change impacts on fisheries are caused by warming sea temperatures that drive species to shift their range and seek new refuges within their thermal preferences and tolerances. This translates to a poleward redistribution of species, the displacement of species with low tolerances and invasion of species that are highly adaptable (Cheung et al. 2009, 2010). Interestingly, while the overall catch trends show considerable decline, there are significant gains in catch potentials for certain highly adaptable, SSF-exploited species such as cannonball jellyfish and California market squid (Chapter 2). However, these analysis and findings, such as in Chapter 2, captures only the ecological dimension.

As fisheries represents an interaction between humans and aquatic resources, there is an added benefit of undertaking an interdisciplinary approach to understand the capacities of our communities and social-economic systems to adapt to these projected biological changes. Further, as SSF and LSF have different social-economic characteristics and fishing behaviours, they possess varied levels of vulnerabilities and adaptive capacities to climate change. For instance, SSF and LSF have markedly different operational costs, which could have an impact on economic profitability, while the type of fishing gear utilized by the SSF and LSF can be used as a measure of the diversity of species caught. Such measures can be an indication of the different potential adaptation and coping strategies available to SSF and LSF under climate change.

Vulnerability is defined as the state of susceptibility to harm from stresses (Adger 2006) or specifically in this case, the degree to which the fishery is susceptible to, or unable to cope with the adverse social-ecological effects of climate change (Islam et al. 2014, adapted from IPCC 2007). Vulnerability assessments are important tools used to understand the key components that contribute to the level of impact of climate change on a system and can help inform adaptation strategies to cope with these impacts. Vulnerability is a function of three components: exposure, sensitivity and adaptive capacity, as discussed below, and understanding the capacity and characteristics of each component is important to recognizing their relationships and interactions within the system.

A step towards understanding and comparing adaptive capacities between fisheries can be achieved by employing vulnerability frameworks. The vulnerability assessment frameworks can allow us to conceptualize and understand the interacting characteristic of fisheries at different scales (Cinner et al. 2013). Vulnerability frameworks, as currently applied in the literature, tend to focus on the ecological aspect; for instance, the implications of climate change on species (IPCC 2014; Jones and Cheung 2018). Additionally, the frameworks can also be applied from a social-ecological perspective towards understanding the vulnerability and adaptive capacity of fisheries, more broadly (Cinner et al. 2013).

In this chapter, we applied the vulnerability framework as adapted in Cinner et al. (2013) to three case illustrations from the PNA region: Alaska's cod fishery (USA), Monterey Bay's wetfish fishery (USA) and Sonora's cannonball jellyfish fishery (Mexico). These three case illustrations were selected as they are significant fisheries based on catch amount (Chapter 2). We seek to qualitatively understand key characteristics that enable fisheries to adapt to climate change, including operational costs as they are an important component to viable fisheries. More specifically, our two-fold research questions are: (a) How do operational costs impact the adaptive capacity of SSF versus LSF to climate change impacts on catch potentials and species richness? (b) What are common adaptive capacity characteristics of SSF that would enable them to successfully adapt to the rapid changes in catch potential and species distributions? The selected fisheries in this study are not intended to be a comprehensive case study nor meant to be generalized as an overarching example of all fisheries in the region. Instead, it provides a glimpse into potential indicators and impacts on fisheries vulnerability and adaptive capacities.

3.2 Methods

3.2.1 Modified social-ecological vulnerability framework

Originally, vulnerability frameworks tend to be considered as isolated ecological and social systems. In this chapter, we used a modified version of the Intergovernmental Panel on Climate Change (IPCC 2014)'s framework on vulnerability which accounts for the link between the ecological and social-economic dimensions. This integrated version has been proposed and applied in Cinner et al. (2013) and Marshall et al. (2010), and slightly modified below (refer to Figure 1.3). The framework and its key components are described below.

3.2.2 Ecological vulnerability

Vulnerability assessments from an ecological perspective captures the interaction between intrinsic biological characteristics of species and the extrinsic environmental factors (Jones and Cheung 2018). Ecological exposure refers to the extent to which the species is exposed to climate related hazards such as warming temperatures, loss of oxygen and ocean acidification. The duration, frequency and magnitude of the exposure to the hazard is also considered. Hazards, as presented in the IPCC's framework, is not explicitly mentioned within this framework, as that dimension and variability within climate related impacts are accounted for within exposure. Ecological sensitivity is defined as the susceptibility of the species to impacts of climate change based on its biological traits. This includes temperature tolerances, body size, association with specific habitats and taxonomic groups. The wider range of temperature tolerances, smaller body sizes, less association with a specific habitat and non-calcified taxonomic groups possess lower sensitivity to climate changes, as they are less susceptible to environmental changes (Jones and Cheung 2018). Ecological adaptive capacity represents the biological ability of species to cope with, or avoid the impacts of climate change. This can be achieved by seeking refuge through shifting latitudes, depths or towards new habitats. High fecundity and the ability to reproduce quickly allows for quick recovery to changes. Accumulated together, the interaction of the three dimensions of exposure, sensitivity and adaptive capacity attributes to a species' ecological vulnerability or the social-economic exposure. This is defined as the degree to which species and the ecological system is unable to cope with the adverse effects of climate change (Figure 1.3) and represents the changes that the social-economic system is exposed to.

3.2.3 Social-ecological vulnerability

Once we develop an understanding of the ecological vulnerability, we integrated it with the social-economic dimension to account for the varying capacities of communities to adapt and manage these ecological changes, resulting in a range of social-ecological vulnerabilities. Social-economic sensitivity is defined as the susceptibility of the community to climate changes. This is influenced by economic, political, cultural and institutional factors, and the degree of dependency on the fisheries resources (Cinner et al. 2013). The social-economic sensitivity interacts with the ecological vulnerability to determine the potential social-ecological impact of climate changes on the system. The social-economic adaptive capacity represents the ability of the social-economic system to respond to the overall climate-driven impacts imposed on the communities. This captures the communities' ability to manage its risk and adapt to changes, including having strong governance capacities, institutions, alternative livelihoods and high education levels and life expectancies. Consecutively, the impact potential interacts with the social-economic adaptive capacity to produce the social-ecological vulnerability.

3.2.4 Applications to case illustrations

The study considered three different case illustrations fisheries in the Pacific North America region; Alaska's Pacific cod fishery, Monterey Bay's wetfish fishery and Sonora's cannonball jellyfish fishery. We applied the social-ecological vulnerability assessment, discussed above, to these three case illustrations to understand the different components, their interactions and the socio-ecological system's vulnerability.

Alaska's Pacific cod fishery is used as a case illustration to answer the first research question on the impacts of operational costs on adaptive capacity. First, we applied the Cinner et al. (2013) framework to Alaska's small-scale and large-scale Pacific cod fishery to understand the different components in its social-ecological vulnerability. Then, we specifically analyzed the operational cost of both SSF and LSF as a measure of adaptive capacity. Operational cost is a key measure of adaptive capacity because cost relates to profitability and hence, it reflects the viability of its continued operations.

The second research question seeks to understand key social-economic adaptive capacity needed in order to capitalize on rapid ecological growth of exploited species. We first applied the Cinner et al. (2013) framework to the two case illustrations, Monterey Bay's wetfish fishery and Sonora's jellyfish fishery. These case illustrations were based primarily on the research of Aguilera et al. (2015) and Girón-Nava et al. (2015). Subsequently, we delved into Monterey Bay's wetfish fishery and Sonora's jellyfish fishery to find common social-economic adaptive capacity characteristics.

3.3 Results and Discussion

3.3.1 Case Illustration #1 – Alaska's Pacific cod fishery

<u>Research Question: How does operational costs (fuel, labour etc.) impact the adaptability of SSF vs. LSF to climate change impacts on catch potentials and species richness?</u>

The Alaskan cod fishery is selected as it is highly prevalent in the catch portfolios of both SSF and LSF in the region, thus allowing for an adequate comparison of species that are significant to the economics of both fishery types. Further, as a species that has been historically caught since 1960s, Pacific cod is an integral component to Alaska's subsistence and industrial sectors (Alaska Fisheries Science Center 2010). Fishing for Pacific cod forms an important subsistence consumption component to Alaskan communities and also contributes about 16% of Pacific cod supply to the global market (McDowell Group 2017).

Operational cost is a key determinant of adaptive capacity, especially as climate change projects poleward redistribution of marine species which requires fishing vessels to travel to new fishing grounds in order to continue to exploit historically caught species (Quentin Grafton 2010). As labour and fuel cost forms an integral component of the operational cost of the fisheries (Lam et al. 2011), travel to distant fishing grounds or longer fishing trips could increase fuel and labour costs to a point where fishing becomes unprofitable. Furthermore, as SSF and LSF have different gear types, vessel sizes and fishing capacities, which ultimately results in different operational costs; these can markedly distinguish the impact of climate change on the adaptation of SSF versus LSF.

3.3.1.1 Pacific cod populations

Pacific cod (*Gadus microcephalus*) is a fast growing, demersal marine species with a lifespan of 18 years (FishBase 2018). They are found along the North Pacific Ocean with a latitudinal range of 43°N to 79°N and up to a depth of 1,280m. They migrate to deeper, cooler waters for spawning in the spring and return to shallower waters in the summer (NOAA;

National Oceanic and Atmospheric Administration 2018d). Pacific cod feeds on copepods, finfishes, octopi and crustaceans (FishBase 2018) and is a prey source for endangered Steller sea lions (Alaska Fisheries Science Center 2010). Pacific cod's temperature preferences ranges from -1°C and 8°C, oxygen between 2 to 8ml/l and salinity of 31 to 34 pps. With such thermal preferences and habitat envelopes, a decline in maximum catch potentials for Pacific cod is projected within Alaska's EEZ for both SSF (Chapter 2; RCP 2.6: -24.1% [-33.1% to -15.0%]; RCP 8.5: -39.2% [-55.8% to -22.5%]) and LSF (Chapter 2; RCP 2.6: -21.8% [-33.1% to -10.5%]; RCP 8.5: -37.2% [-55.8% to -18.6%]). Jones and Cheung (2018) calculated the vulnerability of Pacific cod to climate change to be within the moderate to high vulnerability range.

Pacific cod is a valuable and highly exploited species of groundfish, valuing at $178 in ex-vessel price and contributing about 15.7% to the total Alaskan groundfish fishery. In 2008, Pacific cod was valued at $1.88 per lb and increasing (Alaska Fisheries Science Center 2010). It composed about 12% of total Alaska's fisheries catches in 2016, 1.5 million USD of value and 10,900 jobs (McDowell Group 2017), composing an important species to the livelihoods and income to Alaskan communities.

There are four stocks of Pacific cod; Bering Sea, Gulf of Alaska, Aleutian Island and West Coast (Washington to California) (National Oceanic and Atmospheric Administration 2018d). For the purposes of this case illustration, we analyzed the former three Alaskan stocks which are regulated in federal waters (3 to 200 nautical miles) by National Oceanic and Atmospheric Administration (NOAA) and Gulf of Alaska Groundfish Management Plan and in state waters (defined as the distance from shore to 3 nautical miles) by Alaska Department of Fish and Game (National Oceanic and Atmospheric Administration 2018a).

In both jurisdictions, permits or licenses are required to enter the SSF and LSF. Total allowable catches (TAC) are assessed periodically through the fishing season by the National Marine Fisheries Service (NMFS) and allocated by the number of permits based on gear types and fishing area (National Oceanic and Atmospheric Administration 2018c, 2018b, 2018d). Updated report can be found: https://alaskafisheries.noaa.gov/sites/default/files/reports/outlook.txt (accessed March 28, 2018). As a prey species of Steller Sea Lions, fluctuations to Pacific cod or sea lion populations will have implications for the other.

More specifically, in the Bering Sea/Aleutian Island areas, TAC is allocated by gear type, vessel size and processing ability, with a portion of TAC reserved for the Community Development Quota Program which benefits 65 small-scale fishing communities (Alaska Fisheries Science Center 2010). While in the Gulf of Alaska, the TAC is allocated by sub-area with 90% to the inshore sector and 10% to the offshore sector (processing done at sea). Additionally, the State allows the occurrence of a parallel fishing, where federally allocated TAC can be caught within state waters.

Currently, stock assessments have evaluated the stock to not be overfished and thus, the fisheries to be at low risk (Barbeaux et al. 2017). Despite its low risk status, the biomass has been decreasing (SeaFish 2018) and the TAC has declined from 64,000 t in 2017 to 13,000 t in 2018.

3.3.1.2 Characteristics of Pacific cod fisheries

Pacific cod in Alaska are caught and regulated by four gear types; trawl, longline, pots and, in smaller quantities, by jigs (Alaska Fisheries Science Center 2010). Specifically, in federal waters, Pacific cod are caught using all four gear types, while state waters only permit the use of pots and jigs. Trawling is the main gear type used (over two-thirds of catches) in catching Pacific cod in federal waters (Thompson, Dorn, and Nichol 2006). Studies comparing length distributions of fish caught through different gear types found that trawl tended to harvest smaller and younger fish than longline methods (Huse, Løkkeborg, and Soldal 2000). The use of gear is also highly dependent on seasonality, with use of pots exclusively in March, potentially in response to the movement of cod into deeper spawning grounds (McDowell Group 2017).

3.3.1.3 Defining small-scale and large-scale fishery

Possession of a fishing permit is required to fish for small-scale or large-scale purposes in Alaska (Alaska Department of Fish and Game 2018a). SSF and LSF are not restricted by distance, instead the distinguishing factor between SSF and LSF is the use of non-towed versus towed gear respectively (Doherty, Gibson, et al. 2015). In the case of the Pacific cod fishery, LSF employ the use of trawl, longline, pots and jigs while SSF are restricted to longline, pots and jigs.

Within SSF, licenses are classified as either for subsistence or personal use. Both of which are available exclusively to Alaskan residents who have resided in Alaska for at least 1 year. The differentiation being that subsistence small-scale fishing are restricted to more remote areas, away from densely populated ports such as around Anchorage, Fairbanks and Juneau (http://www.adfg.alaska.gov/index.cfm?adfg=subsistence.nonsubsistence). Further, subsistence SSF permits trading and selling, while personal use SSF is exclusively for personal consumption (Alaska Department of Fish and Game 2018b).

3.3.1.4 Applying social-ecological vulnerability framework

The social-ecological vulnerability framework, discussed above, is applied to Alaska's SSF and LSF Pacific cod fishery (Figure 3.1)

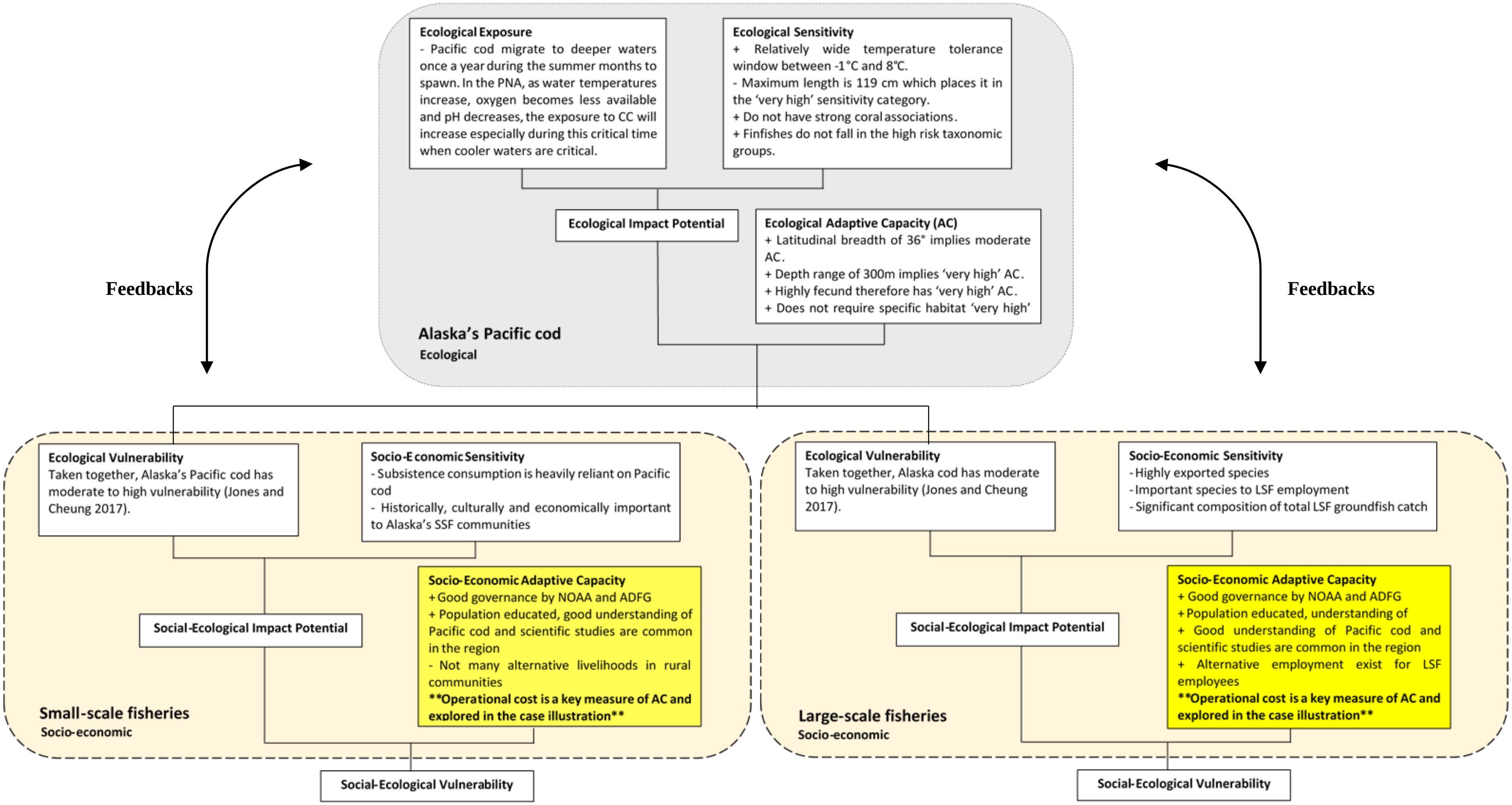


Figure 3.1: Application of the social-ecological vulnerability framework to Alaska's small-scale and large-scale Pacific cod fishery. Framework and definitions adapted from Cinner et al. (2013), Marshall et al. (2010), Jones and Cheung (2017) and Fenton et al. (2007). + and – indicate positive or negative contribution, respectively. Yellow box representing social-economic adaptive capacity was the focus of this case illustration.

3.3.1.5 Ecological framework

The ecological vulnerability for Alaska's Pacific cod SSF and LSF are similar as they exploit the same stock of Pacific cod located in Alaska Sub Arctic's EEZ; therefore, we applied the same ecological framework for both fisheries (Figure 3.1). Using the categories specified in Table 1 in Jones and Cheung (2017), we classified Alaska's Pacific cod and its ecological attributes into the following levels: low, moderate, high and very high risk.

Ecological exposure – Climate change projections include increases in temperatures and lowered oxygen levels (Burkett et al. 2014), Pacific cod will be exposed to less favourable conditions due to climate changes. This change may not pose much of an exposure threat, as Pacific cod are frequently exposed to fluctuating temperatures as they tend to live in shallower, nearshore waters for most of the year. However, during the spring months, Pacific cod need cooler waters to spawn and migrate to deeper waters. This exposure to warmer, acidic and less oxygenated waters especially during this critical spawning period can have implications for the species' ecological impact potential.

Ecological sensitivity – Pacific cod is generally a species with low sensitivity as it is able to tolerate a wide range of environmental conditions; temperature ranges from -1°C and 8°C, oxygen levels between 2 to 8ml/l and salinity ranges between 31 to 34 pps. However, with a maximum body length of 119 cm, it ranks in the "very high" sensitivity category as species with larger body sizes are more sensitive to changes. Further, as Pacific cod are not specifically associated with any habitat nor do they fall in a high risk taxonomic groups to ocean acidification like crustaceans (Jones and Cheung 2018), they have a lower ecological sensitivity to climate changes.

Ecological adaptive capacity – Based on Pacific cod's latitudinal range from 43°N to 79°N, the species is classified as having moderate adaptive capacity as it is able to slightly cope with climate changes by shifting latitudes up to a breadth of 36°. From a depth perspective, Pacific cod is able to shift up to a depth range of 300m, categorizing it as a species with "very high" adaptive capacity (Froese and Pauly 2018). This depth captures Pacific cod's spawning migration to deeper waters in the spring months. Additionally, the high fecundity and non-specific habitat required by Pacific cod leads to its categorization as a species with "very high" adaptive capacity (Jones and Cheung 2018). Overall, the "very high" adaptive capacity of Alaska cod is reflective of its ability to shift towards new habitats to quickly cope with climatic changes.

Ecological vulnerability – While Alaska cod has high adaptive capacity to climate change, its Ecological Impact Potential (the combination of Exposure and Sensitivity) is moderate to high as Pacific cod will be exposed to climate changes impacts during important developmental and life stages. Accumulated together, Pacific cod have moderate to high vulnerability (Jones and Cheung 2018), which indicates a moderate to high inability to cope with the adverse effects of climate change. This also represents the ecological exposure that Alaska's SSF and LSF are exposed to.

3.3.1.6 Social-Economic Framework

Based on this common ecological vulnerability of Alaska's Pacific cod, the overall social-ecological vulnerability was determined by the interaction of this "Ecological Vulnerability" component with SSF and LSF's social-economic sensitivity and adaptive capacity. As SSF and LSF have different social-economic characteristics, including sensitivities and adaptive capacities; they result in different social-ecological vulnerability.

<u>Social-economic sensitivity</u>

Small-scale fisheries – The degree of sensitivity is, in part, governed by the degree of community dependency on Pacific cod. In Alaska's remote communities, Pacific cod has been historically and is currently relied upon for subsistence consumption (McDowell Group 2017). However, as fishing is an integral component to livelihoods in Alaska, they have historically exploited a range of species such as salmon, halibut and black cod, to spread the risk and sustain a livelihood (McDowell Group 2017). This portfolio approach deems the fishery to be less sensitive to changes. Pacific cod is also an important species economically to SSF. It contributes to the livelihoods and income of Alaskan communities, composed about 12% of total Alaska's fisheries catches in 2016, 1.5 million USD of value and 10,900 jobs (McDowell Group 2017). Based on the importance of Pacific cod to Alaska's SSF communities, sensitivity projected for SSF communities to climate change is considered to be moderate.

Large-scale fisheries - Similar to its importance to the SSF, Pacific cod is an important species to Alaska's LSF, contributing a significant portion of exports and providing many employment opportunities. To a certain extent, as SSF and LSF are both operating within the same state and country, they are exposed to similar political conditions and have similar social-economic sensitivity. However, as LSF are usually owned and operated through fishing organizations and large companies, they have comparatively more economic and institutional power, which can reduce their sensitivity to the ecological vulnerability.

Social-economic adaptive capacity

Small-scale fisheries – Alaska's Pacific cod SSF has established and clear governance which increases its adaptive capacity. It is managed by NOAA and Gulf of Alaska Groundfish Management Plan in federal waters (3 to 200 nautical miles), and in state waters (defined as the distance from shore to three nautical miles) by Alaska Department of Fish and Game (ADFG) (National Oceanic and Atmospheric Administration 2018a). Additionally, a thorough scientific understanding of Pacific cod and a receptiveness on the part of the SSF communities towards new management approaches, significantly increases its adaptive capacity. For instance, detailed scientific studies by the National Marine Fisheries Service (NMFS) are done periodically to manage total allowable catches (TAC) for both SSF and LSF (National Oceanic and Atmospheric Administration 2018d, 2018c, 2018b). Additionally, Alaska's population tends to be educated and have an understanding that marine resources are central to their economy and identity. However, the lack of alternative employment opportunities in remote communities greatly reduces adaptive capacity as it presents a challenge in diverting livelihoods from the fishing sector and its associated secondary sectors.

