Estimating the Economic Impacts of Climate Change on 16 Major U.S. Fisheries

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Conflicts of Interest

The authors declare no conflicts of interest relevant to this study.

Abstract

Observational evidence shows marine species are shifting their geographic distribution in response to warming ocean temperatures. These shifts have implications for U.S. fisheries and seafood consumers. The analysis presented here employs a two-stage inverse demand model to estimate the consumer welfare impacts of projected increases or decreases in commercial landings for 16 U.S. fisheries from 2021 to 2100, based on predicted changes in thermally available habitat. The fisheries analyzed together account for 56 percent of current U.S. commercial fishing revenues. The analysis compares welfare impacts under two climate scenarios: a high-emissions case that assumes limited efforts to reduce atmospheric greenhouse gas and a low-emissions case that assumes more stringent mitigation. The present value of consumer surplus impacts when discounted at three percent is a net loss of $2.1 billion (2018 $US) in the low-emissions case and $4.2 billion in the high-emissions scenario. Projected annual losses reach $278 million to $901 million by 2100.

KEY WORDS: commercial fisheries, marine species distribution, welfare impacts, climate change, warming ocean temperatures

1. Introduction

Climate change has resulted in significant impacts on biological communities in marine ecosystems. These changes have included restructuring of species composition (Fodrie et al. 2010; Wernberg et al. 2016; Flanagan et al. 2019), unprecedented changes in species phenology (Edwards and Richardson 2004; Mills et al. 2013; Staudinger et al. 2019), and geographic shifts in species distributions (Pinsky et al. 2013; Poloczanska et al. 2013). Evidence for the redistribution of marine species has also been observed in global fisheries, with changes in catch composition consistent with poleward shifts in species distributions (Cheung et al. 2013). Further, during the last century climate change, along with other stressors, has reduced potential fisheries yields at a global scale (Free et al. 2019), suggesting widespread and negative economic implications. Regional fisheries impacts have also occurred, including declines in accessibility of target species to fisherman (Young et al. 2018; Pinsky and Fogarty 2012; Hughes et al. 2015), changes in stock productivity (Hare and Able 2007; Bell et al. 2014; Pershing et al. 2015), and regional conflicts over quota allocations as species shift across jurisdictional lines (Dubik et al. 2019; Spijkers and Boonstra 2017).

Future projections of climate change impacts in the coming century suggest a global loss of biomass in the oceans, especially at middle and lower latitudes (Lotze et al. 2019). Potential landings are also projected to decline during the 21st century on many of the most valuable fishing grounds (Cheung et al. 2010). Further, factors other than changes in landings, such as changes in catch composition towards lower value species, might lead to dramatic losses of fisheries revenues (Lam et al. 2016). Major changes in the geographic distribution of marine species are also projected during the coming century, as a result of shifts in preferred temperatures (Cheung et al. 2009; Wisz et al. 2015; Morley et al. 2018). Such shifts in distribution will challenge fisheries management as species move across jurisdictional boundaries (Haynie and Pfeiffer 2012; Pinsky et al. 2018).

While global-scale economic analyses of the potential impacts of climate change on fisheries are important (Lam et al. 2016), regional-scale assessments are critical to inform policy makers of expected impacts (e.g., Jones et al. 2015). Indeed, in the U.S., projections of the economic impacts of climate change on fisheries have been identified as a federal research priority (Busch et al. 2016). The U.S. is one of the highest producers of wild-caught marine seafood globally (FAO 2018), and some of the most rapidly increasing ocean temperatures in the world are off the U.S. coast (Burrows et al. 2011). Studies of the Gulf of Maine have documented significant increases in ocean temperatures and evidence of marine heat waves (Mills et al. 2013; Pershing et al. 2015), which satellite observations suggest are becoming more frequent, intense, and extensive (IPCC 2019). Future projections of thermal habitat for hundreds of species on the North American continental shelf predict major shifts in distribution for many economically important species (Morley et al. 2018). These high-resolution projections (0.05° latitude and longitude) can be used to estimate economic impacts on U.S. marine fisheries, mirroring an approach that has been used at a global scale (Lam et al. 2016).