Large-scale fisheries – Similar to Alaska's Pacific cod SSF, clear governance by NOAA and ADFG, a thorough understanding of Pacific cod and compliance on the part of LSF are key to strengthening its adaptive capacity. As some of the employment to the LSF are found outside Alaska, often times, contract jobs hire and pay for travel cost for employees to relocate from Washington to Alaska (McDowell Group 2017). In 2016, 29,600 workers come from other USA states to work in Alaska out of a total 99,000 jobs (McDowell Group 2017). Therefore, as these employees of LSF are not restricted to primarily fisheries dominant communities, some alternative livelihood opportunities would exist for employees of LSF in the continental USA.

Central to both SSF and LSF's social-economic adaptive capacity is economic flexibility, as measured by operational cost. Having economic flexibility is an important component of adaptive capacity as it allows the financial freedom and creates a buffer to implement new management strategies as necessary to adapt. A core component to the economics is the operational cost, which determines the final profits and revenues. In the next section, we specifically analyze the components of operational cost in SSF versus LSF, to determine how it impacts the adaptive capacity of both fisheries.

3.3.1.7 Adaptive capacity – operational costs of SSF versus LSF

As SSF and LSF vary significantly by region, this case illustration focused on Alaska's cod fishery, is not meant to be an indicator of overarching, global trends nor a comprehensive analysis of all attributing factors to the fisheries' adaptability. Instead, it is a step towards understanding the multi-dimensional and intricate factors that can influence adaptability and distinguish the long-term viability of SSF versus LSF in a changing ocean. The key operational indicators and their impact on the economic ability of Alaska's small-scale and large-scale

Pacific cod fisheries to adapt by shifting fishing grounds are defined in Table 3.1 and analyzed in detail below with respect to SSF and LSF.

Table 3.1: Description of indicators of adaptive capacity within operational costs.

Indicators	**Description**
Fuel consumption	The amount of fuel used per unit distance travelled. This represents the engine efficiency and mileage attained.
Fuel prices	The cost of fuel per volume metric.
Gear efficiency	The effectiveness of the gear in exclusively catching the target species. High gear efficiency represents fisheries that have high catches and low bycatch.
Travel distances	This represents the distance between home port and fishing grounds, up to a maximum of 200 nm from shore (EEZ limit).
Ability to switch gear types	The flexibility and ease of changing gear types. Often times, switching target species requires the use of new gear types and the capacity to easily switch gear types enhances the ability to adapt to new target species.
Labour cost	The cost of employment; this could either be an hourly wage or a seasonal wage (often a proportion of the annual catch).
Other technological improvements	Technological improvements to lower operational cost. For example, this could be through enhancing gear efficiency or reducing drag on the boat's hull.

The combination of fuel consumption of a vessel and the fuel price is the total cost of fuel. The type of gear utilized in a fishery plays a crucial factor in influencing the overall fuel expenditure. Generally speaking, the use of mobile and towed gear expends more energy and requires more fuel than static and non-towed gear (Polet and Depestele 2010; Davie et al. 2015). For example, Driscoll and Tyedmers (2010) showed that on average, in the Atlantic herring fishery, mobile gear types such as bottom trawl consumes 20 times more fuel than static gear types such as purse seines; a contrasting 2,000 liters per metric ton compared to 100 liters per metric ton, respectively. Furthermore, as the distinction between SSF and LSF in Alaska is by gear type, we expect tremendous variations in fuel expenditures between SSF and LSF. This assertion is corroborated by Sumaila et al. (2008), which estimates that fuel costs can vary significantly between a range of 30 and 60% of the total fishing cost. Specifically, we expect LSF in Alaska, which uses towed gear (trawl), to have a higher operational cost compared to SSF, which are restricted to non-towed, passive gear (longlines, pots and jigs). Moreover, a study by Lam et al. (2011b) ranks fuel costs to be the second largest expenditure in North American fisheries' variable costs. Thus, we expect this variation between SSF and LSF's fuel costs to play an important role in the economic flexibility and adaptability of the fisheries to climate change, as lower fuel expenses could equate to higher profits. As fish distributions are projected to shift to the poles with climate change, fishing vessels will have to expend more fuel to parallel these shifts and move to farther fishing grounds. Arguably, as SSF employ non-towed gear and possess a lower fuel expenditure, they are better able to adapt to changes and travel to farther distances on less cost. Further, with increased customer demand for low-carbon food production (Parker et al. 2015); this could be an added advantage to SSF in the region.

Surveys of fuel prices in Alaska over the past decades have documented overall increasing trends with further increases forecasted for the future. However, there is a degree of uncertainty and fluctuations to fuel prices, and this volatility further threatens fisheries. Globally, there have been numerous cases of rising fuel prices threatening the viability and livelihood of fishing communities (Abernethy et al. 2010; Wu 2004). Further, it is also common for rural ports to experience significant fuel markups from delivery and retail costs (Szymoniak et al. 2010).

Taken cumulatively, while Alaska's small-scale cod fishery possess gear types that consume less fuel, which drives its operational costs down, these SSF tend to be based in remote areas with limited accessibility to fuel and thus, suffer a larger economic disadvantage and reduced economic adaptability from inflated fuel prices compared to LSF. Furthermore, it was found that globally LSF have received 6.3 billion USD worth of fuel subsidies (Ussif Rashid Sumaila and Pauly 2006). While these subsidies help with the daily operation cost of the LSF, ultimately it masks the unprofitability of LSF and marginalizes the operation of SSF as the market is not truly competitive (Jacquet and Pauly 2008).

While fish distributions are documented to shift northward in Alaska's waters, the effect may be minimal on LSF compared to SSF, as they commonly employ the use of at-sea processors and tender boats to minimize their travelling distance to home port. There are about 25 at-sea processors in Alaskan waters with corresponding tender boats that shuttle catches to the at-sea processors as well as supply fishing vessels with food and fuel (www.jobmonkey.com/alaska/processor_jobs/). Contrastingly, SSF vessels usually fish for personal consumption or subsistence purposes often make day fishing trips and return to home port more frequently than LSF to land their catches. Based on this, we postulate that climate change related shifts on species distribution will have a greater effect on the operational cost of SSF than LSF.

In this case illustration, SSF are presently already utilizing the more fuel-efficient gear type (i.e., non-towed gear). However, one common adaptation strategy is to switch to more fuel-efficient gear types (Table 3.2). For instance, Polet and Depestele (2010) found that otter trawls which require one boat and consume less fuel than pair trawls. Further, midwater trawls, which experience less drag and contact with bottom substrate, have relatively low cost per ton of catch compared to bottom trawls (Polet and Depestele 2010). While switching between gear types appears to be a clear cost-saving strategy, the ability to switch gear types presents a challenge to SSF (Sherman et al. 2009). Especially, as LSF often have subsidies which adds an advantage by masking the true unprofitability and marginalizes the operation of SSF as the market is not truly competitive (Jacquet and Pauly 2008).

Table 3.2: Fuel consumption by fishing method in a case study of Norway

Type of gear	**Kg of oil/kg of catch**
Pelagic factory trawler	0.063
Longliner (coastal)	0.205
Seine nets	0.259
Gillnets	0.302
Purse seine	0.313
Longliner (offshore)	0.380
Bottom trawler	0.800
Shrimp trawler (offshore)	1.800

* *Extracted from Polet and Depestele (2010)*

While fuel is an important component to fisheries operations, labour costs compose the largest component to fisheries operational costs in North America (Lam et al. 2011). Specifically, in Alaska's cod fishery, 40.8% of the operational costs are attributed to labour (256 million out of a total 627 million dollars; McDowell Group 2017). On average, an Alaskan cod deckhand will earn slightly less than $21,000 USD from a fishing season, with a permit holder earning upwards of $29,000 USD (http://work.chron.com/much-average-alaskan-fisherman-make-24495.html).

The use of non-towed methods, such as longline which requires individually releasing the catch from each hook is more labour and cost intensive than LSF's towed and trawl methods (Fisheries and Aquaculture Department 2018). Despite the LSF's advantage on this aspect, generally speaking, employees of LSF operations are paid either on an hourly basis or by splitting the catch shares at the end of each day or season, while SSF derive their worth from immediate sales or consumption. The expense to LSF that operate on an hourly basis is costlier as it is directly correlated to the distance and travel time. In this case, travelling farther distances will be costlier from a LSF's labour cost perspective, while it would not further add to the labour cost for SSF.

The dependency on diesel as the main fuel source highlights the vulnerability of both SSF and LSF to future increases in fuel prices (Tyedmers 2004). With technological advancements, there are a plethora of recommendations for saving fuel and operational costs. Johnson (2011) in a report for the Alaska Sea Grant propose a series of fuel saving strategies including improving engine efficiencies, reducing drag and resistance from the boat's hull, and improving propulsion. These recommendations depend on the development of emerging technology including alternative fuels like bio-diesels, solar and battery powered vessels. While some may be more immediately feasible than others, ultimately such innovation should benefit both SSF and LSF and lower operational costs.

Table 3.3 summarizes the factors within operational costs (fuel, gear efficiency etc.) that impact the adaptability of Pacific cod's SSF versus LSF to climate change impacts. While it appears that LSF have a greater number of positive effects from the indicators analyzed compared to SSF, the magnitude and extend of each effect is not known. It is insufficient to conclude which fishery type has a higher operational cost adaptive capacity but to note the relationship and correlation between each factor.

Table 3.3: Summary of indicators and their impact on the economic ability through operational costs of Alaska's small-scale and large-scale Pacific cod fisheries to adapt by shifting fishing grounds. Using a binary approach for each indicator, red boxes (-) indicates a comparatively lack of adaptive capacity compared to green boxes (+).

Indicators	**Small-scale fisheries**	**Large scale fisheries**
Fuel consumption (Polet and Depestele 2010; Davie et al. 2015)	Non-towed gear uses less fuel. This reduces operational cost and enhance the ability to travel farther distances. (+)	Towed-gear have higher fuel consumption. This increases operational costs and limits ability to travel to farther distances. (-)
Fuel prices (Szymoniak et al. 2010)	Both fishery will experience increases in fuel prices in the future. As SSF tend to be based in remote areas, fuel prices are costlier due to delivery surcharges. Overall, this increases the operational cost. (-)	Both fishery will experience increases in fuel prices. LSF tend to be based in larger and central ports with easier access to competitive fuel prices compared to remote ports. This drives the operational cost down. (+)
Gear efficiency (Polet and Depestele 2010; Davie et al. 2015; Jacquet and Pauly 2008)	As SSF uses more selective, non-towed gear, there is greater catch per fuel consumed. (-)	LSF uses non-selective, towed gear. These tend to catch less per fuel consumed. (+)
Travel distances (www.jobmonkey.com/alaska/processor_jobs/)	SSF often have smaller capacities and travel back to home port after a day of fishing. This increases the travel distance and fuel expenditure. (-)	LSF often employ the use of at-sea processors and tender boats to shuttle catch and receive supplies including fuel, without having to return to home port. This minimizes the travel distance and fuel expenditure. (+)
Ability to switch gear types (Sherman et al. 2009, Jacquet and Pauly 2008)	There is limited ability to switch gear types as it is often not financially possible. (-)	While subsidies mask the true profits of the fishery, it provides LSF with the financial flexibility to more easily switch gear types. (+)

Labour cost* (FAO 2018)	SSF's non-towed methods like longline or pots are more labour and cost intensive than LSF's towed gear types. (-)	LSF's towed methods like trawl are less labour and cost intensive than SSF's towed gear types. (+)
Labour cost* (McDowell Group 2017)	As SSF use catch for personal consumption and immediate sales, their time is not directly compensated by distance. Therefore, operational cost is not affected by increased in climate related shifts on species distributions. (+)	Payment to crew is hourly or by catch shares. Expense is directly related to travel distance and expected to be costlier with climate related shifts on fish distributions. (-)
Other technological improvements (Tyedmers 2004, Johnson 2011)	Emerging technology and innovation will increase fuel efficiencies and reduce the operational cost of both SSF and LSF. (+)	Emerging technology and innovation will increase fuel efficiencies and reduce the operational cost of both SSF and LSF. (+)
Sum of positive adaptive capacity (green boxes)	**3**	**6**

* Labour cost were considered above in two components: labour cost to operate fishing gear and labour cost to travel to fishing grounds

3.3.1.8 Assumptions

The above analysis is based on the assumption that real ex-vessel prices stay constant. If there is an increase in ex-vessel prices due to a decline in catches of Pacific cod, then the higher price of fish may increase economic adaptability and compensate for the adaptive action, such as travelling to farther fishing grounds.

3.3.1.9 Social-ecological vulnerability

It is inconclusive to state which fishery type has a higher adaptive capacity. While SSF have less number of green boxes (Table 3.3) indicating less adaptive capacity attributes compared to LSF, the magnitude and extent of each effect is not known. Instead, we can note the relationship and correlation between each factor. Furthermore, as this is not a comprehensive list, we need to be aware that other attributes can also affect operational cost adaptive capacity. Additionally, analysis of other adaptive capacity factors illustrate that SSF can possess other adaptive capacities such as less reliance on one resource.

Accumulated together, while SSF may have a weaker adaptive capacity in terms of operational cost compared to LSF, the strengths that it displays in the other components of its socio-ecological vulnerability like lower sensitivities may eventually outweigh its weaknesses. The overall social-ecological vulnerability of SSF and LSF are based on the different components of the framework. Caution should be taken when extrapolating the patterns to other fisheries. Blasiak et al. (2007) calculated a vulnerability index for 147 countries by factoring in metrics for exposure, sensitivity and adaptive capacity including sea surface temperature increases, fisheries landing, proportion of active fishers, literacy rate and GDP per capita, among other metrics. As the United States is ranked as a country with overall low national vulnerability (Blasiak et al. 2017), this case study of Alaska’s Pacific cod fisheries has comparatively lower vulnerability to the impacts of climate change on marine fisheries compared to other fisheries and may not be an accurate reflection of all fisheries in the world.

3.3.1.10 Conclusion of case illustration #1

These trends in operational cost and the socio-ecological framework we observe in Alaska's Pacific cod fishery is simply one case illustration. However, the indicators and the relationships can be noted and considered in other applications. For instance, often times, LSF are known to have more resources and capacities in the form of economic flexibility through subsidies and fishing capacities.

Operational cost is a key measure of adaptive capacity because cost relates to profitability and if a fisheries business becomes unprofitable, it will not be viable. To answer our research question of "**How does operational costs impact the economic profitability and adaptive capacity of SSF versus LSF to climate change impacts on catch potentials and species richness?**", it is apparent that within operational cost lies several indicators not limited to fuel consumption, gear efficiency, fuel prices, travel distances, ability to switch gear, labour cost and technological improvements. From this case illustration of Alaska cod fishery, SSF and LSF have different strengths and weaknesses in various operational costs factor. Ultimately, while LSF have more "wins", the magnitude of these "wins" is not quantified in this study. Instead, we can draw valuable understanding on key areas of improvement in operational costs for both SSF and LSF to adapt to CC.

3.3.2 Case Illustration #2 and #3 – Key adaptive capacity for rapid changes

<u>From Chapter 2, we projected rapid changes in fisheries catch portfolio and species distributions in the future. Using case illustration SSF of Mexico's jellyfish and USA's wetfish, what are characteristics that enable them to successfully adapt to these rapid changes?</u>

With the effects of climate change, the ocean, its conditions and species are ever evolving and changing. One of the observations, as projected in chapter 2, is the sudden and rapid appearance of certain species. For example, booms in catches of California market squid (*Loligo opalescens*) and cannonball jellyfish (*Stomolophus meleagris*) are documented for the Pacific coast of North America. Part of a successful fisheries adaptation strategy is being opportunistic to the high adaptive capacity of these species and possessing the capabilities to switch target species easily. In this chapter, we apply the social-ecological vulnerability framework to the two case illustration fisheries: Monterey Bay's wetfish SSF and Sonora's jellyfish fishery. The high ecological adaptive capacity observed for California market squid and cannonball jellyfish represents a general observation of rapid ecological changes anticipated for certain highly adaptable species (Chapter 2). This section of the chapter involves understanding and describing key social-economic adaptive capacity characteristics of SSF that best enable them to adapt to these rapid changes in species distributions or catch availabilities.

The following two case illustrations have significantly different characteristics in catch portfolios, location and management strategies. However, both are examples of fisheries that were able to be opportunistic and quickly adapt to rapid changes in species abundance and distributions. Below, we used the social-economic vulnerability framework to guide our understanding of these fisheries and analyze key components that prompted their adaptation.

3.3.2.1 Monterey Bay's wetfish fishery (USA)

This is an example of a fishery that continues to be able to effectively adapt to climatic-driven changes in species distributions through a multi-species portfolio approach. The "wetfish" fishery refers to a final canned product where fish are canned fresh and cooked within the cans. Operating out of three ports in the Monterey Bay area of California (Santa Cruz, Moss Landing and Monterey) and utilizing a portfolio approach, this fishery rotates through exploitation of three species, Pacific sardine (*Sardinops sagax*), northern anchovy (*Engraulis mordax*) and California market squid (*L. opalescens*) depending on catch availabilities and market demand (Aguilera et al. 2015). The fishery is classified to be small-scale as they are individually-owned family operations, with small crew sizes and fishing done relatively close to shore (day operations). As most fishers hold a federal coastal pelagic species permit and a state market squid limited entry permit, they have the flexibility to easily switch exploited species (Aguilera et al. 2015). Further, exploitation of all three species uses the same purse seine gear type which adds to the ease of rotating through exploited species (Aguilera et al. 2015). The Monterey Bay's wetfish fishery is an economically significant fishery in the region, contributing about 91.3% of landings and 48.3% of ex-vessel revenues across the three ports (Aguilera et al. 2015).

Historically, analysis of the period between 1976 to 2012 indicates that switching between target species has largely been driven by environmental conditions (El Nino), regulations (limited access) and market prices. The fishery mainly targets squids and sardines, with squid being a relatively fast growing and high value species ($0.245/lb) while sardines are slow growing and lower value species ($0.148/lb) (Aguilera et al. 2015). California market squid became the largest California fishery in landings and revenues in the 1990s (Koslow and Allen

2011). The wetfish fishery is readily capable to shift exploited species based on the availability of resources within the fishing area.

3.3.2.1.1 Applying the socio-ecological vulnerability framework

The social-ecological vulnerability framework, discussed above, is applied to Monterey Bay's wetfish SSF (Figure 3.2).

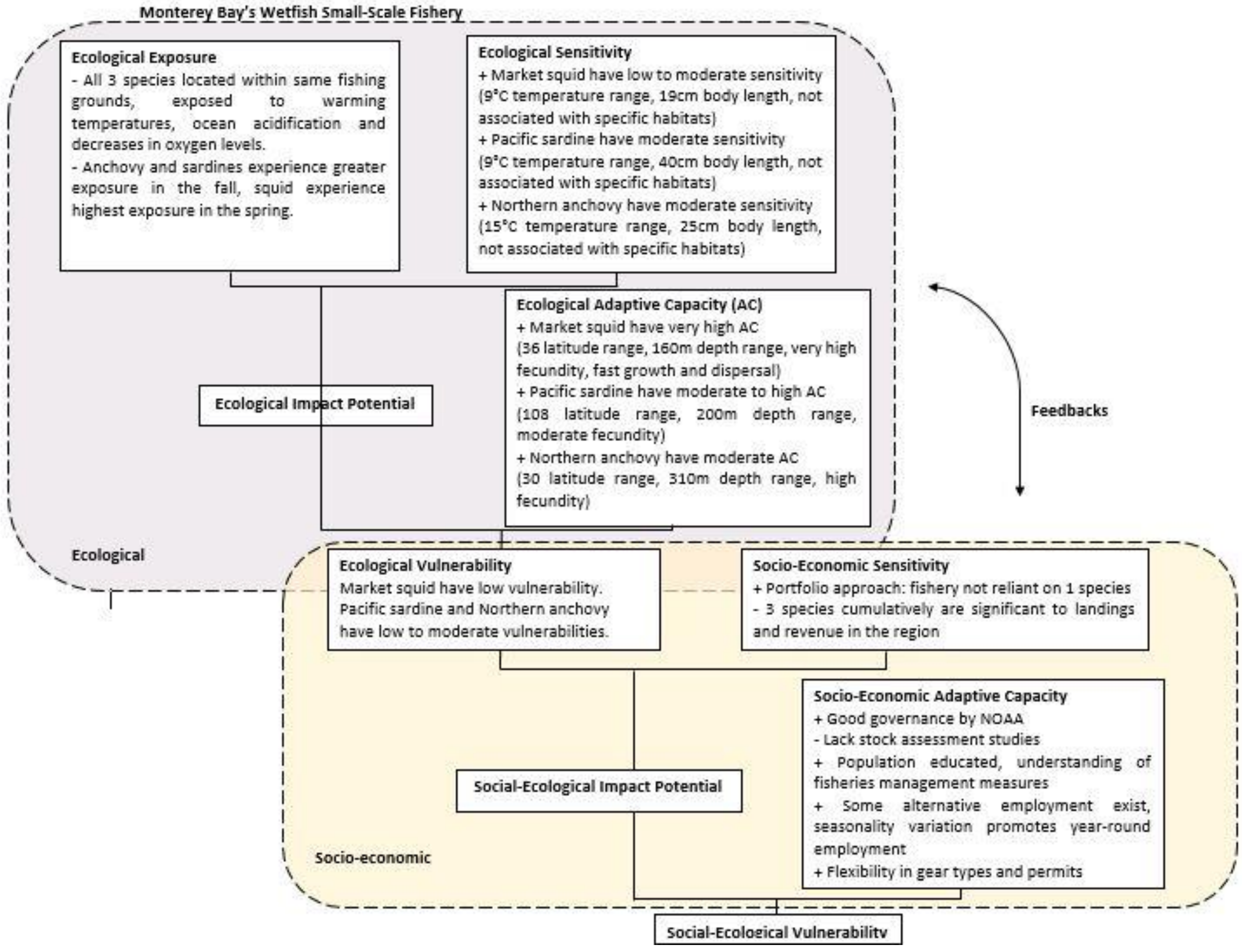


Figure 3.2: Application the social-ecological vulnerability framework to USA's Monterey Bay wetfish fishery. Framework and definitions adapted from Cinner et al. (2013), Marshall et al. (2010), Jones and Cheung (2017) and Fenton et al. (2007). + and – indicate positive or negative contribution respectively.

3.3.2.1.2 Ecological framework

Ecological exposure – All three species are located within similar fishing grounds and are exposed to similar environmental conditions. However, their exposure varies with seasonality, with anchovy and sardine most abundant and experience greater exposure in the fall while squid is primarily caught and exposed in the spring months. Exposure of all three species to climate effects are especially critical during spawning season. For instance, spawning behaviour for squids are stimulated by water temperature between 10 to 14.4°C (Zeidberg et al. 2011), changes to temperature as projected with climate change will have ecological exposure implications for spawning.

Ecological sensitivity –

California market squid is a species with low to moderate sensitivity as it is able to tolerate a range of environmental conditions; temperature tolerances ranges from 4°C and 13°C, oxygen levels between 0 to 7ml/l and salinity ranges between 4 to 44 pps (Palomares and Pauly 2018; Encyclopedia of Life 2018). It has a maximum body length of 19 cm, ranking in the "low" sensitivity category. Further, market squid are not specifically associated with any habitat nor do they fall in a high risk taxonomic groups to ocean acidification like crustaceans (Jones and Cheung 2018), they have a lower ecological sensitivity to climate change.

Pacific sardine is a species with moderate sensitivity, demonstrating the ability to tolerate a moderate range of environmental conditions; temperature tolerances ranges from 8°C and 17°C, oxygen levels between 3 to 6ml/l and salinity ranges between 32 to 36 pps (Froese and Pauly 2018; Encyclopedia of Life 2018). Further, it has a maximum body length of 40 cm, ranking in the "moderate" to "high" sensitivity category. Further, Pacific sardine are not specifically associated with any habitat nor do they fall in a high risk taxonomic groups to ocean acidification like crustaceans (Jones and Cheung 2018), they have a lower ecological sensitivity to climate change.

Similarly, northern anchovy is also a species with moderate sensitivity as it is able to tolerate a moderate range of environmental conditions; temperature ranges from 7°C and 22°C, oxygen levels between 3 to 7ml/l and salinity ranges between 31 to 34 pps (Froese and Pauly 2018; Encyclopedia of Life 2018). It has a maximum body length of 25 cm, ranking in the "moderate" sensitivity category. Further, northern anchovy are not specifically associated with any habitat nor do they fall in a high risk taxonomic groups to ocean acidification like crustaceans (Jones and Cheung 2018), they have a lower ecological sensitivity to climate change. Historically, anchovy populations have displayed sensitivity to climate changes, having undergone fluctuations in populations with climate variability (Thayer et al. 2017).

Ecological adaptive capacity –

California market squid has a latitudinal range from 62°N to 26°N which classifies it as having moderate to high adaptive capacity as it is able to slightly cope with climate changes by shifting latitudes up to a breadth of 36°. From a depth perspective, California market squid is able to shift up to 160m (20-180m), categorizing it as a species with "moderate" to "high" adaptive capacity (Fishbase). This depth captures its migration to benthic habitats for spawning. Additionally, the especially high fecundity and non-specific habitat required by California market squid leads to its categorization as a species with "very high" adaptive capacity, as squids are able to reproduce and recover its population quickly. They are known to be an archetypal live-fast and die-young species (Perretti, Zerofski, and Sedarat 2016) as they have the ability to grow, disperse and reproduce rapidly within a lifespan of 9 months (Aguilera et al. 2015). Overall, the high adaptive capacity of California market squid is reflective of its ability to shift towards new habitats to quickly cope with climatic changes. As water temperature rises along the Pacific, this opens new and otherwise inaccessible habitats to California market squid. This may explain their prevalence and success in extending their range and dominating catches in fisheries projection studies, such as in Chapter 2.

As an equatorial species, Pacific sardines have a large latitudinal range from 61°N to 47°S which classifies it as having “very high” adaptive capacity. From a depth perspective, Pacific sardine is able to shift up to a depth range of 200m, categorizing it as a species with “moderate” to “high” adaptive capacity (Froese and Pauly 2018). Additionally, the moderate fecundity and non-specific habitat required by Pacific sardine adds to its categorization as a species with “high” adaptive capacity.

Northern anchovy has a latitudinal range from 51°N to 21°N which classifies it as having low adaptive capacity as it is able to cope with climate change by shifting latitudes up to a breadth of 30°. From a depth perspective, northern anchovy is able to shift up to a depth range of 310m, categorizing it as a species with “very high” adaptive capacity (Froese and Pauly 2018). Additionally, the high fecundity and non-specific habitat required by northern anchovy leads to its categorization as a species with “high” adaptive capacity. Overall, the moderate adaptive capacity of northern anchovy is reflective of its ability to shift towards new habitats to quickly cope with climatic changes.

Ecological vulnerability – Overall, California market squid have low vulnerability, while Pacific sardine and northern anchovy have low to moderate vulnerabilities (Cheung et al. 2005). This indicates a slight advantage for California market squid in coping with the adverse effects of climate change. While northern anchovy has similar ecological vulnerability to Pacific sardine, it is a low value species with an ex-vessel price of $0.06/lb. Compared to market squid at $0.25/lb and Pacific sardine at $0.15/lb, fishing for northern anchovy makes little economic sense and is often a last resort as there are other more profitable alternatives available (Aguilera et al. 2015). Taken together, this also represents the ecological exposure that the Monterey Bay's wetfish SSF is exposed to.

While these are the reported vulnerabilities, previous studies have also documented that market squid population fluctuates with climate changes (Koslow and Allen 2011). Historically, their populations thrive in cooler La Nina years and decline in warm El Nino years. While they prefer cooler waters, their temperature tolerance ranges between 4 to 13°C, currently concentrating populations off the coast of USA West Coast. As water temperature rises along the Pacific coast, it opens new and otherwise inaccessible habitats to California market squid. This may explain their prevalence and success in extending their range and dominating future catches in North American fisheries, as projected in Chapter 2.

3.3.2.1.3 Social-Economic Framework

Based on this common ecological vulnerability of Monterey Bay's wetfish SSF, the overall social-ecological vulnerability was determined by the interaction of this "Ecological Vulnerability" component with the social-economic sensitivity and adaptive capacity.

Social-economic sensitivity – The fishery and community is not exclusively dependent on one species for its viability. This risk distribution through a portfolio approach reduce the community reliance and social-economic sensitivity to climate change. It allows pressure on any vulnerable species to be reduced with compromising the fishing livelihoods. However, taken cumulatively, all 3 species contribute to the Monterey Bay's wetfish fishery being an economically significant fishery in the region; contributing about 91.3% of landings and 48.3% of ex-vessel revenues across the three ports (Aguilera et al. 2015). Therefore, there is a high community dependency in terms of job security and economic activity on the wetfish fishery as a whole.

Social-economic adaptive capacity – Fisheries in the region are governed by NOAA with clear regulations in place which increases its social-economic adaptive capacity. However, improvements could be made to better understand stocks. Currently, there are no formal stock assessment studies done for the wetfish fishery species, which reduces our understanding of current populations and limits social-economic adaptive capacity. For instance, the squid fishery has restrictions in place on gear, closure dates, seasonal 118,000 t catch limit and permit limits (California Department of Fish and Game 2005). However, these are based on landings from 1998 to 2000 as there are no formal stock assessment studies. The population tend to be well-educated and the fisheries are family-owned and operated. This increases the social-economic adaptive capacity as there is a greater chance of community acceptance and understanding for fisheries management measures like catch or bycatch limits and fishing closures. While some alternative livelihood opportunities exist in the area, Aguilera et al. (2015) argue that the seasonality variation of the three species in the wetfish fishery promotes year round livelihood opportunities in this fisheries. Further, as the same gear type (purse seine) is used to target all three species (Aguilera et al. 2015), the fishery is able to switch target species easily and quickly. This increases the overall adaptive capacity of the wetfish fisheries.

3.3.2.1.4 Social-ecological vulnerability

In summary, the social-ecological vulnerability of the Monterey Bay's wetfish fishery is low. This is due to the low ecological vulnerability of exploited species and high adaptive capacity of the fisheries. The three species in the wetfish fishery have low risk of impacts by climate change as they have overall low to moderate ecological vulnerabilities, with California market squid having the lowest vulnerabilities of the three species. This analysis suggests that the wetfish fisheries possess the adaptive capacity characteristics to thrive and capitalize on this ecological change.

However, under climate change scenarios, where previously inhabitable polar habitat becomes viable, we can expect a northward shift in the geographic range of the three exploited species. More specifically, as California market squid have the lowest vulnerability of the three species, has documented success in climate change projections (Chapter 2) and is presently the primary exploited species of the wetfish fishery, due to its capability to reproduce, grow and disperse quickly, we can expect the quick and successful movement of squid towards more northern waters in Canada and Alaska, and away from equatorial waters. The displacement of this species from the fishery will have broader implications as this implies large potential changes in the catch portfolio. From a social-economic perspective, as described above, the Monterey Bay's wetfish fishery has relatively high adaptive capacity largely due to its flexibility in permits and gear types. Arguably, these key social-economic adaptive capacity characteristics, as further discussed in section 3.2.3 below, will enable it to adapt to new species that newly inhabit the Monterey Bay fishing areas.

3.3.2.2 Sonora's cannonball jellyfish fishery (Mexico)

Cannonball jellyfish (*S. meleagris*) is a non-native species in the Gulf of California. In 2012, the high availability of nutrients, ideal temperatures (20-29°C) and strong northward currents in El Golfo de Santa Clara (located within the State of Sonora, the Northern most point in the Gulf of California) caused a massive cannonball jellyfish bloom. The timing of the bloom in June complemented the local fishery, whose fishing activity for finfishes had decreased during the summer months due to the scarcity of fish from the heat (López-martínez and Álvarez-tello 2013). While the processing of jellyfish is a relatively simple process of salt-drying, the large quantities of jellyfish needed to optimize production and the time sensitive nature to process the jellyfish post-harvest creates hundreds of alternative jobs for the community, which has heavy reliance on fishing for their livelihoods (López-martínez and Álvarez-tello 2013). Additionally, jellyfish is an extremely profitable fishery, drawing upwards of $0.19 to $0.30 USD per kg, with significant demand in Asian markets (López-martínez and Álvarez-tello 2013). Based on its potential, the local community invested millions of dollars into the infrastructure, equipment and training involved in fishing and processing of jellyfish (Girón-Nava et al. 2015b). In 2012, 9 jellyfish export companies and 20 processing plants were built in Sonora and the fishery landed approximately 20,000 t, worth over 3.5 million USD in revenue (Girón-Nava et al. 2015b). Fishing required little gear changes from the existing finfish fishery as fishing was conducted by acquiring reasonably cheap hand-nets to scoop jellyfish from the surface of the water while on pangas or fiberglass boats (López-martínez and Álvarez-tello 2013). The community was able to quickly adapt to the sudden changes in resource availability and capitalize on the wealth that the jellyfish provided. Despite an incredibly successful fishing season and the massive investment, cannonball jellyfish did not return in 2013, wasting millions of dollars' worth of investments.

3.3.2.2.1 Applying the socio-ecological vulnerability framework

The social-ecological vulnerability framework, discussed above, was applied to the Sonora region of Mexico's jellyfish SSF (Figure 3.3).

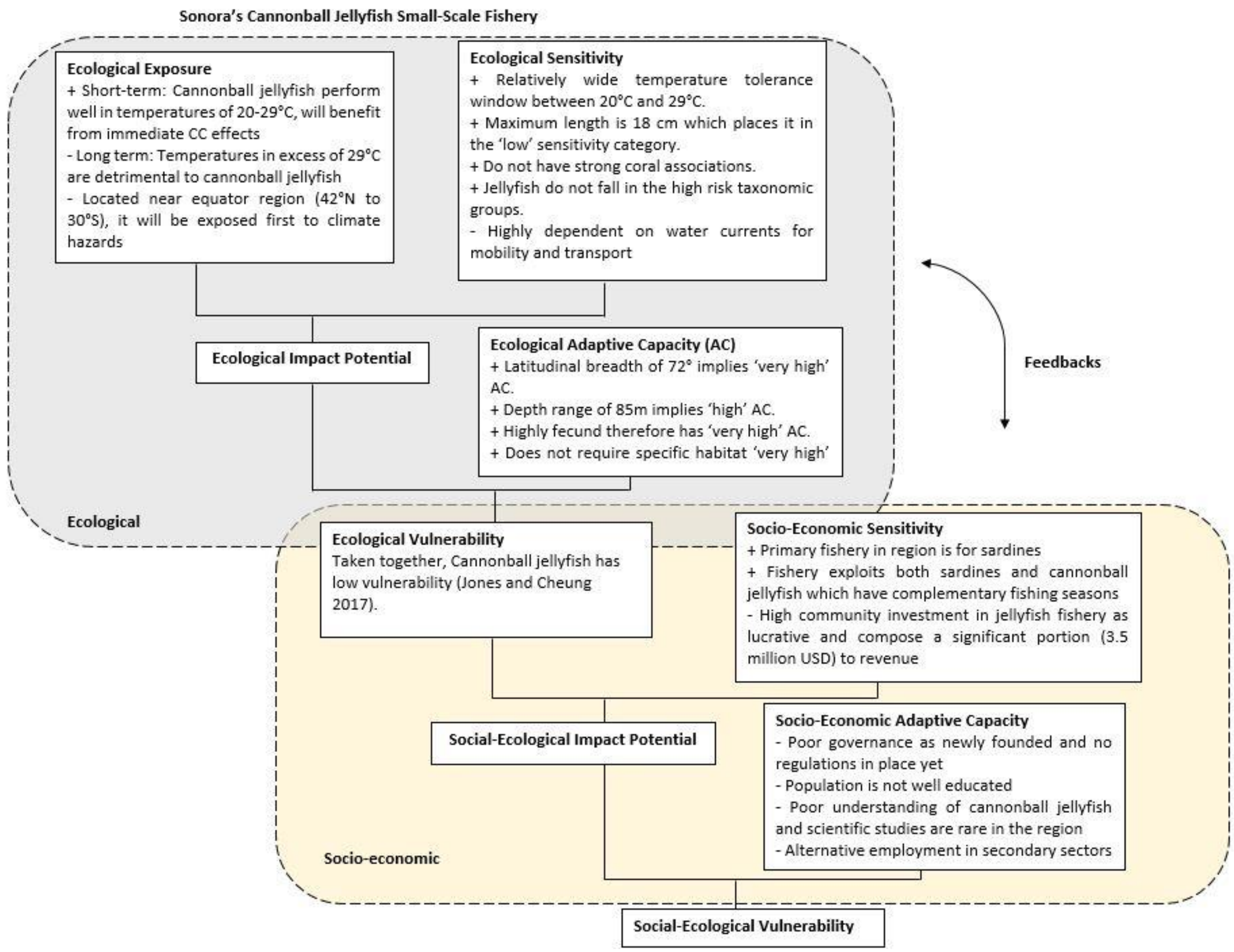


Figure 3.3: Application the social-ecological vulnerability framework to Mexico's cannonball jellyfish fishery. Framework and definitions adapted from Cinner et al. (2013), Marshall et al. (2010), Jones and Cheung (2017) and Fenton et al. (2007). + and – indicate positive or negative contribution respectively.

3.3.2.2.2 Ecological framework

Ecological exposure – Jellyfish perform well in conditions of high nutrient availability, warmer temperatures (20-29°C) and strong currents to further spread its geographic range, which are all oceanographic effects projected with climate change. While warm water temperatures are critical to its growth during the strobilation phase in June, too high of temperatures, in excess of 29°C, is detrimental to its survival (Girón-Nava et al. 2015). Therefore, in terms of its ecological exposure, climate change produces short-term benefits with its warming temperatures. However, in the long-term, this continued warming temperature may surpass the point where they are beneficial to jellyfish. Further, cannonball jellyfish's latitudinal range from 42°N to 30°S spans the equator and tropical regions which will experience the largest effect from climate change (Froese and Pauly 2018).

Ecological sensitivity – Using the categories within sensitivity from Jones and Cheung (2017), cannonball jellyfish is generally a species with low sensitivity as it is able to tolerate a wide range of environmental conditions; temperature ranges from 20 to 29°C, and they are not specifically associated with any habitat nor do they fall in a high risk taxonomic groups to ocean acidification like crustaceans (Jones and Cheung 2018). Cannonball jellyfish are small in size with a maximum body length and a dome-shaped bell of 18 cm, ranking in the "low" sensitivity category.

Despite this low sensitivity to environmental conditions, they are sessile invertebrates that rely on currents to move and the prevalence of cannonball jellyfish is highly dependent on water currents. While 2012 had extremely ideal conditions for jellyfish, the subsequent year had no jellyfish due to changes in water currents. Therefore, they are highly sensitive to other environmental conditions such as water currents.

Ecological adaptive capacity – Based on cannonball jellyfish's latitudinal range from 42°N to 30°S, the species is classified as having "very high" adaptive capacity as it is able to cope with climate changes by shifting latitudes up to a breadth of 72°. From a depth perspective, cannonball jellyfish are able to shift up to a depth range of 85m, categorizing it as a species with "high" adaptive capacity (Froese and Pauly 2018). This depth difference captures the various habitat required at each developmental stage from the low-lying substrate at the scyphistoma stage to free swimming open ocean stage at the ephyrae stage (Encyclopedia of Life 2018). Overall, the "high" adaptive capacity of cannonball jellyfish is reflective of its ability to shift towards new habitats to quickly cope with climatic changes.

Ecological vulnerability – Cannonball jellyfish has high adaptive capacity to climate changes, its Ecological Impact Potential (the combination of Exposure and Sensitivity) is low as cannonball jellyfish will be exposed to climate change impacts that are beneficial for its developmental and life stages. Accumulated together, cannonball jellyfish have low vulnerability (Jones and Cheung 2018), which indicates a low inability to cope with the adverse effects of climate change. This also represents the ecological exposure that the fishery is exposed to.

3.3.2.2.3 Social-Economic Framework

Based on this common ecological vulnerability of Sonora's cannonball jellyfish SSF, the overall social-ecological vulnerability was determined by the interaction of this "ecological vulnerability" component with the social-economic sensitivity and adaptive capacity.

Social-economic sensitivity – The degree of sensitivity is, in part, governed by the degree of community dependency on cannonball jellyfish. The community has not historically relied upon cannonball jellyfish and the primary fishery has been focused on sardines. However, with the appearance of cannonball jellyfish in 2012, the fishery quickly invested capital towards the more lucrative jellyfish fishery (9 jellyfish export companies were established and 20 processing plants were built) and away from the finfish fishery. This hefty investment implies a desire to rely upon this resource in the future. In 2012, the fishery landed approximately 20,000 t of catch, worth over 3.5 million USD in revenue, which composes a significant portion of the income to the fishing communities. Sardines and cannonball jellyfish have different fishing seasons, therefore it lowers the sensitivity as it encourages a portfolio approach by spreading the risk among finfish and invertebrate catches. Based on the importance and investment of cannonball jellyfish to Sonora's SSF communities, there is a moderate sensitivity projected for SSF communities to climate change.

Social-economic adaptive capacity - As this is a new fishery with no governance or regulations in place, it is mismanaged and uncontrolled, ultimately decreasing its social-economic adaptive capacity. The population is not well educated and scientific studies, especially on cannonball jellyfish are rare. Documentation is poor and the species is not well understood in the region, which lowers its adaptive capacity to climate changes. Alternative employment exists beyond fishing, in the seafood processing and export industries, which are ultimately still connected to the fishing sector.

3.3.2.2.4 Social-ecological vulnerability

The high ecological adaptive capacity and low ecological vulnerability of cannonball jellyfish to climate change, as analyzed above, leads to its rapid growth and thriving populations under climate change. Despite these blooms, the social-economic vulnerability assessment suggests that the fishery and community may not be able to adapt and capitalize on these rapid changes. For instance, the lack of management and the absence of thorough scientific understanding on cannonball jellyfish populations may lead the fishing community to demise through overexploitation and reduce the overall social-ecological vulnerability, despite the strong ecological adaptive capacity.

3.3.3 Key social-economic adaptive capacity characteristics for rapid ecological changes

Drawing upon both case illustrations, several social-economic adaptive capacities were proposed that enabled the fisheries to adapt to climate change impacts on catch and species distributions. The following is not meant to be a comprehensive list of all the adaptation enhancing strategies, instead it provides an account of a few characteristics that had positive implications for the case illustration fisheries.

1. Ease of access to gear

In the case illustration of the Monterey Bay's SSF, the fisheries employ the use of seine gear to catch the three target species; sardines, squids and anchovies. The use of common gear, purse seine, amongst the three fishery enables the relative ease and flexibility to switch target species. As no new gear purchase is needed, the fishery is not restricted by financial means. Especially as SSF have reduced and limited financial capacities, adaptation strategies that have minimal costs are more likely to be implemented and have higher success over more cost intensive strategies, such as new purchases of different gear types. In comparison, to transition Sonora's sardine fishery to a jellyfish fishery, it required the purchase of new gear. As the boats were already used in the existing sardine fishery, the purchase of hand-held nets being relatively cheap, especially compared to the return in profits of jellyfish harvest, enabled easy transition in catch profiles. Primarily sold to China, dry-weight of jellyfish can sell for upwards of $0.19-0.30 per kg (López-martínez and Álvarez-tello 2013). While it was fruitful the first fishing season, the purchase of these nets contributed to other expenditures and investments required to develop the new jellyfish fishery ultimately was wasted when the cannonball jellyfish did not appear the following year.

2. Enabling regulations and management

In some cases, fisheries may have the physical and financial abilities to adapt to sudden changes in species availabilities, however enabling regulations need to be in place to afford fisheries the jurisdictional capabilities to make this shift. For example, fisheries with relatively easy entry are more likely to be opportunistic and in a better position to enter a new fishery. In the case of Monterey Bay's SSF, the possession of both the federal coastal pelagic species and a state market squid limited entry permit provide fishers with added economic stability to easily switch between target species based on availability, without the need to undergo lengthy permit applications which can hinder immediate adaptation. While it appears that flexible management is key to adaptation, fisheries with little governance can suffer contrasting pitfalls. For example, in Sonora's SSF, the bloom of jellyfish was a first for the region and the jellyfish fishery developed into open access with no established regulations or permits (López-martínez and

Álvarez-tello 2013). While this open access has enabled easy shifts between target species (from sardines to jellyfish), the lack of governance can be hazardous in terms of ensuring the long-term sustainability of the resources. Arguably, the sudden wealth of cannonball jellyfish populations with little management prompted the complete exploitation of this jellyfish resource in 2012 (Girón-Nava et al. 2015).

Management strategies that enable flexibility in responses to fluctuating conditions and avoid constraining fisheries to certain species or location appear to work best for adaptation. For instance, closed access policies that limits fisheries to a certain area or species such as Territorial Use Rights for Fishing (TURFs) or Individual Transferrable Quotas (ITQs) respectively, impairs the adaptation response (Aguilera et al. 2015). Furthermore, the Monterey Bay's SSF highlights the benefits of a multi-species portfolio management as opposed to management by individual species. Portfolio management allows for the understanding of multi-species interactions and to consider strategies and management that account for the overall ecosystem instead of the effect on a single species.

Other studies in different regions of the world have reached a similar conclusion. In Southeast Asia, Bailey and Pomeroy (1996) have shown that communities with high resource dependencies on a single species are especially vulnerable to externalities. Interestingly, Coulthard (2008) found that poor fishers are better able to adapt compared to fishers who are locked into an overly specialized fishery. Thus, successful regulations that enable access to additional permits and resources will better enable fisheries to adapt to these changing conditions.

3. Strong social capital and community supported approaches

Another common way to increase adaptability to climate induced changes on species distribution is to spread the risk out through membership in fishing cooperatives. In Mexico's Baja California Sur, membership in a cooperative allocates individual fishers with the ability to stack and share multiple permits, which may be difficult and expensive to acquire on their own. This allows fishers to collectively exploit a wider range of species and in more diverse locations (Sievanen 2014). Having the option and flexibility to fish more than one stock, spread the risks and increases the overall ability to adapt to changes.

Strong social capital and community trust as well as common norms and values are characteristics that strengthen the social cohesiveness of a fishing community, which can increase adaptive capacity. Perry et al. (2010) illustrated that the ability to draw on social capital such as family networks and community support during difficult times can increased fisher's adaptive capacity to changes.

4. Knowledge and education

Knowledge is beneficial and can add value to the adaptation capacity of a fishery. One commonly understood method of enhancing adaptation is through capacity building and promotion of education. In addition to enabling fishers to make more informed decisions and engage in safer fishing practices, education and skill building also adds to fishers' understanding of the impacts of climate change on fish resources. This knowledge can be acquired through education and training programs and also through intergenerational and traditional knowledge. For instance, Vásquez-León (1994) found that small-scale shrimp fishers from traditional fishing families had increased awareness and access to knowledge and mechanism that allowed them to diversify when shrimp resources became scarce.

As jellyfish are known to be highly unpredictable stocks that can appear sporadically with low predictability, the Sonora's jellyfish fishery is a clear example of a fishery that should be managed and invested with caution. Jellyfish blooms with its resulting high landings can easily overwhelm the market and lower the competitiveness of prices (Johnson 2015). Therefore, making accurate predictions on stock management can prevent stock collapse and enhance the viability of the fishery. To further exacerbated the issue, scientific studies in the Baja California region are lagging behind the development of the jellyfish fishery (López-martínez and Álvarez-tello 2013). Robust science, partnerships with the fishing communities and proper transfer of knowledge needs to accompany the growth of the fishery to ensure its sustainability.