This study follows the analytic framework established by the Climate Change Impacts and Risk Analysis (CIRA) project for quantifying and monetizing potential climate change impacts across various sectors in the U.S. The CIRA project examines both the potential effects of climate change on the U.S. and the potential economic impacts of mitigating global greenhouse gas (GHG) emissions. CIRA analyses published to date have included only limited consideration of the projected effects of climate change on commercial fishing and ecosystem services (EPA 2015; EPA 2017). Here we leverage ongoing research (i.e., Morley et al. 2018) to address this gap and broaden understanding of approaches to estimating the potential economic effects of climate change on the commercial fishing sector. The analysis first characterizes the potential economic impact of projected changes in annual landings of 177 commercially harvested marine species from 2021 to 2100, based on the use of five general circulation models (GCMs) to project changes in each target species' thermally available habitat within the U.S.

Exclusive Economic Zone (EEZ). It then focuses on 16 U.S. fisheries that together account for 56 percent of current U.S. commercial fishing revenues. Consistent with the recently completed fourth National Climate Assessment of the U.S. Global Change Research Program, the analysis compares welfare impacts for these fisheries under two atmospheric GHG concentration scenarios: Representative Concentration Pathway (RCP) 8.5, a higher-emissions case that assumes limited efforts to reduce atmospheric GHG; and RCP 4.5, a lower end case that assumes more stringent mitigation (NCA4 2018).

2. Methods and Data Sources

2.1 Projected Changes in Thermal Habitat

2.1.1 Approach

The analysis of projected changes in thermal habitat is based on methods described by Morley et al. (2018) to examine the potential impacts of ocean warming on the geographic distribution of 686 marine species on the North American continental shelf from 2021 to 2100. This study examined future habitat shifts across a suite of 16 GCMs within the RCP 2.6 and 8.5 scenarios. To be consistent with the framework of the multi-sectoral CIRA 2.0 project (EPA 2017), the present analysis uses five GCMs. The models and their developers include:

- CanESM2, Canadian Centre for Climate Modeling and Analysis
- CCSM4, National Center for Atmospheric Research
- GISS-E2-R, NASA Goddard Institute for Space Studies
- HadGEM2-ES, Met Office Hadley Centre
- MIROC5, Atmosphere and Ocean Research Institute, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology.

A variety of factors were considered in selecting these five models for impacts analysis in the U.S., including their structural independence, quality, and ability to reasonably capture variability in temperature and precipitation outcomes (EPA 2017). The first three GCMs listed were among the 16 employed in the original analysis of the impacts of ocean warming conducted by Morley et al. (2018); HadGEM2-ES and MIROC5 were added to ensure consistency with CIRA's modeling framework. These five GCMs were run within two carbon emissions scenarios: RCP 8.5 assumes limited efforts to reduce greenhouse gas emissions and results in more ocean warming, while RCP 4.5 assumes more stringent GHG mitigation and less warming.

Projected changes in annual species distribution during the 21st century under the ten potential future climates (2 RCPs x 5 GCMs) were based on statistical thermal niche models for each species (Morley et al. 2018). The niche models were based on 20 long-term bottom trawl surveys, which recorded data on species' presence or absence, as well as biomass (N = 136,044 samples). These surveys are conducted annually by the United States and Canada and encompass most of the continental shelf of these two countries. The niche model predictor variables included mean seasonal sea surface temperature (SST) and sea bottom temperature (SBT); annual maximum SST and SBT; annual minimum SBT; seafloor rugosity (i.e., local variation in depth); and sediment grain size. Environmental data came from multiple sources and were associated with survey catch data based on the date and location of each sample (Morley et al. 2018).

Generalized additive models (GAMs) were used to quantify each species' thermal niche. GAMs provide an effective way to quantify species' relationships with environmental variables because they allow complex nonlinear associations and require no a priori assumption about the shape of these relationships (Brodie et al. 2020). Previously, two GAMs were fitted for each species, one that modeled probability of occurrence using presence and absence data and one that modeled log-biomass using only samples where a species was present; the product of these two GAMs was used for predictions (i.e., the delta-biomass approach). A more recent analysis on the influence of the niche modeling approach on species habitat projections showed that probability of occurrence approaches, as compared to methods that predict biomass, more often had better predictive performance when tested with independent historic data (Morley et al, *in review*). Therefore, for this analysis we based our projections of change in habitat distribution on modeled probability of occurrence, not biomass. For each species, model skill of the GAMs was tested with independent trawl survey data using the area under the receiver operator curve (AUC) statistic, which compares predicted versus observed species occurrence. Only species with AUC scores greater than 0.75 were retained for analysis, which is a limit-value that has been shown to indicate models that are effective at modeling species distribution (Elith et al. 2006).