3.3.4 Conclusion of case illustration #2 and #3

While climate change can produce considerable losses in catch potential and species distributions for most species, certain species are tolerable to climate impacts or are quickly able to adapt to these changes. California market squid and cannonball jellyfish are among two of these species with rapid growth in abundance projected for the future. The above analysis of our case illustrations in Monterey Bay's wetfish fishery and Sonora's jellyfish fishery, suggests that common fisheries social-economic adaptive capacities exist which are associated with the ability to capitalize on the ecological abundance. Such includes ease of access to fishing gear, enabling regulations and management, strong social capital and a foundational knowledge and education. These common social-economic adaptive capacities are widely recognized in other successful fisheries (Aguilera et al. 2015; Cinner et al. 2012; Cinner et al. 2013). Finally, PNA region countries exhibits moderate to high adaptive capacity and low to moderate vulnerability, according to a national fisheries vulnerability study conducted by Allison et al. (2009). Therefore, it is important to place this analysis into a global context as it represents countries and case illustrations that perform better and have higher abilities to cope.

3.4 Chapter conclusion

Projections for the coming decades forecast large-scale changes in catch potentials and species richness along the PNA region (Chapter 2). Majority of the species in PNA will experience negative effects from climate change, although selected low vulnerability-high adaptive capacity species will thrive under climate change conditions. The ability of fisheries and fishing communities to adapt to these ecological changes will determine their continued viability. Vulnerability frameworks are tools that can be used to disaggregate and understand each component of the fisheries from an ecological or social-economic dimension and to recognize their contribution to the overall socio-ecological vulnerability of the system.

The aim of this chapter is to understand the complex and linked interactions between the ecological, social and economic components within a fishery by applying the Cinner et al. (2013) framework to the three case illustrations in the PNA region. Ultimately, to answer our research questions: **(a) How does operational costs impact the adaptive capacity of SSF versus LSF to climate change impacts on catch potentials and species richness? (b) What are common adaptive capacity characteristics of SSF that enable them to successfully adapt to the rapid changes in catch potential and species distributions?**

As viable fisheries are profitable businesses, having strong financial capabilities can buffer against the impacts of climate change and add adaptive capacity. As lower operational costs create more financial flexibility for fisheries, characteristics that reduce costs such as having non-towed and more efficient gear, cheaper fuel, shorter travel distance, easy of flexibility in switching gear, less labour intensity and employing emerging technology tend to be associated with increased fisheries' adaptive capacity. More specifically within our case illustration of Alaska's cod fishery, LSF tend to exhibit more of these cost saving characteristics. Generally, countries in the PNA region tend to have lower vulnerabilities and higher adaptive capacities to climate change compared to other fishing countries (Blasiak et al. 2017; Allison et al. 2009), however there is still some variations in vulnerabilities across the region. According to Allison et al. (2009), Mexico has a "moderate" vulnerability, Canada ranks as "low" vulnerability" and USA has "very low" vulnerability. As species are projected to move northwards away from Mexico's waters with climate change, the impacts to Mexico's fisheries may be more severe. Furthermore, there can also be high variability within an EEZ. For instance, Okey et al. (2013) analyzed the ecological vulnerability in Pacific Canada and revealed that habitat structure, depth in water column and spatial characteristics produces significant changes in ecological vulnerability to climate change.

This particular vulnerability framework applied in this chapter, from Cinner et al. (2013), as adapted from IPCC (2014), improves upon previous versions by positively accounts for both the ecological and social-economic components. Additionally, it captures the dynamic nature of each component in the system and its constant interactions and feedbacks. Vulnerability, through this framework, is expressed as evolving and shifting over time. However, the framework could be improved upon by explicitly accounting for social aspects through detailing key factors that contribute to sensitivity or adaptive capacity such as governance capacity. In this case, an increased in governance capacity directly reduces vulnerability as it could provide social cohesiveness or increase development. Finally, it is important to note that the methodology used to evaluate the levels within the social-economic components of the Cinner et al. (2013) framework are largely qualitative in nature and are thus, relative measures. Efforts could be made such as in Blasiak et al. (2017) to quantify the social-economic components and vulnerability.

The analysis suggests that within PNA, SSF with flexibility in gear type, flexible management and clear regulations, strong social capital with well-educated communities often have strong adaptive capacities, and possess the ability to adapt to ecological shocks of rapid growth in exploited species.

4. Conclusion

4.1 Summary

This research presents a contribution towards understanding the impacts of climate change on small-scale fisheries compared to large-scale fisheries, in the context of vulnerability and adaptability. By implementing an interdisciplinary approach, we can better understand the similarities and differences in projected impacts of climate change between small-scale fisheries and large-scale fisheries (Chapter 2) and the vulnerability and adaptive capacity characteristics that could enable these fisheries to adapt to climate-induced changes (Chapter 3).

Chapter 2 projects an overall trend of increasing relative maximum catch potential for small-scale fisheries compared to large-scale fisheries in the Pacific North America region under both low and high emission scenarios. The increase in the maximum catch potential of small-scale fisheries is attributed to a few species that have tremendous projected gains by 2080, while the majority of exploited species are projected to experience declines. This suggests that the diversity in catch may be reduced over time. Furthermore, small-scale fisheries currently catch a larger proportion of species with positive projected changes in maximum catch potential, suggesting that small-scale fisheries would likely be more positively impacted by climate change. However, as there is substantial overlap in exploited species between small-scale fisheries and large-scale fisheries, this suggest the potential for large-scale fisheries to focus on exploiting these high maximum catch potential species at larger amounts and divert away from the species with declining maximum catch potential.

Chapter 3 seeks to qualitatively understand key commonalities and differences that would enable small-scale fisheries and large-scale fisheries to adapt to the climate-induced impacts as projected in Chapter 2. Operational cost is one of the important measures of adaptive capacity. Within operational cost lies several specific factors such as fuel consumption, gear efficiency, fuel prices, travel distances, ability to switch gear, labour cost and technological improvements. In the case of Alaska's Pacific cod fishery, the differences in large-scale fisheries' operational cost characteristics such as its efficiency, subsidies and being less capital intensive, enable their operation to be less costly and hence, more adaptable in these factors compared to small-scale fisheries. It is challenging to determine the magnitude of these operational cost attributes, or to draw inferences and generalizations from the Alaska cod fishery case illustration to all fisheries as each has its unique characteristics. Instead, the aim is to suggest key areas that fisheries managers and policy-makers can direct their efforts towards to improve their adaptive capacity.

Furthermore, through two small-scale fisheries case illustrations, Monterey Bay's wetfish fishery and Sonora's jellyfish fishery, other commonalities of positive small-scale fisheries social-economic adaptive capacities are evident. These includes ease of access to fishing gear, enabling regulations and management, strong social capital and a foundational knowledge and education. While these characteristics may be inherent to the success of the case illustrations' small-scale fisheries, there are also many context dependent factors, and careful examination of each fishery is imperative.

4.2 Future directions

To improve model certainty, future studies could include additional Earth System Models such as MPI (Max Planck Institute for Meteorology), which captures different biogeochemical scenarios. As alternative species distribution models can lead to variability in projections (Jones and Cheung 2015), further research could take a multi-model approach, incorporating Maxent and Aquamaps, for instance, to compare outputs and determine the sensitivity of the results obtained between different species distribution models. Finally, species distribution models are one type of marine ecosystem models that explore the effects of climate change on biodiversity and fisheries. Inter-model comparisons could be made (Tittensor et al. 2018), such as with projections from trophodynamic models, which also incorporate climate change scenarios and fishing pressure (e.g., Ainsworth et al. 2011).

Improvements can be made in vulnerability assessments by undertaking a participatory approach with key stakeholders to identify and evaluate components that attribute to vulnerability. For instance, in Mamauag et al. (2013), local stakeholders were actively involved in a series of workshops to identify key components and score them based on their importance to the viability of their small-scale fisheries. As the aim of Chapter 3 was to conduct a vulnerability assessment and a comparison of fisheries in the region, I used a guiding framework and a variety of literature sources to this extend. I believe there is added value for future research to take a bottom-up approach, which could highlight places and fisheries specific components that might otherwise be overshadowed.

Finally, it would be intriguing to apply this comparative approach to fisheries of other regions and on a global scale to determine if the outcomes and projections observed from this regional study is indicative of other small-scale fisheries.

4.3 Policy implications

The results summarized in the conclusion above (4.1) are largely regional trends, and there are variations within countries and between communities. It is evident through this research that regional collaboration, dialogue and knowledge sharing are crucial towards collective and complementary efforts in adapting to the impacts of climate change. As species move without consideration to national borders, the actions (or inactions) of a country could have repercussions across the region. Research initiatives such as Too Big To Ignore (www.toobigtoignore.net), and projects by non-governmental or local organizations are needed to help facilitate these conversation, as well as direct localized efforts to create and better understand context-specific fisheries management. Likewise, dialogue between stakeholders, large-scale fisheries and small-scale fisheries, as well as their continued involvement and inclusion in the management and policy processes have value.

This research also suggests several adaptive capacity characteristics that tend to be associated with successful fisheries, as seen through the case illustrations. Some of these proposed characteristics, for instance, strong social capital and investment in education, have other societal benefits, not exclusive to fisheries. Development of these areas are urgently needed if they are to have positive societal effects, especially as many require long term efforts and on-going investments. The list of adaptive capacity characteristics is by no means exhaustive, and there are many additional factors that should be considered when implementing policy measures to reduce vulnerability and increase adaptive capacity.

The value of projection studies such as in this thesis can be to anticipate and identify key stakeholders, sensitive regions and vulnerable species that are likely to be most impacted by these climate-induced changes on fisheries. Based on my research in this region, I can echo some suggestions, in addition to the ones mentioned in the above paragraphs, that can contribute towards the viability of small-scale fisheries. This includes reducing large-scale fisheries subsidies (Sumaila et al. 2016), protecting key climate refuges potentially through marine protected areas (Ban et al. 2016) and increased funding for small-scale fisheries advocacy (Jacquet and Pauly 2008). More specifically, potential scenarios identified in this research that could arise in the Pacific North America region include the loss of species diversity and the increased dependency on selected few species, and ultimately, reducing the breadth of small-scale fisheries' catch portfolio. If large-scale fisheries are to increased their efforts towards exploiting these same few species, we may find a future where small-scale fisheries will be displaced by large-scale fisheries, as a result of direct competition for resources. Then, efforts such as marine culture could help alleviate imminent pressure on food security, development of alternative livelihoods could reduce dependency on exclusively fisheries as a source of income, and clear policies on fishing jurisdictions should be mutually established to avoid direct conflicts between small-scale fisheries and large-scale fisheries. I would like to reiterate the importance of an individual place and fisheries-based approach, including proper consultation with the fisheries, community and stakeholders involved, as each case is unique and context dependent. Historical, traditional and local ecological knowledge should be sought.

At the international level, there have been ongoing efforts, agreements and policy advancements to elevate the profile of small-scale fisheries and to ensure their sustainable development such as through the FAO Small-Scale Fisheries Guidelines and State of the World's Fisheries and Aquaculture report (Chapter 1). It is my hope that this research contributes to the existing knowledge and understanding of small-scale fisheries, in the context of climate change, vulnerability and adaptive capacity.

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Appendix A. The 312 modelled species, representing the top 70% of the catches in Pacific North America

Scientific Name	**Common Name**
Acanthocybium solandri	Wahoo
Alopias superciliosus	Bigeye thresher
Alopias vulpinus	Thintail thresher
Alosa sapidissima	American shad
Anadara tuberculosa	Black ark
Anarrhichthys ocellatus	Wolf-eel
Anoplopoma fimbria	Sablefish
Argopecten ventricosus	Pacific Calico Scallop
Ariopsis guatemalensis	Blue sea catfish
Arothron meleagris	Guineafowl puffer
Atheresthes evermanni	Kamchatka flounder
Atheresthes stomias	Arrowtooth flounder
Atractoscion nobilis	White weakfish
Auxis thazard	Frigate tuna
Bagre panamensis	Chilhuil sea catfish
Bagre pinnimaculatus	Red sea catfish
Balistes polylepis	Finescale triggerfish
Bathyraja abyssicola	Deepsea skate
Bathyraja aleutica	Aleutian skate
Bathyraja interrupta	Sandpaper skate
Beringraja binoculata	Big skate
Boreogadus saida	Polar cod
Callinectes arcuatus	Arched swimming crab
Callinectes bellicosus	Warrior swimcrab
Cancer magister	Dungeness crab
Cancer productus	Pacific rock crab
Canthigaster punctatissima	Spotted sharpnosed puffer
Caranx caballus	Green jack
Caranx sexfasciatus	Bigeye trevally
Caranx vinctus	Cocinero
Carcharhinus brachyurus	Copper shark
Carcharhinus falciformis	Silky shark
Carcharhinus limbatus	Blacktip shark
Carcharhinus longimanus	Oceanic whitetip shark
Carcharhinus obscurus	Dusky shark

Carcharodon carcharias	Great white shark
Centropomus medius	Blackfin snook
Centropomus nigrescens	Black snook
Centropomus robalito	Yellowfin snook
Centropomus viridis	White snook
Cetengraulis mysticetus	Pacific anchoveta
Cetorhinus maximus	Basking shark
Chaenomugil proboscideus	Snouted mullet
Cheilotrema saturnum	Black croaker
Chione californiensis	California venus
Chionoecetes angulatus	Triangle tanner crab
Chionoecetes bairdi	Southern tanner crab
Chionoecetes opilio	Queen crab
Chionoecetes tanneri	Tanner crab
Citharichthys sordidus	Pacific sanddab
Citharichthys stigmaeus	Speckled sanddab
Citharichthys fragilis	Gulf sanddab
Clinocardium nuttallii	Nuttall cockle
Clupea pallasii	Pacific herring
Clupea pallasii pallasii	Pacific herring
Coregonus laurettae	Bering cisco
Coregonus nasus	Broad whitefish
Coregonus pidschian	Humpback whitefish
Coregonus sardinella	Sardine cisco
Coryphaena hippurus	Common dolphinfish
Crassostrea gigas	Pacific cupped oyster
Cynoscion albus	Whitefin weakfish
Cynoscion parvipinnis	Shortfin weakfish
Cynoscion xanthulus	Orangemouth weakfish
Dasyatis brevis	Whiptail stingray
Diplectrum pacificum	Inshore sand perch
Doryteuthis opalescens	California market squid
Dosidicus gigas	Jumbo flying squid
Echinorhinus cookei	Prickly shark
Eleginus gracilis	Saffron cod
Embassichthys bathybius	Deepsea sole
Engraulis mordax	Californian anchovy
Enteroctopus dofleini	Giant Pacific octopus
Eopsetta jordani	Petrale sole

Epinephelus analogus	Spotted grouper
Erimacrus isenbeckii	Hair Crab
Errex zachirus	Rex sole
Euphausia pacifica	North Pacific krill
Euthynnus lineatus	Black skipjack
Euvola vogdesi	Concave scallop
Farfantepenaeus brevirostris	Crystal shrimp
Farfantepenaeus californiensis	Yellowleg shrimp
Gadus chalcogrammus	Alaska pollock
Gadus macrocephalus	Pacific cod
Galeocerdo cuvier	Tiger shark
Galeorhinus galeus	Tope shark
Genyonemus lineatus	White croaker
Glyptocephalus zachirus	Rex sole
Gnathophis cinctus	Hardtail conger
Gymnothorax mordax	California moray
Haliotis corrugata	Pink abalone
Haliotis cracherodii	Black abalone
Haliotis fulgens	Green abalone
Haliotis kamtschatkana	Northern abalone
Haliotis rufescens	Red abalone
Haliotis sorenseni	White abalone
Hemilepidotus jordani	Yellow Irish lord
Hexagrammos decagrammus	Kelp greenling
Hexanchus griseus	Bluntnose sixgill shark
Hippoglossina stomata	Bigmouth flounder
Hippoglossoides elassodon	Flathead sole
Hippoglossoides robustus	Bering flounder
Hippoglossus stenolepis	Pacific halibut
Hydrolagus colliei	Spotted ratfish
Hypomesus pretiosus	Surf smelt
Hypomesus pretiosus	Surf smelt
Hyporthodus acanthistius	Rooster hind
Isopsetta isolepis	Butter sole
Istiophorus platypterus	Indo-Pacific sailfish
Isurus oxyrinchus	Shortfin mako
Janthina janthina	Violet sea-snail
Katsuwonus pelamis	Skipjack tuna
Kyphosus analogus	Blue-bronze sea chub

Kyphosus azureus	Zebra-perch sea chub
Kyphosus elegans	Cortez sea chub
Lagocephalus lagocephalus	Oceanic puffer
Lepidopsetta bilineata	Rock sole
Lepidopsetta polyxystra	Northern rock sole
Leukoma staminea	Pacific littleneck clam
Limanda aspera	Yellowfin sole
Limanda proboscidea	Longhead dab
Liopsetta glacialis	Arctic flounder
Lithodes aequispinus	King crab
Lithodes couesi	Scarlet king crab
Litopenaeus stylirostris	Blue shrimp
Litopenaeus vannamei	Whiteleg shrimp
Loligo opalescens	California market squid
Lutjanus aratus	Mullet snapper
Lutjanus argentiventris	Yellow snapper
Lutjanus colorado	Colorado snapper
Lutjanus novemfasciatus	Pacific cubera snapper
Lutjanus viridis	Blue and gold snapper
Lyopsetta exilis	Slender sole
Macoma balthica	Baltic clam
Makaira indica	Black marlin
Mallotus villosus	Capelin
Menticirrhus undulatus	California kingcroaker
Merluccius angustimanus	Panama hake
Merluccius productus	North Pacific hake
Metacarcinus magister	Dungeness crab
Microgadus proximus	Pacific tomcod
Microstomus pacificus	Dover sole
Mugil cephalus	Flathead mullet
Mustelus californicus	Grey smooth-hound
Mustelus henlei	Brown smooth-hound
Mustelus lunulatus	Sicklefin smooth-hound
Mya arenaria	Sand gaper
Myliobatis longirostris	Snouted eagle ray
Myoxocephalus polyacanthocephalus	Great sculpin
Nasolamia velox	Whitenose shark
Nezumia convergens	Peruvian grenadier
Nezumia liolepis	Smooth grenadier

Nezumia stelgidolepis	California grenadier
Nodipecten subnodosus	Giant lion's paw
Nuttallia obscurata	Varnish clam
Oligocottus maculosus	Tidepool sculpin
Oncorhynchus gorbuscha	Pink salmon
Oncorhynchus keta	Chum salmon
Oncorhynchus kisutch	Coho salmon
Oncorhynchus mykiss	Rainbow trout
Oncorhynchus nerka	Sockeye salmon
Oncorhynchus tshawytscha	Chinook salmon
Ophichthus triserialis	Pacific snake-eel
Ophichthus zophochir	Yellow snake-eel
Ophiodon elongatus	Lingcod
Opisthonema bulleri	Slender thread herring
Opisthonema libertate	Pacific thread herring
Opisthonema medirastre	Middling thread herring
Osmerus dentex	Pacific rainbow smelt
Osmerus mordax	Rainbow smelt
Ostrea lurida	Olympia flat oyster
Pandalus borealis	Northern prawn
Pandalus jordani	Ocean shrimp
Pandalus platyceros	Spot shrimp
Panopea abrupta	Pacific geoduck
Panopea generosa	Pacific geoduck
Panulirus gracilis	Panulirus gracilis
Panulirus inflatus	Blue spiny lobster
Panulirus interruptus	California spiny lobster
Panulirus penicillatus	Pronghorn spiny lobster
Paralabrax clathratus	Kelp bass
Paralabrax nebulifer	Barred sand bass
Paralichthys californicus	California flounder
Paralithodes californiensis	Spiny king crab
Paralithodes camtschaticus	Red king crab
Paralithodes platypus	Blue King Crab
Parophrys vetulus	English sole
Patinopecten caurinus	Weathervane scallop
Peprilus medius	Pacific harvestfish
Peprilus ovatus	Shining butterfish
Peprilus simillimus	Pacific pompano

Peprilus snyderi	Salema butterfish
Physiculus talarae	Peruvian mora
Platichthys stellatus	Starry flounder
Platyrhinoidis triseriata	Thornback guitarfish
Pleuronectes quadrituberculatus	Alaska plaice
Pleuronichthys coenosus	C-O sole
Pleuronichthys decurrens	Curlfin sole
Porichthys notatus	Plainfin midshipman
Prionace glauca	Blue shark
Protothaca staminea	Pacific littleneck clam
Psettichthys melanostictus	West American sand sole
Raja rhina	Longnose skate
Raja stellulata	Starry skate
Reinhardtius hippoglossoides	Greenland halibut
Rhinobatos spinosus	Spiny guitarfish
Rhizoprionodon longurio	Pacific sharpnose shark
Roncador stearnsii	Spotfin croaker
Salvelinus malma malma	Dolly varden
Sardinops caeruleus	California pilchard
Sardinops sagax	South American pilchard
Scomber japonicus	Chub mackerel
Scomberomorus concolor	Monterey Spanish mackerel
Scomberomorus sierra	Pacific sierra
Scorpaena guttata	California scorpionfish
Scorpaenichthys marmoratus	Cabezon
Sebastes aleutianus	Rougheye rockfish
Sebastes alutus	Pacific ocean perch
Sebastes atrovirens	Kelp rockfish
Sebastes auriculatus	Brown rockfish
Sebastes aurora	Aurora rockfish
Sebastes babcocki	Redbanded rockfish
Sebastes borealis	Shortraker rockfish
Sebastes carnatus	Gopher rockfish
Sebastes caurinus	Copper rockfish
Sebastes chrysomelas	Black-and-yellow rockfish
Sebastes constellatus	Starry rockfish
Sebastes crameri	Darkblotched rockfish
Sebastes diploproa	Splitnose rockfish
Sebastes elongatus	Greenstriped rockfish

Sebastes ensifer	Swordspine rockfish
Sebastes entomelas	Widow rockfish
Sebastes eos	Pink rockfish
Sebastes flavidus	Yellowtail rockfish
Sebastes gilli	Bronzespotted rockfish
Sebastes goodei	Chilipepper
Sebastes hopkinsi	Squarespot rockfish
Sebastes jordani	Shortbelly rockfish
Sebastes maliger	Quillback rockfish
Sebastes melanops	Black rockfish
Sebastes melanostomus	Blackgill rockfish
Sebastes miniatus	Vermilion rockfish
Sebastes mystinus	Blue rockfish
Sebastes nebulosus	China rockfish
Sebastes nigrocinctus	Tiger rockfish
Sebastes ovalis	Speckled rockfish
Sebastes paucispinis	Bocaccio
Sebastes pinniger	Canary rockfish
Sebastes proriger	Redstripe rockfish
Sebastes rastrelliger	Grass rockfish
Sebastes rosaceus	Rosy rockfish
Sebastes rosenblatti	Greenblotched rockfish
Sebastes ruberrimus	Yelloweye rockfish
Sebastes rubrivinctus	Flag rockfish
Sebastes rufus	Bank rockfish
Sebastes saxicola	Stripetail rockfish
Sebastes serranoides	Olive rockfish
Sebastes serriceps	Treefish
Sebastes simulator	Pinkrose rockfish
Sebastes umbrosus	Honeycomb rockfish
Sebastolobus alascanus	Shortspine thornyhead
Sebastolobus altivelis	Longspine thornyhead
Selar crumenophthalmus	Bigeye scad
Selene peruviana	Pacific moonfish
Semicossyphus pulcher	California sheephead
Seriola lalandi	Yellowtail amberjack
Seriphus politus	Queen croaker
Serrivomer samoensis	Serrivomer samoensis
Sicyonia ingentis	Sicyonia ingentis