Future projections of species distributions were based on annual forecasts for mean summer (July – September) ocean conditions and represent an expanded version of the data set used in Morley et al. (2018). Climate projections that were added for this study (i.e., RCP 4.5 and two new GCMs) were processed in an identical manner to Morley et al. (2018). Specifically, projected changes in ocean temperatures from GCMs were downscaled to a ~0.25° latitude and longitude grid based on a mean temperature climatology that was developed from the SODA3.3.1 ocean reanalysis product for 1995-2014 (Carton et al. 2016). The modeled historic climate data that was used for downscaling temperature projections was highly correlated to in situ historic observations of sea surface (slope(se) = 0.91(0.001), $P < 0.001$, $DF = 102048$, $r^2 = 0.90$) and bottom (slope(se) = 1.00(0.001), $P < 0.001$, $DF = 120859$ $r^2 = 0.86$) temperatures. The climate projection grid was further refined to 0.05° latitude and longitude based on the spatial resolution of the seafloor data; depth was limited to 400m or shallower. The resulting projection grid consisted of 65,826 individual cells on the Pacific coast, 69,209 on the Atlantic coast, and 13,383 in the Gulf of Mexico (Figure 1). This projection grid was then restricted to waters within the U.S.

Exclusive Economic Zone (EEZ), where the U.S. has sovereign fishing rights, and partitioned into four regions for analysis: U.S East Coast; Gulf of Mexico; U.S. West Coast; and Alaska.

For each species, a set of ten (2 RCPs x 5 GCMs) annual-summer thermal habitat distributions from 2007 to 2100 were developed. Annual grid cell values were aggregated by averaging projections within five multi-year bins, which included a baseline period of 2007-2020 and four future time periods: (T1) 2021-2040; (T2) 2041-2060; (T3) 2061-2080; and (T4) 2081-2100. During each time period, total available thermal habitat within U.S. regions was calculated as the sum of all grid cell values (i.e., modeled probability of occurrence). The percentage change in future thermal habitat availability was calculated based on differences between the baseline and future time periods. For each future time period, we then calculated an ensemble mean value across GCMs for RCPs 4.5 and 8.5. This process produced a total of 1,085 unique species-region projections for initial consideration in our economic analysis.