Siliqua patula	Pacific razor clam
Sphoeroides annulatus	Bullseye puffer
Sphoeroides lobatus	Longnose puffer
Sphoeroides sechurae	Peruvian puffer
Sphyraena argentea	Pacific barracuda
Sphyraena barracuda	Great barracuda
Sphyrna lewini	Scalloped hammerhead
Sphyrna media	Scoophead
Sphyrna zygaena	Smooth hammerhead
Spirinchus starksi	Night smelt
Squalus suckleyi	Pacific spiny dogfish
Squatina californica	Pacific angelshark
Stereolepis gigas	Giant sea-bass
Stomolophus meleagris	Cannonball jellyfish
Strongylocentrotus franciscanus	Red sea urchin
Strongylocentrotus purpuratus	Purple sea urchin
Sufflamen verres	Orangeside triggerfish
Synodus lacertinus	Sauro lizardfish
Synodus scituliceps	Shorthead lizardfish
Tagelus californianus	California tagelus
Tetrapturus angustirostris	Shortbill spearfish
Thaleichthys pacificus	Eulachon
Theragra chalcogramma	Alaska pollock
Thunnus alalunga	Albacore
Thunnus albacares	Yellowfin tuna
Thunnus obesus	Bigeye tuna
Thunnus orientalis	Pacific bluefin tuna
Thunnus thynnus	Northern bluefin tuna
Thysanoessa inspinata	Euphausiid
Thysanoessa longipes	Euphausiid
Thysanoessa spinifera	Euphausiid
Tivela stultorum	Pismo clam
Totoaba macdonaldi	Totoaba
Trachurus symmetricus	Pacific jack mackerel
Tresus nuttallii	Pacific gaper clam
Trichiurus lepturus	Largehead hairtail
Umbrina roncador	Yellowfin drum
Upogebia pugettensis	Blue mud shrimp
Venerupis philippinarum	Manila clam

Xiphias gladius	Swordfish
Xystreurys liolepis	Fantail flounder
Zapteryx exasperata	Banded guitarfish
Zapteryx xyster	Zapteryx xyster

Appendix B. Parameters required by species distribution models

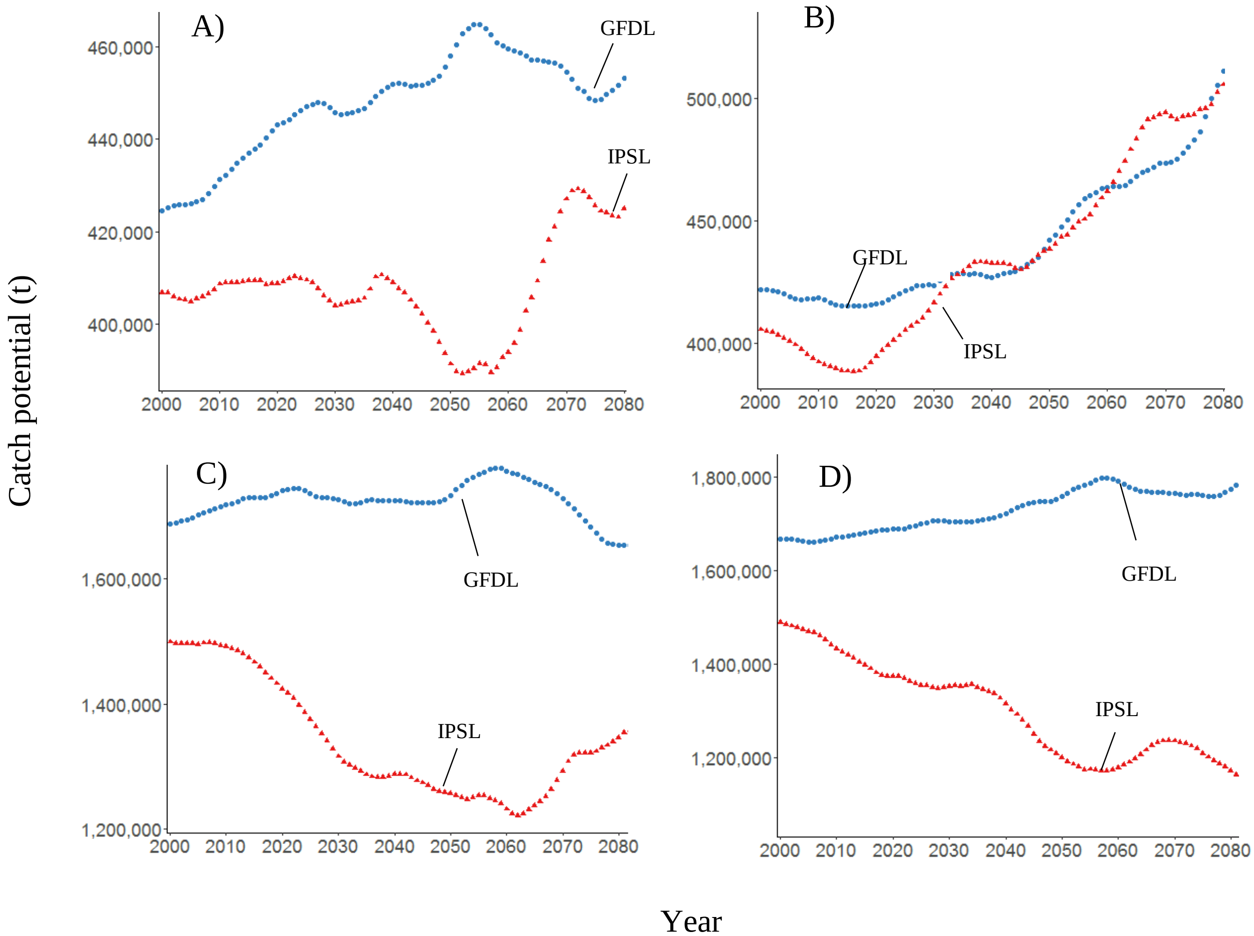
Definitions directly obtained and applied from FishBase.

Parameters	**Definitons**
Demersal-Pelagic	Demersal or pelagic species
Depth	Maximum depth of species
Intrinsic R	Intrinsic rate of increase captures the change in population between successive time periods; estimated by recruitment increases + growth – natural mortality
L_{inf}	Length infinity (also known as asymptotic length); the length that a fish in a population would reach if they could grow indefinitely
Von Bert K (K)	In the von Bertalanffy growth function, the rate at which length approaches asymptotic length (above; usually 1/year)
t_o*	Hypothetical age (years) the fish would have at zero length
LwA	Length a value; based on the length-weight relationship where $w = a \times L^b$
LwB	Length b value; based on the length-weight relationship where $w = a \times L^b$
Habitat Association (Salinity, Coral, Upwelling)	Affinity to certain habitats
Inshore/Offshore	Presence in the inshore or offshore
Shelf	Presence on shelf
Trophic Level	The rank of a species in a food web; Troph = 1 + mean trophs of food items
Max Length	Maximum length of a species
Standard length maximum	Standard length is the measurement from the most anterior tip of the body to the midlateral posterior edge of the hypural plate or the posterior end of the vertebral column
Latitude North/South	Maximum northern and southern latitude

* not directly applied in the model, but implicitly needed to calculate a required parameter

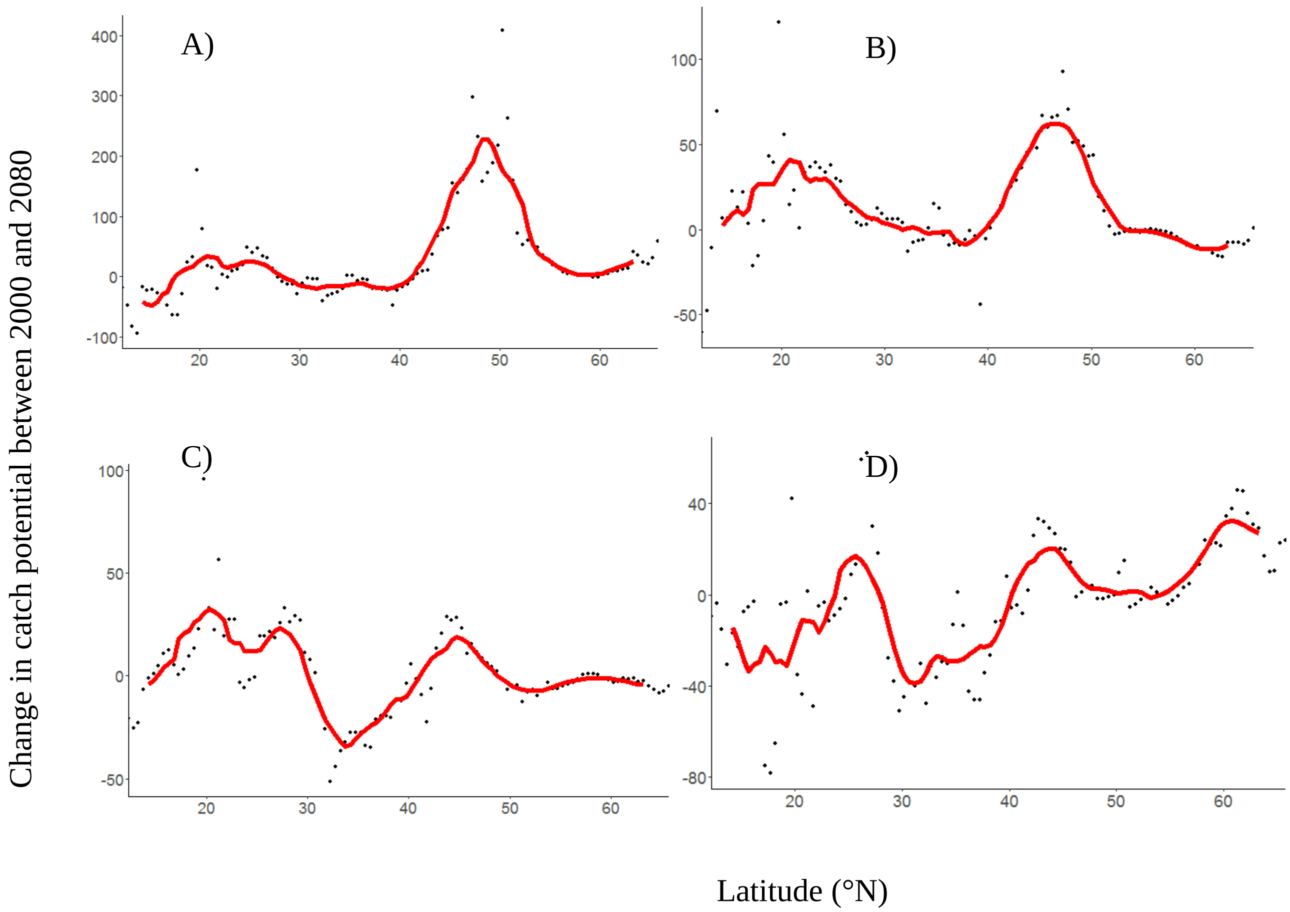
Appendix C. Changes in maximum catch potential by Earth System Model

Maximum catch potentials in the PNA region from 2000 to 2080 for GFDL (circle) and IPSL (triangle) for the following scenarios: (a) SSF RCP 2.6 (b) SSF RCP 8.5 (c) LSF RCP 2.6 (d) LSF RCP 8.5. With exception to SSF at RCP 8.5, there appears to be large intermodal variability between the two ESMs, GFDL and IPSL, in its projected maximum catch potentials across the time period. IPSL consistently yields lower maximum catch potentials relative to GFDL.



Appendix D. Changes in maximum catch potential by latitude

Across both fisheries and RCP scenarios, there is a peak in catches between the 40-50 N latitude, which occurs off the coast of British Columbia.



Relationship between changes in maximum catch potential (%) in PNA between 2080 and 2000 and latitudes for (a) small-scale fisheries under low (RCP 2.6) emission scenario, (b) small-scale fisheries under high (RCP 8.5) emission scenario, (c) large-scale fisheries under low (RCP 2.6) emission scenario, (d) large-scale fisheries under high (RCP 8.5) emission scenario. High emission scenario exhibiting a positive correlation while low emission scenario has variable effects.

Appendix E. Projected changes in catch for small-scale fisheries in Pacific North America between 2080 and 2000.

Species	Common name	RCP 2.6				RCP 8.5			
		GFDL		IPSL		GFDL		IPSL	
		2000	2080	2000	2080	2000	2080	2000	2080
Coryphaena hippurus	Common dolphinfish	2.4	1.9	2.6	1.9	2.4	1.9	2.6	0.3
Cetorhinus maximus	Basking shark	2.4	2.0	2.3	1.9	2.3	2.0	2.2	2.1
Katsuwonus pelamis	Skipjack tuna	5.6	5.5	5.8	5.4	5.6	5.7	5.8	3.8
Scomber japonicus	Chub mackerel	2.0	1.9	2.0	1.9	2.0	2.1	2.0	2.0
Scomberomorus sierra	Pacific sierra	4,639.6	5,978.3	5,001.3	4,798.6	4,700.5	5,679.0	5,014.7	3,395.7
Thunnus alalunga	Albacore	1.3	1.2	1.2	1.1	1.3	1.1	1.2	1.0
Thunnus albacares	Yellowfin tuna	6.9	6.9	7.3	6.8	7.0	7.1	7.3	5.1
Thunnus obesus	Bigeye tuna	3.3	3.3	3.5	3.3	3.4	3.5	3.5	2.7
Thunnus thynnus	Northern bluefin tuna	78.1	79.0	84.0	77.6	79.0	84.8	83.9	82.0
Xiphias gladius	Swordfish	17.9	17.9	19.0	18.0	18.2	17.8	18.9	13.6
Oncorhynchus mykiss	Rainbow trout	66.1	69.1	66.0	54.3	66.1	80.8	66.1	64.4
Oncorhynchus gorbuscha	Pink salmon	37,237.7	35,907.0	34,001.4	27,909.2	35,792.9	39,535.7	33,637.8	19,248.0
Oncorhynchus keta	Chum salmon	13,773.6	13,211.0	12,998.4	10,588.8	14,204.0	15,389.8	12,914.0	7,689.5
Oncorhynchus nerka	Sockeye salmon	33,695.5	29,869.7	32,078.3	25,379.2	33,553.8	29,656.6	31,705.2	13,287.3
Oncorhynchus tshawytscha	Chinook salmon	4,158.0	4,181.6	4,143.3	3,399.7	4,176.0	4,383.0	4,134.3	3,138.2
Oncorhynchus kisutch	Coho salmon	6,078.7	5,758.9	5,775.0	4,946.5	6,230.2	6,615.9	5,746.5	4,621.1
Mallotus villosus	Capelin	15.6	13.9	15.8	8.7	16.0	3.3	15.6	3.7
Hypomesus pretiosus	Surf smelt	58.9	55.4	57.6	41.9	58.9	58.9	57.6	37.6
Thaleichthys pacificus	Eulachon	77.9	74.7	77.9	53.4	77.9	81.4	77.9	63.8
Gadus macrocephalus	Pacific cod	71,584.6	61,342.2	56,474.6	40,052.9	70,026.3	55,340.1	55,938.3	30,320.5
Eleginus gracilis	Saffron cod	35.3	31.7	31.3	23.5	37.4	33.3	31.0	17.8
Theragra chalcogramma	Alaska pollock	304.0	287.4	244.9	198.7	297.5	324.7	241.9	132.6
Boreogadus saida	Polar cod	3.6	2.8	3.1	1.8	4.5	3.9	3.0	0.2
Merluccius productus	North Pacific hake	3,546.8	3,257.6	3,546.8	3,029.0	3,546.8	3,022.4	3,546.8	3,103.0
Epinephelus analogus	Spotted grouper	7.4	3.4	11.0	9.1	10.7	2.0	8.8	7.0
Trachurus symmetricus	Pacific jack mackerel	201.6	203.9	201.6	166.0	201.6	218.7	201.6	182.3

Selar crumenophthalmus	Bigeye scad	34.8	36.0	37.2	37.5	35.0	45.1	37.0	27.6
Genyonemus lineatus	White croaker	311.8	319.7	312.1	265.7	312.1	654.1	312.1	314.8
Peprilus simillimus	Pacific pompano	2,556.3	2,454.6	2,556.1	2,039.4	2,556.3	2,659.8	2,556.1	2,343.2
Sebastes entomelas	Widow rockfish	154.2	174.0	154.3	145.9	154.4	201.4	154.3	160.0
Sebastes flavidus	Yellowtail rockfish	13.6	8.6	14.5	11.9	13.8	15.0	13.9	12.1
Sebastes alutus	Pacific ocean perch	138.5	97.3	108.1	89.5	133.3	108.5	107.9	98.3
Ophiodon elongatus	Lingcod	25.9	13.8	28.2	23.3	28.9	22.4	28.0	25.1
Anoplopoma fimbria	Sablefish	6,656.9	5,352.1	5,387.5	4,497.5	5,987.5	3,566.3	5,354.7	3,728.4
Hippoglossus stenolepis	Pacific halibut	13,981.3	11,187.4	13,265.1	11,966.0	14,220.7	12,433.8	13,251.0	11,189.9
Reinhardtius hippoglossoides	Greenland halibut	629.8	575.3	560.7	478.5	642.3	553.2	560.2	445.0
Atheresthes stomias	Arrowtooth flounder	2,976.5	2,274.5	2,296.2	1,937.5	3,086.1	2,220.9	2,288.2	1,809.0
Atheresthes evermanni	Kamchatka flounder	29.8	27.0	24.1	19.9	30.0	26.7	24.1	16.1
Hippoglossoides elassodon	Flathead sole	20.8	18.5	14.3	12.2	20.9	15.9	14.1	11.2
Limanda aspera	Yellowfin sole	18.0	17.3	14.7	12.2	18.7	18.3	14.6	11.6
Cetengraulis mysticetus	Pacific anchoveta	1,380.9	1,575.1	1,471.1	1,341.6	1,422.8	1,451.0	1,465.3	1,335.4
Isurus oxyrinchus	Shortfin mako	24.6	18.7	6.5	6.0	20.1	17.7	6.3	6.2
Mugil cephalus	Flathead mullet	10.0	0.0	33.1	27.7	9.1	1.3	30.2	27.0
Carcharhinus falciformis	Silky shark	53.0	11.1	68.8	63.0	59.5	21.8	68.7	59.8
Carcharhinus limbatus	Blacktip shark	13.3	13.3	12.3	11.6	12.1	15.9	12.3	12.6
Carcharhinus longimanus	Oceanic whitetip shark	2.9	2.3	1.2	1.0	2.8	4.7	1.1	1.2
Carcharhinus obscurus	Dusky shark	25.6	6.3	24.1	19.8	25.7	15.9	24.3	23.7
Galeocerdo cuvier	Tiger shark	3.0	0.1	0.1	0.1	0.5	0.0	0.1	0.1
Prionace glauca	Blue shark	3.5	2.9	3.7	3.4	4.0	3.1	3.5	3.5
Sphyrna lewini	Scalloped hammerhead	13.0	12.7	14.1	13.0	13.0	16.0	14.1	14.6
Sphyrna zygaena	Smooth hammerhead	6.6	3.6	3.5	3.0	6.4	5.0	3.5	3.5
Sphyraena barracuda	Great barracuda	0.7	0.5	0.0	0.0	0.5	0.0	0.0	0.0
Trichiurus lepturus	Largehead hairtail	34.3	35.1	34.6	31.9	35.0	37.1	34.6	33.5
Lutjanus argentiventris	Yellow snapper	5.1	0.0	1.9	2.0	2.5	0.0	1.9	0.0
Sardinops sagax	South American pilchard	4.1	4.1	3.7	3.4	4.2	4.9	3.6	2.8

Opisthonema libertate	Pacific thread herring	1,316.9	1,483.1	1,274.1	1,316.0	1,354.6	1,378.0	1,272.4	1,035.4
Clupea pallasii pallasii	Pacific herring	17,908.0	17,149.3	17,122.4	15,139.0	18,166.0	17,982.2	16,915.5	11,362.1
Alosa sapidissima	American shad	13.2	13.4	13.6	16.7	14.4	15.8	13.3	11.4
Engraulis mordax	Californian anchovy	2,550.1	2,446.1	2,551.5	2,088.6	2,551.5	1,948.7	2,551.1	2,581.6
Merluccius angustimanus	Panama hake	1,335.3	1,948.8	1,985.4	1,533.4	1,576.0	1,924.7	1,984.7	1,295.1
Microgadus proximus	Pacific tomcod	62.3	61.2	62.2	54.9	62.3	71.2	62.3	61.7
Caranx sexfasciatus	Bigeye trevally	100.0	115.4	92.8	105.8	105.0	133.8	92.5	107.9
Alopias superciliosus	Bigeye thresher	4.0	4.6	3.5	3.3	4.1	5.6	3.2	3.6
Alopias vulpinus	Thintail thresher	10.8	10.6	8.2	7.7	10.0	10.2	8.3	8.4
Stereolepis gigas	Giant sea-bass	1.9	1.8	1.3	0.7	3.3	2.5	1.2	0.7
Atractoscion nobilis	White weakfish	58.3	25.2	58.3	47.2	58.3	48.0	58.3	48.5
Semicossyphus pulcher	California sheephead	52.2	49.4	47.0	32.0	89.5	107.2	47.7	28.9
Sebastes goodei	Chilipepper	15.0	7.3	13.7	12.7	5.5	3.2	14.1	15.0
Sebastes melanops	Black rockfish	20.9	18.4	15.6	16.4	18.2	20.5	15.6	16.8
Sebastes paucispinis	Bocaccio	154.7	165.5	153.6	143.3	154.6	195.5	153.4	136.3
Sebastes pinniger	Canary rockfish	155.7	104.1	155.2	128.1	155.7	149.0	155.3	138.9
Sebastolobus alascanus	Shortspine thornyhead	185.2	162.3	160.0	129.6	183.2	138.3	158.7	117.2
Scorpaenichthys marmoratus	Cabezon	8.9	7.8	9.2	8.9	7.9	10.4	9.1	9.5
Citharichthys sordidus	Pacific sanddab	20.7	18.6	19.2	17.0	20.3	19.8	19.1	15.0
Paralichthys californicus	California flounder	17.2	13.1	15.5	14.7	13.3	14.5	15.5	15.4
Eopsetta jordani	Petrale sole	64.8	39.1	64.5	62.6	64.7	51.6	64.4	67.4
Glyptocephalus zachirus	Rex sole	63.7	50.1	63.0	61.2	62.4	62.2	62.6	61.2
Microstomus pacificus	Dover sole	13.2	10.4	10.5	9.3	13.8	9.1	10.4	8.8
Parophrys vetulus	English sole	64.8	33.3	64.8	59.5	64.8	51.1	64.8	66.8
Platichthys stellatus	Starry flounder	23.4	20.3	20.2	15.5	23.1	21.3	20.1	11.4
Pleuronectes quadrituberculatus	Alaska plaice	39.2	28.4	34.4	33.2	39.4	37.1	34.4	31.3
Pleuronichthys decurrens	Curlfin sole	10.4	5.7	9.5	8.7	10.2	7.1	9.4	8.7
Psettichthys melanostictus	West American sand sole	64.8	59.5	64.8	61.4	64.8	88.7	64.8	87.5
Galeorhinus galeus	Tope shark	21.7	8.8	23.9	21.5	27.8	24.3	23.8	23.5
Totoaba macdonaldi	Totoaba	2,556.3	2,903.6	2,556.3	1,841.4	2,556.3	1,534.3	2,556.3	1,854.5