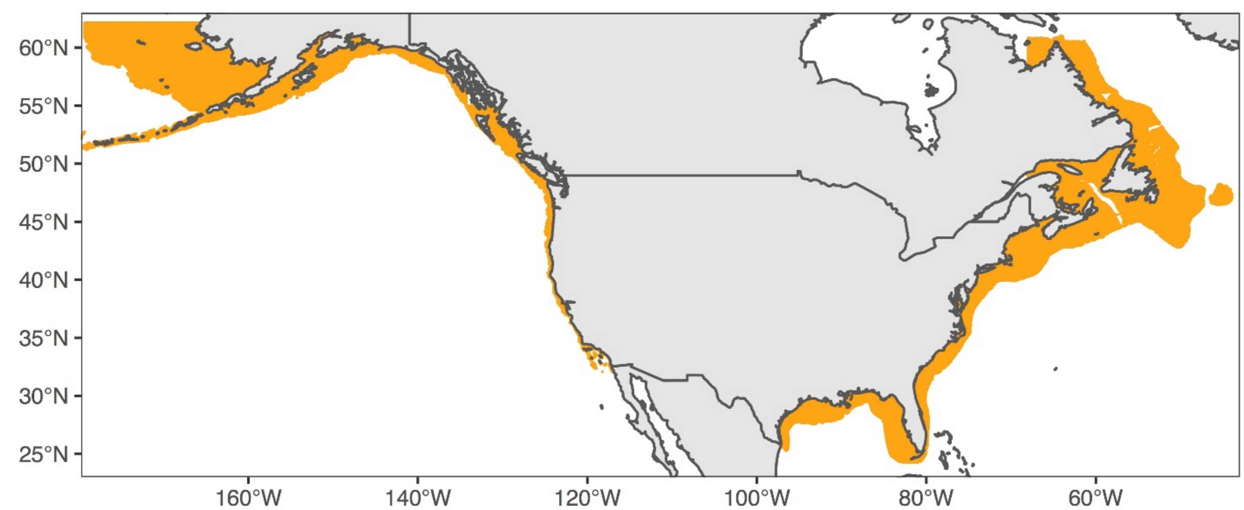

Figure 1. Projection Grid for Thermal Habitat Analysis

2.1.2 Limitations of Species Distribution Projections

The projected changes in species distribution suggested by this modeling exercise reflect only predicted changes in the areal extent and quality of potentially suitable habitat. The analysis does not employ predictions of changes in the absolute biomass of any stock and excludes many factors that may influence species abundance, such as potential changes in primary productivity, species interactions, population dynamics, or fisheries management. The boundaries of the projection grid are also a limiting factor, particularly in northern Alaska, and may affect the results for species found primarily in that region. In the Gulf of Mexico, the thermal niche models may not adequately characterize the upper temperature limits for some species, which may be reached at temperatures above the maximums observed in the underlying trawl surveys. In addition, the analysis does not account for a variety of other factors that may influence marine habitat or species productivity. These include but are not limited to potential changes in weather or ocean circulation patterns, changes in sea level, changes in nutrient loads, or changes in ocean acidity. Models that consider such factors are under development but have yet to be applied at a broad scale.

Despite these limitations, the modeling exercise provides useful insights to potential changes in suitable habitat for hundreds of species across a geographic range that includes much of the U.S. EEZ and many of the nation’s most highly valued fisheries. The breadth of the analysis, coupled with the information it provides on potential changes in habitat, offers a useful basis for a first-order analysis of the effects of increased sea temperatures on commercial harvests of economically important species.

2.2 Economic Screening Analysis

2.2.1 Overview of Data

As a first step in assessing the potential economic impacts of changes in species distribution on the commercial fishing sector, we obtained data from the National Marine Fisheries Service (NMFS) on commercial landings in the United States from 2007 to 2016, disaggregated by species and region (East Coast, Gulf Coast, West Coast, and Alaska). The NMFS dataset reports both the quantity (pounds) and dollar value (i.e., ex-vessel revenue) of landings in these regions, which together accounted for 97.4 percent of the value of U.S. commercial landings in 2016 (NMFS 2017). Hawaii, the Great Lakes region, and U.S. territories account for the balance of U.S. landings.

For each species-region, we calculated mean annual landings by weight and value for 2007-2016, using the Consumer Price Index (CPI) to convert the annual data on ex-vessel revenues to 2018 dollars (BLS 2018). After collapsing the data to a single record for each species-region, the resulting dataset consisted of 883 records. Table 1 summarizes the data on landings by region.

Table 1. Commercial Fishing Landings by Region, 2007-2016

Region	Average Annual Weight (Pounds, Billions)	Average Annual Value (2018 Dollars, Billions)
East Coast	1.4	$1.9
Gulf Coast	1.4	$0.9
West Coast	1.1	$0.7
Alaska	5.2	$1.8
Total	9.2	$5.3

We employed an automated process to match the 883 species-region records on commercial landings to the 1,085 species-region records for habitat projections, using taxonomic nomenclature. This resulted in a match for 247 records. We then initiated a manual review of the remaining records to identify potential matches the automated process might have missed.

We were unable to link 88 records from the NMFS dataset to a habitat projection because the records represent commercial landings for more than one species (e.g., skates). NMFS frequently reports landings at a higher taxonomic level, in some cases because taxonomic identification in port is difficult – particularly when species that are physically similar are landed together – and in others to protect the confidentiality of industry participants (i.e., when only one or two vessels account for all landings of an individual species). The aggregated data provided by NMFS cannot be disaggregated by species. This narrowed the scope of our analysis to individual species for which comparable commercial landings data are available.

We sorted the remaining 548 unmatched species-region records from the NMFS dataset by economic value. We set aside 414 of these records – all those with an average annual value of less than $100,000, which together represent approximately 0.1 percent of total revenues – as being of minimal economic significance. We reviewed the remaining 134 records to attempt to match them to the available future habitat projections. This manual review identified five cases in which the use of taxonomic synonyms by the two datasets had prevented an automated match. We confirmed that projections of changes in thermally available habitat were not available for the species represented by the remaining 129 records. These included some commercially important species that are not effectively sampled in the biological surveys upon which the niche modeling is based (e.g., eastern oyster, Atlantic surf clam, Caribbean spiny lobster, and multiple species of salmon and tuna).