Peprilus snyderi	Salema butterfish	1,740.2	1,781.3	1,753.7	1,424.8	1,687.5	1,807.5	1,754.2	1,311.8
Thunnus orientalis	Pacific bluefin tuna	3.3	3.3	3.3	3.2	3.3	3.5	3.3	2.5
Lepidopsetta bilineata	Rock sole	41.3	38.6	33.1	25.5	41.5	40.9	33.0	19.7
Coregonus laurettae	Bering cisco	57.5	62.0	56.2	34.3	58.1	43.6	55.5	12.6
Litopenaeus stylirostris	Western blue shrimp	4,309.3	5,306.8	3,858.7	3,442.4	3,301.2	3,580.3	3,807.8	3,319.8
Farfantepenaeus brevirostris	Crystal shrimp	24.4	14.5	64.0	24.4	29.9	19.2	44.1	21.1
Cancer magister	Dungeness crab	1,849.8	1,810.4	1,849.8	1,691.9	1,849.9	2,315.6	1,849.9	2,344.0
Dosidicus gigas	Jumbo flying squid	5.6	5.5	5.5	5.3	5.7	5.8	5.5	4.8
Pandalus borealis	Northern prawn	70.3	68.7	57.8	61.9	61.5	61.5	57.7	43.9
Ostrea lurida	Olympia flat oyster	22.1	16.7	22.1	21.3	22.1	22.4	22.1	23.1
Crassostrea gigas	Pacific cupped oyster	44.4	46.7	58.0	55.7	42.9	53.4	57.4	56.0
Panopea abrupta	Pacific geoduck	664.9	676.9	664.9	920.8	664.9	670.7	664.9	1,084.5
Protothaca staminea	Pacific littleneck clam	312.9	288.4	313.1	290.1	312.9	337.4	313.1	392.5
Siliqua patula	Pacific razor clam	189.8	174.8	189.3	173.2	190.0	209.6	189.1	193.6
Cancer productus	Pacific rock crab	4,885.7	4,922.8	4,885.6	4,563.0	4,885.7	6,369.0	4,885.6	6,779.0
Chionoecetes opilio	Queen crab	20.3	20.4	20.2	17.8	19.1	25.8	20.1	18.2
Haliotis rufescens	Red abalone	11.7	11.6	11.7	11.5	11.7	8.6	11.7	12.5
Mya arenaria	Sand gaper	13.8	8.2	10.5	9.8	11.1	6.4	10.3	10.7
Patinopecten caurinus	Weathervane scallop	1,876.2	1,258.2	1,876.2	1,855.2	1,876.2	1,930.0	1,876.2	2,697.8
Erimacrus isenbeckii	Hair Crab	29.3	27.0	29.3	26.9	29.3	38.1	29.3	28.6
Lithodes aequispinus	Golden king crab	12.5	12.2	10.8	9.5	11.9	12.2	10.8	10.2
Paralithodes camtschaticus	Red king crab	5,765.6	5,436.4	5,768.3	5,013.0	5,586.8	7,133.1	5,761.0	4,469.4
Paralithodes platypus	Blue King Crab	38.1	39.7	37.8	25.3	38.1	35.4	37.8	14.9
Clinocardium nuttallii	Nuttall cockle	81.6	61.2	85.0	70.7	86.2	76.0	84.3	74.9
Loligo opalescens	California market squid	60,589.1	73,738.1	60,548.3	89,463.3	60,589.1	111,041.3	60,549.9	165,392.0
Pandalus jordani	Ocean shrimp	114.5	104.2	114.5	103.3	114.5	147.7	114.5	114.4
Tresus nuttallii	Pacific gaper clam	17.3	20.7	17.3	14.8	17.3	17.8	17.3	15.3
Upogebia pugettensis	Blue mud shrimp	8.9	8.8	8.9	7.5	8.9	10.0	8.9	9.6
Enteroctopus dofleini	Giant pacific octopus	147.6	143.3	143.9	118.4	147.5	196.8	143.6	123.9
Anadara tuberculosa	Black ark	9.2	15.4	17.4	14.7	3.1	4.0	17.4	12.1

Ariopsis guatemalensis	Blue sea catfish	1,741.5	1,792.0	1,558.9	1,389.9	1,475.5	1,897.7	1,556.9	1,282.2
Arothron meleagris	Guineafowl puffer	1,098.6	1,101.1	1,032.5	863.1	1,172.4	655.6	1,034.4	732.3
Bagre panamensis	Chilhuil sea catfish	1,088.0	1,197.4	1,205.9	1,014.2	955.0	1,630.2	1,206.7	959.9
Bagre pinnimaculatus	Red sea catfish	1,029.6	1,187.1	1,198.3	996.2	1,068.6	1,563.4	1,198.4	947.4
Bathyraja abyssicola	Deepsea skate	149.1	169.4	130.1	112.2	140.0	139.3	130.5	107.6
Bathyraja aleutica	Aleutian skate	174.7	165.2	165.8	153.8	134.0	255.3	165.9	148.3
Bathyraja interrupta	Sandpaper skate	211.9	201.0	213.2	194.3	212.7	234.3	213.0	166.8
Beringraja binoculata	Big skate	1,003.4	1,132.8	1,003.4	861.0	1,003.4	920.5	1,003.4	897.0
Canthigaster punctatissima	Spotted sharpnosed puffer	1,345.6	1,357.1	1,195.1	1,229.1	1,359.6	671.6	1,195.3	778.3
Caranx vinctus	Cocinero	921.2	1,185.3	924.8	1,689.6	1,012.6	2,342.8	931.2	2,757.7
Centropomus medius	Blackfin snook	1,239.8	1,170.1	1,309.2	1,114.1	918.3	1,766.8	1,306.7	1,068.5
Centropomus nigrescens	Black snook	635.1	775.9	462.1	383.2	320.2	280.4	461.7	337.4
Centropomus robalito	Yellowfin snook	1,108.5	2,280.5	1,283.5	2,904.6	1,167.7	3,721.9	1,296.8	3,847.2
Centropomus viridis	White snook	841.1	1,010.4	923.6	780.5	386.8	573.7	921.5	728.9
Chaenomugil proboscideus	Snouted mullet	501.4	530.7	531.3	502.7	514.7	307.1	533.8	204.0
Chione californiensis	California venus	77.0	81.3	77.0	70.6	77.0	48.4	77.0	64.4
Chionoecetes angulatus	Triangular tanner crab	24.4	24.6	24.6	21.5	24.7	26.1	24.6	21.2
Chionoecetes tanneri	Tanner crab	24.5	24.7	24.3	21.2	24.7	26.1	24.3	21.1
Dasyatis brevis	Whiptail stingray	437.4	504.8	199.8	89.5	254.6	242.4	199.8	88.0
Doryteuthis opalescens	California market squid	31.7	45.0	31.0	42.4	31.4	82.8	31.1	101.8
Echinorhinus cookei	Prickly shark	206.2	216.1	180.1	168.0	226.6	259.6	180.4	170.9
Euvola vogdesi	Concave scallop	77.0	78.8	75.0	47.0	77.0	30.7	75.0	35.2
Gadus chalcogrammus	Alaska pollock	57.4	55.3	57.4	49.3	57.4	62.4	57.4	51.9
Gnathophis cinctus	Hardtail conger	113.4	117.7	120.9	97.0	112.0	134.6	121.4	94.5
Haliotis corrugata	Pink abalone	4.7	6.8	4.5	4.2	2.9	0.9	4.5	4.0
Haliotis cracherodii	Black abalone	11.7	10.7	11.7	8.8	11.7	7.8	11.7	9.3
Haliotis fulgens	Green abalone	11.1	13.2	9.4	7.4	10.6	6.6	9.4	7.9
Haliotis sorenseni	White abalone	11.7	14.3	8.9	9.5	11.7	6.4	8.9	9.9
Hemilepidotus jordani	Yellow Irish lord	41.9	40.6	40.9	30.5	41.9	41.9	41.0	23.6
Hippoglossoides robustus	Bering flounder	63.6	62.0	63.3	48.1	63.6	61.9	63.2	30.9
Hyporthodus acanthistius	Rooster hind	897.6	1,122.5	1,035.4	833.7	655.0	1,261.6	1,037.8	806.9
Janthina janthina	Violet sea-snail	840.9	956.2	717.3	530.5	840.9	732.6	717.6	525.1

Kyphosus analogus	Blue-bronze sea chub	754.5	910.2	957.0	812.2	351.3	480.9	956.1	767.4
Kyphosus elegans	Cortez sea chub	383.5	496.7	1,365.1	2,903.4	1,235.6	1,543.4	1,389.9	3,527.6
Lagocephalus lagocephalus	Oceanic puffer	1,023.7	1,080.9	1,095.5	920.2	925.7	1,176.1	1,095.4	884.1
Lepidopsetta polyxystra	Northern rock sole	64.6	58.0	64.2	66.4	64.5	78.4	64.2	56.2
Leukoma staminea	Pacific littleneck clam	11.3	11.1	11.3	10.2	11.3	12.1	11.3	12.3
Limanda proboscidea	Longhead dab	63.1	65.7	62.4	40.0	63.0	55.0	62.1	18.8
Liopsetta glacialis	Arctic flounder	53.8	51.9	55.3	49.0	48.7	79.1	55.2	38.2
Lithodes couesi	Scarlet king crab	38.9	35.9	38.9	34.3	38.9	51.2	38.9	38.0
Lutjanus aratus	Mullet snapper	1,371.2	1,369.3	1,435.0	1,199.5	1,473.5	931.9	1,447.3	1,067.1
Lutjanus colorado	Colorado snapper	730.7	770.5	1,782.3	3,393.2	1,393.9	1,780.1	1,837.9	5,340.7
Lutjanus novemfasciatus	Pacific cubera snapper	556.9	388.3	762.8	1,210.8	1,047.1	1,561.8	749.5	748.8
Lutjanus viridis	Blue and gold snapper	717.0	1,135.0	1,271.0	2,279.0	1,065.5	1,364.4	1,305.6	2,447.2
Macoma balthica	Baltic clam	165.3	160.6	164.7	140.4	164.7	177.8	164.4	124.4
Myliobatis longirostris	Snouted eagle ray	581.7	630.4	489.9	340.1	580.0	425.4	489.7	307.1
Nasolamia velox	Whitenose shark	189.9	212.3	199.6	168.1	175.1	284.0	199.5	155.0
Nezumia convergens	Peruvian grenadier	613.2	554.5	458.5	371.2	122.3	129.4	462.5	347.1
Nezumia liolepis	Smooth grenadier	2,300.6	2,270.1	2,138.5	1,747.7	2,091.6	1,725.8	2,126.2	1,626.3
Nezumia stelgidolepis	California grenadier	1,023.9	922.4	1,032.4	858.2	788.8	1,142.2	1,031.3	811.8
Nodipecten subnodosus	Giant lion's paw	9.6	15.7	20.2	16.4	4.1	6.2	19.6	15.2
Oligocottus maculosus	Tidepool sculpin	41.6	39.8	41.2	42.4	41.4	54.6	41.1	36.2
Ophichthus triserialis	Pacific snake-eel	68.7	83.0	83.3	69.3	50.4	75.3	83.3	65.8
Ophichthus zophochir	Yellow snake-eel	74.0	88.6	82.2	67.7	55.8	79.9	82.2	66.1
Opisthonema bulleri	Slender thread herring	738.0	1,222.0	732.6	1,584.7	781.3	2,135.7	730.4	2,237.3
Opisthonema medirastre	Middling thread herring	1,013.4	1,195.8	1,000.0	1,615.7	1,056.5	1,811.1	1,013.2	2,303.6
Osmerus dentex	Pacific rainbow smelt	60.7	58.4	59.7	45.4	60.1	58.4	59.4	18.4
Osmerus mordax	Rainbow smelt	61.0	57.6	60.5	50.4	60.6	67.4	60.3	27.8
Panopea generosa	Pacific geoduck	167.2	157.9	167.2	142.3	167.2	216.5	167.2	149.8
Panulirus inflatus	Blue spiny lobster	1,400.2	1,486.3	1,281.7	1,006.1	1,412.3	1,593.4	1,282.3	888.9

Panulirus interruptus	California spiny lobster	47.5	55.8	42.4	33.4	47.0	31.8	42.5	32.6
Peprilus medius	Pacific harvestfish	424.2	733.1	723.7	609.4	418.6	771.3	731.3	606.2
Peprilus ovatus	Shining butterfish	2,552.6	2,719.2	2,547.4	1,731.9	2,550.9	1,557.0	2,547.6	1,968.3
Physiculus talarae	Peruvian mora	489.7	596.1	675.2	592.8	321.6	739.2	674.7	558.5
Rhinobatos spinosus	Spiny guitarfish	844.8	975.0	790.3	580.6	843.4	560.0	791.8	542.2
Rhizoprionodon longurio	Pacific sharpnose shark	201.7	234.6	215.2	179.7	174.7	268.4	215.1	169.4
Sardinops caeruleus	California pilchard	1,075.5	1,053.2	1,129.3	1,064.5	1,081.8	892.1	1,132.6	1,152.6
Selene peruviana	Pacific moonfish	920.7	1,384.9	1,210.7	1,030.0	857.8	1,378.5	1,204.1	997.0
Sphoeroides annulatus	Bullseye puffer	1,359.6	1,406.9	1,261.9	1,234.4	1,404.8	928.0	1,269.3	1,017.4
Sphoeroides lobatus	Longnose puffer	672.7	796.6	889.3	737.3	575.3	1,196.1	895.4	726.2
Sphoeroides sechurae	Peruvian puffer	415.7	717.7	719.0	602.8	395.9	694.3	714.9	519.4
Stomolophus meleagris	Cannonball jellyfish	6,708.6	11,594.4	6,692.7	9,871.5	6,709.0	38,514.6	6,692.2	52,727.7
Strongylocentrotus franciscanus	Red sea urchin	559.6	506.6	559.6	500.9	559.5	749.7	559.5	543.8
Strongylocentrotus purpuratus	Purple sea urchin	1,777.9	1,918.8	1,777.9	1,554.4	1,777.9	2,500.7	1,777.9	1,786.7
Sufflamen verres	Orangeside triggerfish	452.5	715.5	1,140.8	2,107.9	1,062.9	1,502.4	1,162.4	1,521.3
Synodus lacertinus	Sauro lizardfish	781.6	1,326.7	1,090.5	2,129.8	1,052.4	1,722.5	1,112.3	1,892.7
Tagelus californianus	California tagelus	9.4	11.2	8.6	6.8	9.9	7.3	8.5	6.6
Tivela stultorum	Pismo clam	62.4	74.1	59.3	46.7	63.3	50.1	59.3	41.8
Zapteryx xyster	Zapteryx xyster	310.8	251.8	307.2	146.5	321.2	12.3	306.9	69.1
Scomberomorus concolor	Monterey Spanish mackerel	2,101.0	2,358.2	2,052.5	1,548.6	2,086.8	1,538.8	2,044.9	1,725.1
Caranx caballus	Green jack	1,770.3	1,844.4	1,556.5	1,579.5	1,795.3	1,753.1	1,558.0	1,471.5
Paralabrax clathratus	Kelp bass	3,108.1	3,782.2	2,926.8	2,499.7	3,108.1	3,289.0	2,932.5	2,565.1
Paralabrax nebulifer	Barred sand bass	5,208.1	5,671.0	5,180.2	5,321.0	5,279.2	2,698.1	5,216.3	3,695.2
Cynoscion parvipinnis	Shortfin weakfish	187.6	211.1	165.7	133.9	184.5	105.1	165.8	125.8
Cynoscion xanthulus	Orangemouth weakfish	169.7	170.1	161.5	128.2	173.9	164.9	161.5	118.4
Menticirrhus undulatus	California kingcroaker	59.2	71.3	68.7	58.7	45.8	79.0	68.3	56.2
Umbrina roncador	Yellowfin drum	199.4	226.2	187.5	161.3	200.5	126.0	187.5	157.3
Kyphosus azureus	Zebra-perch sea chub	2,368.0	2,664.3	2,118.6	1,781.0	2,319.0	1,566.4	2,119.4	1,703.4

Sphyraena argentea	Pacific barracuda	1,472.3	2,127.8	2,449.9	3,167.0	2,282.2	7,843.3	2,452.2	9,142.7
Hippoglossina stomata	Bigmouth flounder	2,782.8	3,354.4	2,627.7	2,162.5	2,823.2	1,959.3	2,623.9	2,029.5
Xystreurys liolepis	Fantail flounder	2,946.6	3,510.2	2,768.5	2,373.8	2,896.2	1,907.2	2,770.1	2,330.5
Balistes polylepis	Finescale triggerfish	467.0	624.0	1,160.1	1,860.8	1,089.5	1,488.7	1,172.5	1,993.8
Cynoscion albus	Whitefin weakfish	371.2	416.5	474.0	462.1	382.8	337.8	472.9	437.7
Mustelus californicus	Grey smooth-hound	673.0	786.3	605.0	508.5	685.6	629.1	605.7	484.0
Mustelus lunulatus	Sicklefin smooth-hound	380.8	388.5	397.6	312.4	390.4	497.0	397.8	278.2
Platyrhinoidis triseriata	Thornback guitarfish	89.0	111.4	101.9	86.3	82.9	131.7	102.0	82.3
Zapteryx exasperata	Banded guitarfish	49.1	61.5	116.9	188.6	106.7	101.7	118.9	208.0
Gymnothorax mordax	California moray	71.3	92.9	87.0	73.8	57.1	95.5	87.1	72.3
Cheilotrema saturnum	Black croaker	157.0	178.1	58.6	13.6	29.1	107.2	58.9	12.2
Roncador stearnsii	Spotfin croaker	178.8	195.8	158.4	124.8	173.6	91.2	158.7	118.8
Seriphus politus	Queen croaker	188.4	204.3	166.9	132.5	184.3	201.4	167.1	153.1
Anarrhichthys ocellatus	Wolf-eel	195.4	193.3	194.1	166.4	193.5	184.2	193.7	119.9
Scorpaena guttata	California scorpionfish	200.3	231.9	199.7	176.4	199.8	143.9	199.7	189.1
Sebastes atrovirens	Kelp rockfish	243.9	309.0	244.3	212.4	243.4	160.6	244.3	225.5
Sebastes auriculatus	Brown rockfish	244.2	232.6	243.8	212.6	243.9	318.4	243.7	211.4
Sebastes aurora	Aurora rockfish	244.3	255.5	244.3	214.9	244.3	290.0	244.3	232.3
Sebastes carnatus	Gopher rockfish	244.1	304.3	244.3	213.4	243.5	204.9	244.3	228.0
Sebastes chrysomelas	Black-and-yellow rockfish	244.0	305.8	244.3	211.2	243.3	209.7	244.3	224.7
Sebastes constellatus	Starry rockfish	230.9	288.8	235.0	199.9	222.4	150.4	235.6	124.0
Sebastes diploproa	Splitnose rockfish	244.3	226.9	244.3	237.7	244.3	329.8	244.2	251.8
Sebastes elongatus	Greenstriped rockfish	244.3	236.8	244.3	236.1	244.3	335.9	244.2	254.2
Sebastes ensifer	Swordspine rockfish	244.3	323.7	244.3	217.0	244.3	186.6	244.3	233.0
Sebastes eos	Pink rockfish	244.3	339.4	244.3	217.5	244.3	170.9	244.3	232.4
Sebastes gilli	Bronzespotted rockfish	244.3	308.2	244.3	218.8	244.3	116.6	244.3	240.7
Sebastes hopkinsi	Squarespot rockfish	244.3	254.9	244.3	0.0	244.3	180.8	244.3	0.0
Sebastes jordani	Shortbelly rockfish	244.3	227.9	244.3	210.4	244.3	320.9	244.2	223.5

Sebastes melanostomus	Blackgill rockfish	244.3	317.8	244.3	211.2	244.3	250.2	244.3	223.5
Sebastes mystinus	Blue rockfish	176.3	217.6	244.3	817.2	244.3	317.5	244.3	673.8
Sebastes ovalis	Speckled rockfish	244.3	327.4	244.3	214.6	244.3	139.9	244.3	230.6
Sebastes rastrelliger	Grass rockfish	244.3	302.0	244.3	213.6	244.3	185.9	244.3	231.2
Sebastes rosaceus	Rosy rockfish	244.2	233.0	244.3	239.7	244.3	339.9	244.2	260.8
Sebastes rosenblatti	Greenblotched rockfish	244.3	337.0	244.3	217.2	244.3	185.3	244.3	233.0
Sebastes rubrivinctus	Flag rockfish	244.3	306.2	244.3	216.5	244.3	134.6	244.3	235.2
Sebastes rufus	Bank rockfish	244.3	300.4	244.3	216.7	244.3	228.6	244.3	233.8
Sebastes saxicola	Stripetail rockfish	244.3	241.7	244.3	237.7	244.3	343.7	244.2	254.9
Sebastes serranoides	Olive rockfish	97.9	517.3	244.0	1,695.0	244.3	794.5	244.1	1,129.9
Sebastes serriceps	Treefish	244.0	316.2	243.0	216.0	243.3	186.3	243.0	230.5
Sebastes simulator	Pinkrose rockfish	244.3	326.4	244.3	215.5	244.3	156.1	244.3	231.3
Sebastes umbrosus	Honeycomb rockfish	244.3	317.1	231.6	205.7	244.2	180.6	231.6	220.5
Myoxocephalus polyacanthocephalus	Great sculpin	197.6	180.4	197.7	177.2	197.4	228.8	197.5	136.1
Embassichthys bathybius	Deepsea sole	198.6	183.3	197.9	188.0	198.6	221.0	197.9	175.2
Isopsetta isolepis	Butter sole	198.9	186.1	197.1	175.2	198.1	221.6	196.9	147.4
Lyopsetta exilis	Slender sole	196.5	193.4	189.1	169.2	195.1	237.8	189.0	171.0
Pleuronichthys coenosus	C-O sole	147.4	149.2	134.2	111.5	144.9	152.5	134.6	116.0
Sebastes ruberrimus	Yelloweye rockfish	243.3	233.1	244.3	248.6	244.2	318.3	244.2	185.2
Sebastes caurinus	Copper rockfish	244.3	236.6	244.3	238.8	244.3	334.6	244.2	261.1
Sebastes nebulosus	China rockfish	244.3	231.3	244.3	258.1	244.2	308.6	244.2	204.6
Sebastes miniatus	Vermilion rockfish	244.3	270.0	244.3	198.9	244.3	184.4	244.3	120.6
Sebastes babcocki	Redbanded rockfish	243.0	230.8	242.1	234.5	243.0	275.1	242.0	218.9
Raja rhina	Longnose skate	238.9	236.0	230.5	219.0	234.8	310.7	230.6	205.9
Chionoecetes bairdi	Southern tanner crab	3,339.0	3,265.9	3,152.2	2,693.7	3,287.4	4,769.8	3,147.2	2,977.6
Pandalus platyceros	Spot shrimp	114.5	106.9	114.5	101.9	114.5	156.2	114.5	110.7
Venerupis philippinarum	Manila clam	7.9	9.7	7.7	7.0	9.0	9.4	7.7	6.7
		401,947.3	411,792.6	383,022.0	376,108.5	399,989.9	481,335.0	381,516.6	464,399.9

Appendix F. Projected changes in catch for large-scale fisheries in Pacific North America between 2080 and 2000.

Species	Common name	RCP 2.6				RCP 8.5			
		GFDL		IPSL		GFDL		IPSL	
		2000	2080	2000	2080	2000	2080	2000	2080
Sebastes serranoides	Olive rockfish	307.0	806.5	306.6	2,130.0	307.0	1,061.2	306.8	1,419.9
Cheilotrema saturnum	Black croaker	6.4	28.5	13.0	3.0	6.4	25.0	13.0	2.7
Alopias pelagicus	Pelagic thresher	121.2	283.3	112.7	239.1	123.3	322.2	113.1	296.6
Sebastes mystinus	Blue rockfish	307.0	333.1	307.0	1,026.9	307.0	422.9	307.0	846.8
Centropomus robalito	Yellowfin snook	190.4	385.2	214.9	486.4	195.5	658.4	217.2	644.2
Sphyrna mokarran	Great hammerhead	216.4	542.9	90.5	149.4	217.8	443.8	90.7	355.6
Opisthonema bulleri	Slender thread herring	126.3	227.7	122.7	265.4	130.8	378.7	122.3	374.6
Lutjanus jordani	Jordans snapper	99.2	210.4	157.5	280.5	102.1	91.9	160.9	190.8
Callinectes arcuatus	Arched swimming crab	330.2	997.5	1,889.0	1,622.0	362.3	1,998.4	1,887.8	1,520.8
Kyphosus elegans	Cortez sea chub	201.8	346.4	228.6	486.2	206.9	269.4	232.7	590.7
Synodus lacertinus	Sauro lizardfish	171.2	311.6	182.6	356.6	176.2	301.2	186.2	316.9
Sufflamen verres	Orangeside triggerfish	173.8	290.0	191.0	353.0	178.0	262.3	194.7	254.7
Lutjanus viridis	Blue and gold snapper	174.1	290.0	212.8	381.6	178.4	238.5	218.6	409.8
Dasyatis longa	Longtail stingray	234.8	368.7	359.8	662.4	235.9	87.9	359.8	503.4
Caranx vinctus	Cocinero	164.1	244.1	154.9	282.9	169.6	415.0	155.9	461.8
Balistes polylepis	Finescale triggerfish	179.4	282.4	194.3	311.6	182.4	263.4	196.3	333.9
Lutjanus colorado	Colorado snapper	225.1	261.5	298.5	568.2	233.4	313.4	307.8	894.3
Arothron hispidus	White-spotted puffer	144.2	194.9	139.3	236.7	145.7	162.1	139.6	200.0
Lutjanus novemfasciatus	Pacific cubera snapper	171.5	242.0	127.7	202.8	175.3	274.4	125.5	125.4
Hoplopagrus guentherii	Mexican barred snapper	220.1	233.8	299.0	565.1	229.7	264.7	308.3	914.5
Opisthonema medirastre	Middling thread herring	175.5	227.8	167.5	270.6	176.9	320.9	169.7	385.7

Doryteuthis opalescens	California market squid	26.0	40.1	25.7	35.1	25.9	72.3	25.7	84.2
Carcharhinus leucas	Bull shark	138.9	172.7	147.4	241.3	140.7	192.9	147.3	208.8
Zapteryx exasperata	Banded guitarfish	267.1	322.7	299.4	482.9	273.1	270.4	304.4	532.6
Aetobatus narinari	Spotted eagle ray	6.1	8.3	8.0	11.6	6.2	8.7	8.0	6.7
Loligo opalescens	California market squid	5.3	6.8	5.3	7.9	5.3	9.8	5.3	14.5
Manta birostris	Giant manta	141.0	165.1	126.4	191.3	142.9	150.7	125.8	207.9
Sphyraena ensis	Mexican barracuda	163.9	193.9	156.8	232.8	168.2	289.0	158.6	337.2
Selar crumenophthalmus	Bigeye scad	4.7	6.3	4.7	6.0	4.8	6.3	4.1	8.3
Physiculus talarae	Peruvian mora	41.1	69.0	113.1	99.3	53.8	131.4	113.0	93.5
Sphoeroides sechurae	Peruvian puffer	66.2	113.7	120.4	100.9	66.3	124.8	119.7	87.0
Peprilus medius	Pacific harvestfish	1,038.8	1,692.4	1,546.8	1,302.5	894.7	1,784.3	1,563.0	1,295.6
Alectis ciliaris	African pompano	202.7	214.6	199.3	276.9	204.5	186.6	200.1	330.4
Panopea abrupta	Pacific geoduck	8,554.4	9,083.2	8,554.4	11,847.5	8,554.4	9,113.5	8,554.4	13,953.5
Pomadasys macracanthus	Longspine grunt	619.9	931.3	1,088.5	1,022.0	560.4	418.8	1,087.2	994.6
Sphyraena argentea	Pacific barracuda	382.8	425.8	410.2	530.3	382.2	1,385.9	410.6	1,531.0
Kyphosus analogus	Blue-bronze sea chub	61.8	95.6	160.3	136.0	58.8	85.9	160.1	128.5
Naucrates ductor	Pilotfish	2,138.7	2,435.5	1,998.7	2,485.2	2,140.8	2,758.4	2,002.5	1,941.3
Decapterus macarellus	Mackerel scad	144.9	175.2	158.9	184.5	143.7	217.7	159.4	312.7
Caranx sexfasciatus	Bigeye trevally	10.2	12.4	9.5	10.8	10.7	13.7	9.4	11.0
Synodus scituliceps	Shorthead lizardfish	969.3	1,383.4	3,379.6	3,048.5	758.8	938.9	3,330.1	2,950.5
Selene peruviana	Pacific moonfish	138.0	204.0	202.7	172.5	143.6	244.1	201.6	167.0
Syacium ovale	Oval flounder	1,018.4	1,371.9	1,516.5	1,477.6	958.8	2,371.6	1,537.7	1,330.4
Merluccius angustimanus	Panama hake	223.6	344.4	332.5	256.8	263.9	322.3	332.3	216.9
Scomberomorus sierra	Pacific sierra	347.6	470.4	374.7	359.6	352.2	425.5	375.7	254.4
Alosa sapidissima	American shad	3.4	3.6	3.5	4.3	3.7	4.0	3.4	2.9
Diapterus peruvianus	Peruvian mojarra	76.3	89.4	52.1	57.7	73.1	108.1	61.5	53.8

Panulirus gracilis	Panulirus gracilis	191.9	261.9	259.2	230.4	223.8	460.3	261.4	308.0
Liopsetta glacialis	Arctic flounder	1,095.0	1,487.0	1,234.3	1,094.0	1,087.5	1,860.0	1,231.8	853.1
Paralithodes californiensis	Spiny king crab	18.5	21.5	18.1	19.7	17.5	25.6	18.9	24.8
Opisthonema libertate	Pacific thread herring	23,105.3	27,354.8	22,353.3	23,089.4	23,765.7	24,176.7	22,324.2	18,165.7
Haemulopsis leuciscus	Raucous grunt	1,218.1	1,643.0	1,706.0	1,477.3	1,183.1	2,068.0	1,699.4	1,412.5
Platyrhinoidis triseriata	Thornback guitarfish	212.4	290.5	261.0	220.9	212.3	356.3	261.2	210.7
Citharichthys fragilis	Gulf sanddab	1,426.8	1,639.0	1,427.0	1,514.6	1,426.6	960.6	1,386.9	1,144.0
Eucinostomus argenteus	Silver mojarra	1,575.0	1,716.2	1,447.3	1,601.0	1,586.7	1,188.8	1,453.5	1,128.3
Cynoscion albus	Whitefin weakfish	56.0	67.8	68.8	67.1	55.5	52.5	68.6	63.5
Litopenaeus stylirostris	Blue shrimp	5,017.7	6,455.5	4,493.0	4,008.4	3,843.9	4,168.9	4,433.8	3,865.6
Pomadasys panamensis	Panama grunt	567.8	756.0	836.2	708.0	576.7	1,230.4	838.0	676.4
Sphoeroides lobatus	Longnose puffer	96.5	130.0	148.9	123.5	96.3	213.4	149.9	121.6
Nuttallia obscurata	Varnish clam	445.1	495.6	445.1	470.5	443.4	695.6	445.2	912.0
Alopias superciliosus	Bigeye thresher	8.1	9.8	7.1	6.7	8.4	11.4	6.6	7.4
Centropomus medius	Blackfin snook	147.1	188.9	219.2	186.6	153.8	312.3	218.8	178.9
Sebastes nigrocinctus	Tiger rockfish	5,305.1	5,772.9	5,308.2	5,543.1	5,305.2	7,233.4	5,307.4	4,319.9
Sebastes entomelas	Widow rockfish	6,156.8	7,304.3	6,158.9	5,824.4	6,162.5	8,482.2	6,158.1	6,388.0
Caranx caballus	Green jack	188.0	208.2	163.6	166.0	188.7	193.4	163.7	154.6
Makaira indica	Black marlin	2.2	2.4	2.1	2.1	2.2	2.5	2.1	2.1
Cetengraulis mysticetus	Pacific anchoveta	6,319.7	7,574.3	6,732.4	6,139.8	6,511.4	6,640.5	6,705.8	6,111.5
Hippoglossina tetrophthalma	Fourspot flounder	126.3	160.3	181.3	152.3	117.5	187.9	181.8	144.8
Gymnura marmorata	California butterfly ray	178.6	224.6	203.7	173.3	184.8	256.0	203.8	167.1
Gymnothorax mordax	California moray	13.3	16.8	19.4	16.4	12.7	22.6	19.4	16.1
Sebastes nebulosus	China rockfish	5,613.4	5,892.8	5,614.8	5,932.7	5,613.6	7,489.9	5,613.9	4,703.3
Hyporthodus acanthistius	Rooster hind	110.7	143.2	173.4	139.6	109.7	224.0	173.8	135.1
Menticirrhus undulatus	California kingcroaker	115.4	143.2	160.9	137.6	107.2	197.6	160.0	131.7

Diplectrum pacificum	Inshore sand perch	5,728.6	7,144.9	7,032.2	5,910.2	5,634.6	9,136.0	7,008.5	5,895.2
Canthigaster punctatissima	Spotted sharpnosed puffer	225.1	237.9	200.1	205.8	227.7	118.0	200.1	130.3
Carcharhinus altimus	Bignose shark	32.9	32.4	32.6	35.9	33.1	22.6	32.7	37.9
Sebastes ruberrimus	Yelloweye rockfish	306.9	326.3	307.0	312.4	306.9	422.2	306.9	232.7
Sarda lineolata	Pacific bonito	537.4	655.7	567.5	484.2	533.6	1,592.5	564.4	1,112.1
Cynoscion reticulatus	Striped weakfish	181.1	223.7	222.7	186.6	193.5	316.7	222.5	172.3
Centropomus viridis	White snook	76.6	94.1	154.7	130.7	64.8	102.8	154.3	122.1
Sebastes borealis	Shortraker rockfish	5,291.1	5,387.6	5,285.7	5,570.2	5,292.0	7,579.7	5,283.5	5,750.8
Ophichthus triserialis	Pacific snake-eel	11.8	14.6	18.6	15.4	11.2	17.9	18.6	14.7
Crassostrea gigas	Pacific cupped oyster	389.8	430.8	509.3	488.3	376.7	494.9	503.6	491.2
Echinorhinus cookei	Prickly shark	118.3	133.1	94.5	88.2	119.0	143.4	94.7	89.7
Sebastes paucispinis	Bocaccio	2,800.0	3,147.7	2,779.1	2,593.5	2,797.9	3,729.3	2,776.3	2,467.5
Sarda chiliensis lineolata	Pacific bonito	1,120.2	1,165.6	1,123.1	1,138.6	1,119.6	1,676.4	1,121.3	1,513.0
Sebastes aleutianus	Rougheye rockfish	5,235.6	5,308.6	5,206.8	5,391.7	5,241.4	6,672.4	5,197.4	4,659.7
Eucinostomus gracilis	Graceful mojarra	794.7	1,039.8	1,177.7	872.0	805.9	1,560.4	1,173.1	861.2
Sebastes proriger	Redstripe rockfish	5,256.7	5,324.4	5,233.7	5,407.8	5,256.9	6,829.7	5,227.8	4,778.9
Pleurogrammus monopterygius	Atka mackerel	61,467.1	61,747.3	61,261.9	63,785.9	61,486.5	82,864.6	61,163.9	54,101.4
Venerupis philippinarum	Manila clam	352.8	401.2	306.2	276.6	356.4	389.1	305.0	267.2
Lepidopsetta polyxystra	Northern rock sole	1,568.1	1,578.3	1,562.4	1,615.3	1,569.0	2,011.6	1,561.4	1,367.8
Sebastes crameri	Darkblotched rockfish	2,724.0	2,771.5	2,714.0	2,773.4	2,724.3	3,496.8	2,711.2	2,465.5
Sphoeroides annulatus	Bullseye puffer	232.8	246.8	211.3	206.7	235.2	163.4	212.5	170.4
Thunnus orientalis	Pacific bluefin tuna	244.0	261.6	244.0	235.3	247.4	277.5	244.0	188.7
Prionotus stephanophrys	Lumptail searobin	2,036.1	2,394.0	2,004.6	1,716.6	2,131.1	3,097.2	2,005.4	1,587.4
Oligocottus maculosus	Tidepool sculpin	82.1	82.2	81.6	84.1	82.1	114.1	81.5	71.9

Raja stellulata	Starry skate	1,593.2	1,605.9	1,593.0	1,593.4	1,593.3	2,252.1	1,592.7	1,741.8
Thunnus obesus	Bigeye tuna	18.3	19.3	19.1	18.2	18.5	20.0	19.1	14.6
Sebastes babcocki	Redbanded rockfish	5,585.3	5,783.1	5,564.3	5,390.4	5,585.7	6,660.9	5,561.8	5,031.0
Hexagrammos decagrammus	Kelp greenling	347.9	359.4	346.3	336.1	348.0	430.1	346.1	308.7
Sebastes rosaceus	Rosy rockfish	307.0	313.4	307.0	301.3	307.0	450.7	306.9	327.8
Sebastes caurinus	Copper rockfish	5,615.2	5,752.1	5,614.8	5,488.3	5,615.7	8,119.3	5,613.5	6,001.4
Myliobatis longirostris	Snouted eagle ray	277.8	362.2	249.9	173.5	295.9	228.1	249.9	156.7
Dosidicus gigas	Jumbo flying squid	181.5	188.2	179.0	172.0	185.7	202.0	179.2	157.0
Xiphias gladius	Swordfish	5.1	5.4	5.4	5.1	5.2	5.1	5.4	3.9
Trichiurus lepturus	Largehead hairtail	5.7	6.2	5.8	5.3	5.9	6.2	5.8	5.6
Bathyraja aleutica	Aleutian skate	105.6	113.0	130.5	121.1	105.4	211.9	130.6	116.8
Nezumia convergens	Peruvian grenadier	17.0	20.1	76.8	62.2	20.5	22.9	77.5	58.1
Sebastes diploproa	Splitnose rockfish	307.0	314.2	307.0	298.7	307.0	437.5	306.9	316.4
Carcharhinus limbatus	Blacktip shark	16.3	17.1	15.0	14.2	14.8	19.4	15.1	15.4
Sebastes saxicola	Stripetail rockfish	307.0	313.6	307.0	298.7	307.0	456.0	306.9	320.4
Cancer productus	Pacific rock crab	3,888.6	4,121.0	3,888.5	3,631.8	3,888.6	5,069.2	3,888.5	5,395.5
Ophichthus zophochir	Yellow snake-eel	12.8	14.9	18.3	15.1	12.4	18.9	18.3	14.7
Embassichthys bathybius	Deepsea sole	128.5	133.8	128.0	121.6	128.5	150.6	128.0	113.3
Istiophorus platypterus	Indo-Pacific sailfish	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0
Lagocephalus lagocephalus	Oceanic puffer	154.9	178.1	183.4	154.1	155.0	208.9	183.4	148.1
Sebastes elongatus	Greenstriped rockfish	307.0	314.2	307.0	296.7	307.0	445.6	306.9	319.5
Thunnus thynnus	Northern bluefin tuna	13.1	13.9	14.1	13.0	13.2	14.2	14.0	13.7
Tetrapturus angustirostris	Shortbill spearfish	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0
Sebastes melanops	Black rockfish	271.5	252.1	203.5	213.0	236.5	282.0	203.5	218.0

Alopias vulpinus	Thintail thresher	10.1	10.4	7.7	7.2	9.3	9.5	7.7	7.9
Raja rhina	Longnose skate	6,147.5	6,288.6	6,034.4	5,733.2	6,147.0	8,578.5	6,035.8	5,389.2
Thunnus albacares	Yellowfin tuna	855.6	889.2	903.2	842.3	866.2	919.1	901.9	633.8
Clidoderma asperrimum	Roughscale sole	121.5	124.9	120.8	113.6	121.4	153.9	120.9	104.7
Paralabrax nebulifer	Barred sand bass	7,733.1	7,270.9	7,602.6	7,809.3	7,747.9	4,125.4	7,655.6	5,423.2
Sebastolobus altivelis	Longspine thornyhead	5,224.1	5,509.5	5,156.1	4,678.3	5,225.2	6,039.6	5,159.6	4,910.2
Leukoma staminea	Pacific littleneck clam	0.5	0.6	0.5	0.5	0.5	0.6	0.5	0.6
Mustelus californicus	Grey smooth-hound	361.6	404.8	317.6	266.9	359.9	346.4	318.0	254.1
Auxis thazard	Frigate tuna	15.5	16.1	16.1	14.8	15.7	16.7	16.0	8.8
Euphausia pacifica	North Pacific krill	130.2	143.1	128.9	110.8	130.2	211.3	128.4	180.1
Sardinops caeruleus	California pilchard	181.6	183.7	189.1	178.3	181.2	156.9	189.7	193.0
Bagre panamensis	Chilhuil sea catfish	172.5	192.0	201.9	169.8	159.9	289.8	202.1	160.7
Scomber japonicus	Chub mackerel	1,226.5	1,242.3	1,217.1	1,140.2	1,229.0	1,333.7	1,211.5	1,182.4
Sebastes constellatus	Starry rockfish	279.4	306.8	295.3	251.2	279.5	198.3	296.1	155.8
Bathyraja interrupta	Sandpaper skate	167.3	173.0	167.8	153.0	167.4	194.2	167.7	131.3
Hypomesus pretiosus	Surf smelt	338.9	339.9	338.9	319.5	338.9	642.4	338.8	376.6
Sphyrna lewini	Scalloped hammerhead	8.6	8.8	9.3	8.6	8.6	10.6	9.3	9.6
Cancer magister	Dungeness crab	627.6	646.0	627.6	574.1	627.6	785.7	627.6	795.3
Sebastes umbrosus	Honeycomb rockfish	306.9	322.3	291.0	258.5	306.9	237.7	291.0	277.1
Sebastes carnatus	Gopher rockfish	306.0	324.8	307.0	268.2	306.0	271.0	307.0	286.5
Haliotis sorenseni	White abalone	0.5	0.5	0.4	0.4	0.5	0.3	0.4	0.4
Genyonemus lineatus	White croaker	10,302.0	11,101.8	10,310.1	8,778.6	10,310.1	21,609.4	10,310.1	10,399.5
Haliotis rufescens	Red abalone	0.5	0.5	0.5	0.5	0.5	0.4	0.5	0.6
Lyopsetta exilis	Slender sole	126.2	130.5	122.3	109.4	126.2	162.3	122.3	110.6
Sebastes serriceps	Treefish	305.8	317.8	305.3	271.4	305.8	246.2	305.3	289.7
Spirinchus starksi	Night smelt	338.9	348.6	338.9	303.4	339.0	448.8	338.7	337.0
Bathyraja abyssicola	Deepsea skate	109.5	116.2	102.4	88.3	110.2	115.7	102.7	84.7
Sebastes eos	Pink rockfish	307.0	316.6	307.0	273.3	307.0	225.4	307.0	292.0

Oncorhynchus mykiss	Rainbow trout	310.6	341.5	310.3	255.1	310.6	400.0	310.4	302.7
Totoaba macdonaldi	Totoaba	428.1	513.9	428.1	308.4	428.1	256.9	428.1	310.5
Isopsetta isolepis	Butter sole	128.0	131.9	127.5	113.3	128.1	151.0	127.4	95.3
Coregonus pidschian	Humpback whitefish	301.1	322.7	300.5	254.5	301.2	344.1	300.2	231.0
Paralabrax clathratus	Kelp bass	428.1	455.1	403.1	344.3	428.1	476.7	403.9	353.3
Sebastes aurora	Aurora rockfish	307.0	318.5	307.0	270.0	307.0	385.2	307.0	292.0
Microgadus proximus	Pacific tomcod	304.9	315.2	304.5	268.6	304.9	365.8	304.8	301.8
Sebastes rosenblatti	Greenblotched rockfish	307.0	314.7	307.0	272.9	307.0	244.7	307.0	292.8
Sebastes chrysomelas	Black-and-yellow rockfish	305.7	320.6	307.0	265.4	305.7	277.6	307.0	282.4
Psettichthys melanostictus	West American sand sole	1,738.2	1,678.4	1,738.1	1,646.9	1,738.2	2,506.0	1,738.1	2,346.5
Sebastes simulator	Pinkrose rockfish	307.0	316.5	307.0	270.8	307.0	205.9	307.0	290.7
Metacarcinus magister	Dungeness crab	11,572.0	11,342.2	11,572.1	10,791.8	11,568.6	15,955.7	11,572.9	15,729.6
Mustelus lunulatus	Sicklefin smooth-hound	206.0	232.0	208.7	164.0	205.0	273.9	208.8	146.1
Scorpaena guttata	California scorpionfish	45.0	46.3	45.0	39.8	45.0	34.1	45.0	42.6
Anarrhichthys ocellatus	Wolf-eel	42.8	45.1	43.0	36.8	42.8	42.9	42.9	26.5
Myoxocephalus polyacanthocephalus	Great sculpin	44.5	45.1	44.6	39.9	44.5	54.2	44.5	30.7
Sebastes ensifer	Swordspine rockfish	307.0	313.5	307.0	272.7	307.0	246.4	307.0	292.8
Umbrina roncador	Yellowfin drum	10,638.4	11,120.6	9,952.0	8,560.7	10,638.6	7,027.3	9,949.5	8,345.9
Thysanoessa inspinata	Euphausiid	112.3	123.7	113.0	90.7	112.3	201.1	112.5	161.5
Sebastes rufus	Bank rockfish	307.0	312.2	307.0	272.3	307.0	303.6	307.0	293.8
Sebastes maliger	Quillback rockfish	5,300.8	5,321.6	5,294.6	4,757.0	5,301.8	6,839.8	5,294.0	4,615.7
Sebastes auriculatus	Brown rockfish	306.4	315.3	306.3	267.1	306.4	421.6	306.3	265.7
Sebastes melanostomus	Blackgill rockfish	307.0	318.1	307.0	265.3	307.0	331.9	307.0	280.8
Sebastes atrovirens	Kelp rockfish	305.9	315.2	307.0	266.9	305.9	212.0	307.0	283.3
Tresus nuttallii	Pacific gaper clam	16.1	16.8	16.1	13.8	16.1	17.6	16.1	14.3

Protothaca staminea	Pacific littleneck clam	452.4	438.2	452.5	419.3	452.3	514.6	452.5	567.3
Scorpaenichthys marmoratus	Cabezon	38.8	36.0	40.2	38.9	34.7	48.2	39.9	41.6
Xystreurys liolepis	Fantail flounder	1,865.0	1,934.2	1,755.3	1,505.1	1,836.3	1,270.3	1,756.4	1,477.6
Sebastes rubrivinctus	Flag rockfish	307.0	309.4	307.0	272.1	307.0	177.2	307.0	295.5
Clupea pallasii pallasii	Pacific herring	14,445.0	14,586.9	13,811.3	12,211.4	14,653.1	15,210.8	13,644.4	9,164.9
Sebastes gilli	Bronzespotted rockfish	307.0	306.4	307.0	274.9	307.0	153.1	307.0	302.4
Rhizoprionodon longurio	Pacific sharpnose shark	104.8	110.9	133.1	111.1	108.0	176.8	133.0	104.8
Scomberomorus concolor	Monterey Spanish mackerel	350.2	398.6	343.7	259.3	349.4	272.0	342.4	288.9
Sebastes rastrelliger	Grass rockfish	307.0	312.3	307.0	268.5	307.0	245.7	307.0	290.5
Gnathophis cinctus	Hardtail conger	24.7	26.9	26.9	21.6	25.0	31.6	27.1	21.0
Sebastes ovalis	Speckled rockfish	307.0	310.1	307.0	269.7	307.0	184.5	307.0	289.8
Panulirus interruptus	California spiny lobster	735.9	809.1	650.9	512.7	722.6	513.3	653.0	501.2
Siliqua patula	Pacific razor clam	452.1	438.7	450.8	412.6	452.4	524.5	450.4	461.1
Macoma balthica	Baltic clam	6.3	6.5	6.3	5.4	6.3	7.2	6.3	4.8
Hippoglossina stomata	Bigmouth flounder	403.6	427.2	381.5	313.9	409.8	298.3	380.9	294.6
Trachurus symmetricus	Pacific jack mackerel	1,814.6	1,918.8	1,814.6	1,494.3	1,814.6	1,968.1	1,814.6	1,640.6
Lutjanus guttatus	Spotted rose snapper	232.5	237.2	229.3	197.0	235.0	155.6	230.4	185.9
Oncorhynchus tshawytscha	Chinook salmon	5,645.0	5,975.3	5,625.0	4,615.5	5,669.5	6,266.5	5,612.9	4,260.6
Sebastes jordani	Shortbelly rockfish	307.0	312.1	307.0	264.4	307.0	425.2	306.9	280.9
Panulirus penicillatus	Pronghorn spiny lobster	231.7	245.7	232.4	190.0	219.8	343.3	232.2	187.5
Errex zachirus	Rex sole	5,131.9	5,098.4	5,131.9	4,532.7	5,131.9	4,896.0	5,131.9	4,797.5
Lutjanus peru	Pacific red snapper	202.4	213.2	148.3	122.0	205.5	137.5	149.0	74.5
Kyphosus azureus	Zebra-perch sea chub	387.9	401.1	354.8	298.2	388.3	275.5	354.9	285.2

Pandalus jordani	Ocean shrimp	16,637.7	16,161.5	16,636.9	15,012.5	16,637.8	22,526.9	16,636.0	16,633.6
Pandalus platyceros	Spot shrimp	43.7	43.0	43.7	38.9	43.7	62.7	43.7	42.3
Callinectes bellicosus	Warrior swimcrab	5,328.7	5,588.5	4,815.4	3,955.1	5,513.7	1,545.5	4,828.4	3,900.2
Strongylocentrotus franciscanus	Red sea urchin	17.9	17.4	17.9	16.0	17.9	25.3	17.9	17.4
Seriphus politus	Queen croaker	41.9	44.8	36.9	29.3	40.8	47.0	37.0	33.9
Peprilus ovatus	Shining butterfish	426.8	505.1	426.6	290.0	427.2	274.1	426.6	329.6
Beringraja binoculata	Big skate	1,174.7	1,180.2	1,174.7	1,007.9	1,174.7	1,133.6	1,174.7	1,050.1
Porichthys notatus	Plainfin midshipman	7,484.8	7,544.8	7,484.7	6,393.6	7,484.9	12,576.0	7,484.5	7,498.2
Paralithodes camtschaticus	Red king crab	9.8	9.7	10.2	8.8	9.9	13.3	10.2	7.9
Panopea generosa	Pacific geoduck	108.7	109.6	108.7	92.5	108.7	148.3	108.6	97.4
Cynoscion xanthulus	Orangemouth weakfish	385.8	411.1	378.3	300.3	407.4	405.9	378.5	277.4
Peprilus snyderi	Salema butterfish	282.5	294.0	293.7	238.6	282.6	318.6	293.7	219.7
Oncorhynchus kisutch	Coho salmon	8,679.0	8,647.4	8,245.4	7,062.4	8,895.2	9,944.6	8,204.7	6,597.9
Nezumia liolepis	Smooth grenadier	353.1	365.5	358.1	292.6	350.2	302.6	356.0	272.3
Osmerus mordax	Rainbow smelt	297.3	301.9	296.9	247.6	297.6	348.1	295.9	136.4
Tagelus californianus	California tagelus	0.4	0.5	0.4	0.3	0.5	0.4	0.4	0.3
Sicyonia ingentis	Sicyonia ingentis	149.6	162.0	136.2	104.2	147.7	97.3	136.7	95.4
Pleuronichthys coenosus	C-O sole	93.9	95.3	86.8	72.1	93.7	104.3	87.1	75.0
Citharichthys stigmaeus	Speckled sanddab	1,093.0	1,100.2	1,056.3	886.3	1,091.0	1,598.6	1,064.5	1,040.7
Chionoecetes bairdi	Southern tanner crab	335.0	331.8	317.3	271.1	330.9	506.1	316.8	299.7
Chionoecetes opilio	Queen crab	3.5	3.4	3.7	3.3	3.5	5.0	3.7	3.4
Enteroctopus dofleini	Giant Pacific octopus	6.6	6.8	6.5	5.3	6.6	9.3	6.4	5.6
Panulirus inflatus	Blue spiny lobster	626.8	663.1	587.0	460.7	646.8	769.8	587.2	407.1
Arothron meleagris	Guineafowl puffer	195.0	195.6	172.9	144.5	196.3	115.6	173.2	122.6

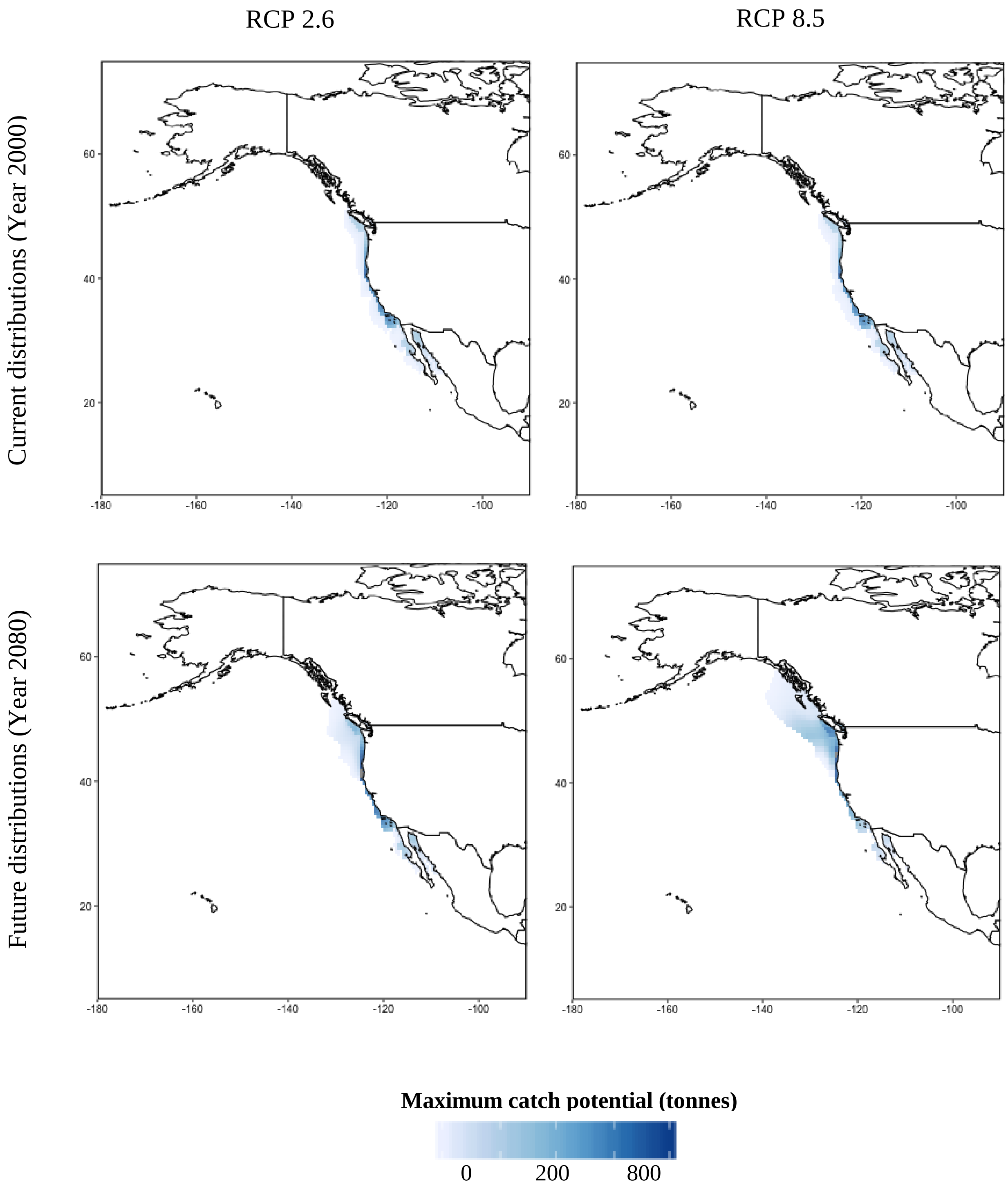
Limanda aspera	Yellowfin sole	25,422.3	25,702.1	20,730.9	17,168.5	26,364.9	27,223.4	20,615.0	16,300.6
Oncorhynchus gorbuscha	Pink salmon	42,646.3	43,327.0	38,939.9	31,962.8	40,991.6	47,595.4	38,523.5	22,043.7
Citharichthys sordidus	Pacific sanddab	1,306.0	1,233.0	1,209.6	1,075.8	1,278.8	1,314.5	1,202.6	946.3
Lutjanus aratus	Mullet snapper	244.2	243.2	240.3	200.9	246.7	164.4	242.4	178.7
Cynoscion parvipinnis	Shortfin weakfish	426.9	436.5	388.2	313.8	432.4	259.1	388.6	294.8
Hippoglossoides robustus	Bering flounder	1,419.2	1,514.5	1,414.4	1,074.6	1,420.5	1,452.0	1,410.5	689.2
Engraulis mordax	Californian anchovy	15,044.4	15,154.7	15,052.4	12,321.5	15,052.7	11,496.2	15,050.1	15,229.9
Myoxocephalus quadricornis	Fourhorn sculpin	81.0	87.7	80.7	59.8	81.0	77.1	80.4	38.6
Oncorhynchus keta	Chum salmon	19,968.5	20,148.0	18,844.6	15,351.2	20,592.5	23,487.3	18,722.3	11,148.0
Bagre pinnimaculatus	Red sea catfish	180.9	179.2	200.7	166.8	178.9	277.2	200.7	158.6
Merluccius productus	North Pacific hake	201,571.2	194,801.6	201,571.2	172,147.3	201,571.2	171,771.8	201,571.2	176,351.2
Thysanoessa spinifera	Euphausiid	116.2	116.8	116.6	94.7	116.2	157.0	116.1	57.1
Gadus chalcogrammus	Alaska pollock	304.9	291.2	304.9	261.6	304.9	348.3	304.9	275.4
Reinhardtius hippoglossoides	Greenland halibut	1,933.4	1,855.7	1,721.3	1,468.8	1,971.7	1,784.5	1,719.8	1,366.1
Coregonus sardinella	Sardine cisco	300.6	317.0	298.1	225.9	300.7	367.8	296.3	83.6
Hexanchus griseus	Bluntnose sixgill shark	75.5	69.0	82.4	73.8	75.7	113.6	82.4	70.4
Peprilus simillimus	Pacific pompano	5,463.8	5,520.4	5,463.3	4,359.0	5,463.8	5,684.9	5,463.3	5,008.3
Theragra chalcogramma	Alaska pollock	738,503.6	734,760.5	594,915.0	482,681.5	722,778.6	828,381.6	587,713.9	321,990.3
Roncador stearnsii	Spotfin croaker	38.5	39.2	35.0	27.6	38.4	21.3	35.1	26.3
Janthina janthina	Violet sea-snail	4,398.8	4,684.7	3,752.4	2,775.2	4,398.8	4,037.2	3,753.5	2,746.8
Glyptocephalus zachirus	Rex sole	4,834.7	3,997.4	4,782.5	4,651.8	4,742.8	4,965.2	4,756.7	4,645.9
Nasolamia velox	Whitenose shark	95.5	91.0	104.8	88.2	91.9	158.0	104.7	81.3
Rhinobatos spinosus	Spiny guitarfish	352.7	373.7	332.9	244.6	355.3	247.9	333.5	228.4
Nezumia stelgidolepis	California grenadier	133.3	128.3	172.9	143.7	132.1	201.8	172.7	135.9
Hippoglossoides elassodon	Flathead sole	5,067.0	4,727.7	3,482.2	2,972.7	5,073.1	4,054.6	3,429.4	2,734.5
Prionace glauca	Blue shark	104.2	90.2	108.5	99.9	119.0	95.8	104.6	101.8

Atheresthes evermanni	Kamchatka flounder	664.6	635.6	538.9	445.4	669.2	627.0	537.5	360.0
Ariopsis guatemalensis	Blue sea catfish	277.7	246.8	261.0	232.7	247.1	335.0	260.7	214.7
Sebastes miniatus	Vermilion rockfish	306.9	296.5	307.0	250.0	306.9	243.4	307.0	151.6
Hemilepidotus jordani	Yellow Irish lord	83.2	85.9	81.2	60.5	83.2	87.4	81.3	46.9
Osmerus dentex	Pacific rainbow smelt	295.1	298.7	293.0	222.7	295.3	301.7	291.7	90.2
Thysanoessa longipes	Euphausiid	116.9	119.0	116.7	87.5	117.0	125.5	115.6	42.5
Centropomus nigrescens	Black snook	54.1	50.8	77.4	64.2	53.6	49.9	77.3	56.5
Dasyatis brevis	Whiptail stingray	81.2	106.7	55.2	24.8	70.4	70.6	55.3	24.3
Cetorhinus maximus	Basking shark	12.2	11.0	11.5	9.9	11.7	11.0	11.4	10.5
Lepidopsetta bilineata	Rock sole	32,219.4	31,673.4	25,835.2	19,935.8	32,373.9	33,571.5	25,718.0	15,390.4
Paralichthys californicus	California flounder	98.4	79.0	88.5	84.1	76.1	82.9	88.4	88.0
Limanda proboscidea	Longhead dab	1,406.6	1,557.9	1,393.9	892.4	1,407.4	1,289.8	1,387.5	420.5
Hippoglossus stenolepis	Pacific halibut	7,296.3	6,132.5	6,922.6	6,244.6	7,421.2	6,827.5	6,915.2	5,839.6
Pleuronectes quadrituberculatus	Alaska plaice	3,454.2	2,622.5	3,029.2	2,928.8	3,473.1	3,435.8	3,027.7	2,761.1
Oncorhynchus nerka	Sockeye salmon	42,828.1	40,017.7	40,772.6	32,257.8	42,648.0	39,568.1	40,298.3	16,888.5
Squatina californica	Pacific angelshark	628.1	632.5	597.2	427.7	627.1	766.1	596.7	418.3
Microstomus pacificus	Dover sole	3,926.2	3,229.2	3,111.8	2,772.8	4,088.4	2,827.0	3,090.9	2,606.3
Hypomesus pretiosus	Surf smelt	4,078.7	4,019.5	3,991.7	2,905.5	4,081.9	4,282.6	3,989.8	2,606.4
Haliotis fulgens	Green abalone	0.5	0.4	0.4	0.3	0.5	0.3	0.4	0.4
Patinopecten caurinus	Weathervane scallop	6.4	4.5	6.4	6.3	6.4	6.9	6.4	9.2
Eleginus gracilis	Saffron cod	179.8	169.6	159.7	119.8	190.5	178.6	157.9	91.0
Thaleichthys pacificus	Eulachon	667.2	670.7	667.2	457.9	667.2	731.5	667.2	546.5
Salvelinus malma malma	Dolly varden	296.0	282.6	295.0	217.1	296.4	287.1	294.1	178.3
Carcharhinus longimanus	Oceanic whitetip shark	1.8	1.5	0.7	0.6	1.8	2.9	0.7	0.7
Anoplopoma fimbria	Sablefish	6,635.9	5,613.1	5,370.5	4,483.3	5,968.6	3,734.3	5,337.8	3,716.6
Platichthys stellatus	Starry flounder	2,364.1	2,163.3	2,045.5	1,565.5	2,342.5	2,264.0	2,031.1	1,153.8

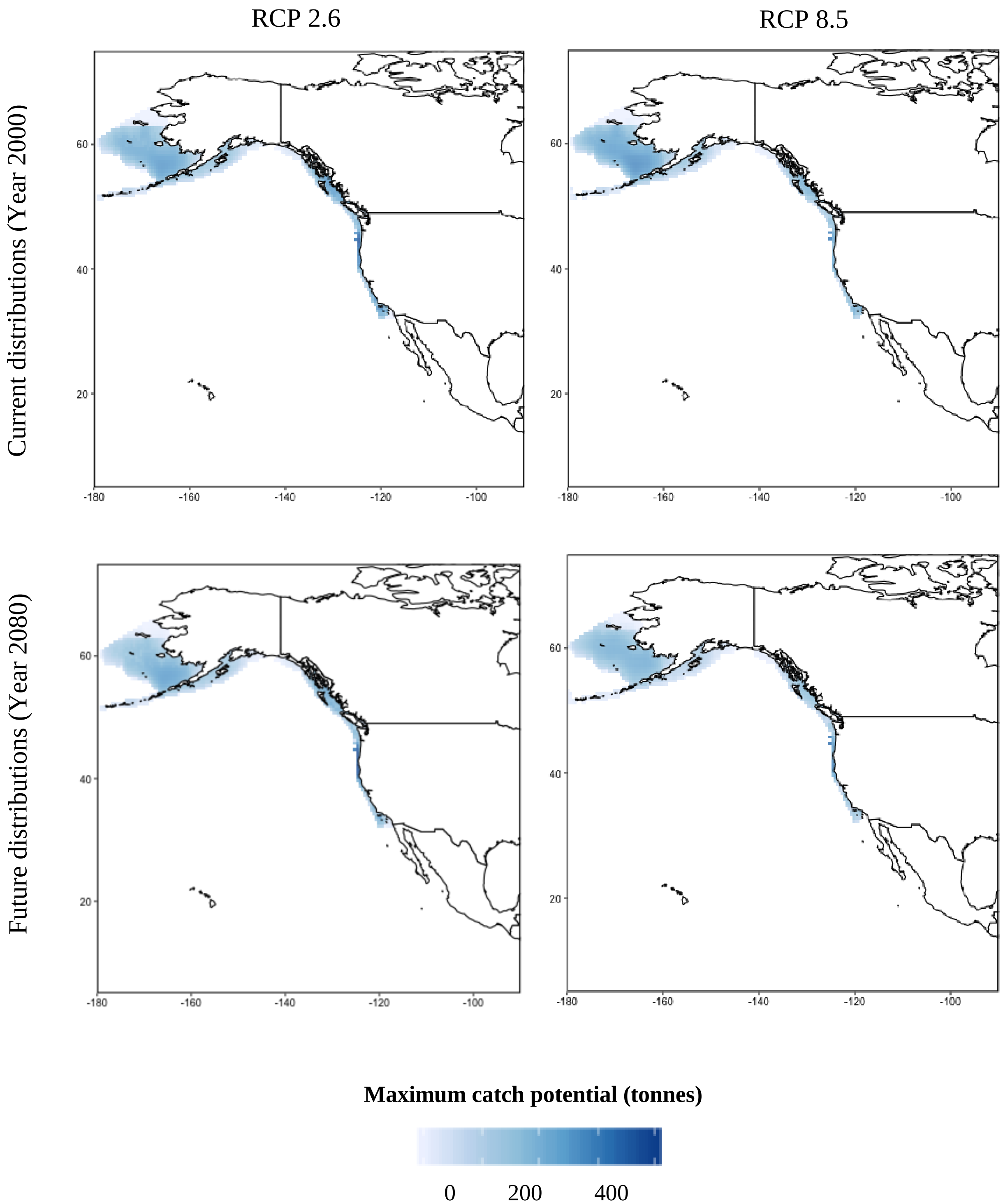
Semicossyphus pulcher	California sheephead	8.7	8.7	7.9	5.4	15.0	17.9	8.0	4.8
Atheresthes stomias	Arrowtooth flounder	8,741.0	7,013.9	6,743.3	5,689.8	9,062.9	6,853.1	6,719.8	5,312.4
Coregonus nasus	Broad whitefish	289.8	302.4	280.9	168.0	290.3	180.0	280.5	71.9
Squalus suckleyi	Pacific spiny dogfish	4,504.0	3,926.4	4,504.0	3,430.7	4,504.0	4,221.7	4,504.0	3,446.3
Coregonus laurettae	Bering cisco	291.9	297.3	283.0	172.9	292.4	230.9	279.2	63.2
Stereolepis gigas	Giant sea-bass	4.4	4.5	2.9	1.7	7.8	5.8	2.9	1.6
Clinocardium nuttallii	Nuttall cockle	2.7	2.1	2.8	2.3	2.9	2.7	2.8	2.5
Gadus macrocephalus	Pacific cod	82,273.2	74,210.9	64,907.1	46,033.3	80,482.2	66,841.2	64,290.7	34,847.8
Eopsetta jordani	Petrale sole	12,645.8	8,005.0	12,582.2	12,209.8	12,627.6	10,609.1	12,555.4	13,139.3
Negaprion brevirostris	Lemon shark	310.7	301.9	348.5	216.1	312.8	308.6	348.7	123.1
Coryphaena hippurus	Common dolphinfish	16.8	14.1	18.4	13.7	17.3	14.0	18.2	2.3
Sebastes alutus	Pacific ocean perch	31,372.3	23,232.1	24,483.3	20,275.9	30,199.6	25,853.5	24,435.8	22,265.9
Mya arenaria	Sand gaper	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sebastes pinniger	Canary rockfish	8,162.4	5,736.2	8,141.0	6,719.0	8,162.4	8,236.5	8,142.6	7,281.5
Haliotis cracherodii	Black abalone	0.5	0.4	0.5	0.4	0.5	0.4	0.5	0.4
Pleuronichthys decurrens	Curlfin sole	82.3	47.3	74.4	68.8	80.3	59.1	74.1	68.9
Mallotus villosus	Capelin	157.0	147.2	159.0	87.6	160.9	32.7	156.9	37.5
Sebastes flavidus	Yellowtail rockfish	899.8	594.1	957.9	781.9	908.9	1,043.8	919.4	798.2
Parophrys vetulus	English sole	8,313.2	4,471.3	8,313.2	7,635.9	8,313.2	6,905.1	8,313.2	8,571.6
Sphyrna zygaena	Smooth hammerhead	4.4	2.5	2.3	2.0	4.2	3.3	2.3	2.3
Sebastes goodei	Chilipepper	23.3	11.8	21.2	19.7	8.6	4.9	21.9	23.3
Boreogadus saida	Polar cod	19.2	15.8	16.2	9.4	24.0	21.5	15.9	1.3
Ophiodon elongatus	Lingcod	656.7	367.0	715.8	590.6	734.4	599.0	711.3	636.2
Galeorhinus galeus	Tope shark	5.2	2.2	5.8	5.2	6.7	5.9	5.7	5.7
Epinephelus analogus	Spotted grouper	1.0	0.5	1.5	1.2	1.5	0.3	1.2	1.0
Haliotis corrugata	Pink abalone	0.1	0.0	0.2	0.2	0.1	0.0	0.2	0.2
Atractoscion nobilis	White weakfish	777.6	352.1	777.6	630.7	777.6	674.9	777.6	647.8
Zapteryx xyster	Zapteryx xyster	133.2	95.8	129.4	61.7	135.3	5.2	129.3	29.1

Sebastes hopkinsi	Squarespot rockfish	307.0	361.6	307.0	0.0	307.0	237.5	307.0	0.0
Hydrolagus colliei	Spotted ratfish	10.9	1.6	20.9	21.3	9.2	0.2	20.7	22.0
Carcharhinus falciformis	Silky shark	254.8	55.9	330.8	302.7	285.9	104.7	330.4	287.3
Carcharhinus obscurus	Dusky shark	15.8	4.1	14.9	12.2	15.9	9.8	15.0	14.6
Carcharodon carcharias	Great white shark	8.8	1.7	7.0	6.2	26.8	5.2	7.7	7.2
Clupea pallasii	Pacific herring	4,791.6	3,049.7	4,791.6	2,082.2	4,791.6	1,401.7	4,791.6	465.4
Galeocerdo cuvier	Tiger shark	1.8	0.1	0.1	0.1	0.3	0.0	0.1	0.1
Lutjanus argentiventris	Yellow snapper	0.4	0.0	0.1	0.1	0.2	0.0	0.1	0.0
Farfantepenaeus brevirostris	Crystal shrimp	86.4	54.1	226.8	86.5	106.0	68.0	156.3	74.9
Mugil cephalus	Flathead mullet	0.9	0.0	2.8	2.4	0.8	0.1	2.6	2.3
Sphyrna media	Scoophead	0.5	0.3	6.1	0.7	0.4	3.8	6.2	0.7
Sphyraena barracuda	Great barracuda	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.0
Carcharhinus brachyurus	Copper shark	0.5	0.0	0.7	0.5	0.1	0.0	0.9	0.8
		1,687,430.4	1,661,018.8	1,498,671.4	1,277,192.4	1,668,671.1	1,801,352.5	1,488,784.0	1,066,305.6

Appendix G. Maximum catch potentials (tonnes) of California market squid (*Loligo opalescens*) displayed spatially between years 2000 and 2080 under both RCP scenarios.



Appendix H. Maximum catch potentials (tonnes) of Pacific cod (*Gadus macrocephalus*) displayed spatially between years 2000 and 2080 under both RCP scenarios.



Appendix I. Maximum catch potentials (tonnes) of Cannonball jellyfish (*Stomolophus meleagris*) displayed spatially between years 2000 and 2080 under both RCP scenarios.