Table 2 shows the disposition of the 883 NMFS landings records from the matching process. The results are shown for both the count of records and with respect to average annual ex-vessel value. As the exhibit indicates, projections of changes in thermally available habitat are available for 252 species-region records. These records represent a total of 177 species and account for 70.8 percent of average annual commercial fishing revenues (2007-2016) in the four regions analyzed. Our screening assessment of the potential impact of ocean warming on commercial landings focuses on these species.

Table 2. Matching of NMFS Records to Available Habitat Projections

Status	Disposition	Count	Percent of Average Annual Ex-Vessel Value, 2007-2016
Match	Automated Match	247	66.0%
	Manual Match	5	4.8%
	Subtotal	252	70.8%
No Match /Excluded	Multi-Species Records	88	7.8%
	No Habitat Projection	129	21.3%
	De Minimis Revenues	414	0.1%
	Subtotal	631	29.2%
Total		883	100.0%

The screening analysis provides good coverage of high value fisheries. As Table 3 shows, the species for which projections of changes in habitat are available include nine of the nation's ten leading fisheries from 2007 to 2016, as measured by average annual revenue: American lobster (*Homarus americanus*); sea scallops (*Placopecten magellanicus*); walleye pollock (*Theragra chalcogramma*); white shrimp (*Litopenaeus setiferus*); Pacific cod (G*adus macrocephalus*); brown shrimp (*Farfantepenaeus aztecus*); Dungeness crab (*Metacarcinus magister*); Pacific halibut (*Hippoglossus stenolepis*); and blue crab (*Callinectes sapidus*). The exception is sockeye salmon (*Oncorhynchus nerka*), which ranked fourth in average annual revenue over the period of interest.

Table 3. Coverage of High Value Fisheries

Rank	Fishery	Region	Average Annual Ex-Vessel Revenues, 2007-2016 (2018 Dollars, Millions)	Habitat Projection Available
1	American Lobster	East Coast	$502.5	Yes
2	Sea Scallop	East Coast	$501.4	Yes
3	Walleye Pollock	West Coast & Alaska	$390.4	Yes
4	Sockeye Salmon	West Coast & Alaska	$272.9	No
5	White Shrimp	East Coast & Gulf Coast	$246.3	Yes
6	Brown Shrimp	East Coast & Gulf Coast	$216.2	Yes
6	Pacific Cod	West Coast & Alaska	$212.1	Yes
7	Blue Crab	East Coast & Gulf Coast	$209.4	Yes
8	Dungeness Crab	West Coast & Alaska	$186.1	Yes
9	Pacific Halibut	West Coast & Alaska	$182.9	Yes
10	Sablefish	West Coast & Alaska	$140.0	Yes

Table 4 provides an overview of the availability of data for the screening analysis by region. As the table indicates, the species for which habitat projections are available account for nearly 80 percent of average annual ex-vessel revenues on the East Coast. Coverage is somewhat lower in the other three regions, where the species for which habitat projections are available account for between 63 and 68 percent of average annual revenue.

Table 4. Coverage of Commercial Fishing Revenue by Region

	Average Annual Ex-Vessel Revenues, 2007-2016 (2018 Dollars, Billions)		
Region	**All Fisheries**	**Fisheries with Habitat Projections**	**Percent of Area's Total Revenue**
East Coast	$1.906	$1.519	79.7%
Gulf Coast	$0.885	$0.567	64.1%
Subtotal: Atlantic	$2.792	$2.086	74.7%
West Coast	$0.693	$0.443	63.9%
Alaska	$1.848	$1.247	67.5%
Subtotal: Pacific	$2.541	$1.689	66.5%
Total	$5.333	$3.775	70.8%

2.2.2 Projections of Potential Changes in Landings

To conduct the screening assessment, we focused on the 252 species-region records from the NMFS dataset for which projected changes in thermally available habitat are available. Figure 2 provides an example of these projections, showing the predicted change in thermally available habitat for American lobster within the Atlantic region of the U.S. EEZ, as represented by the five-GCM mean. The figure illustrates the predicted change in habitat for both RCP 4.5 and RCP 8.5 from 2021 to 2100. The projections show relatively little net change under RCP 4.5 through the end of the century, but a decline under RCP 8.5 beginning mid-century. Figure 3 provides a second example, illustrating the projected change in available habitat for blue crab in the Gulf of Mexico. In this case, available habitat is projected to increase under both RCP 4.5 and RCP 8.5 from 2021 through the end of the century. Under the latter scenario, thermally available habitat for blue crab is projected to more than double.

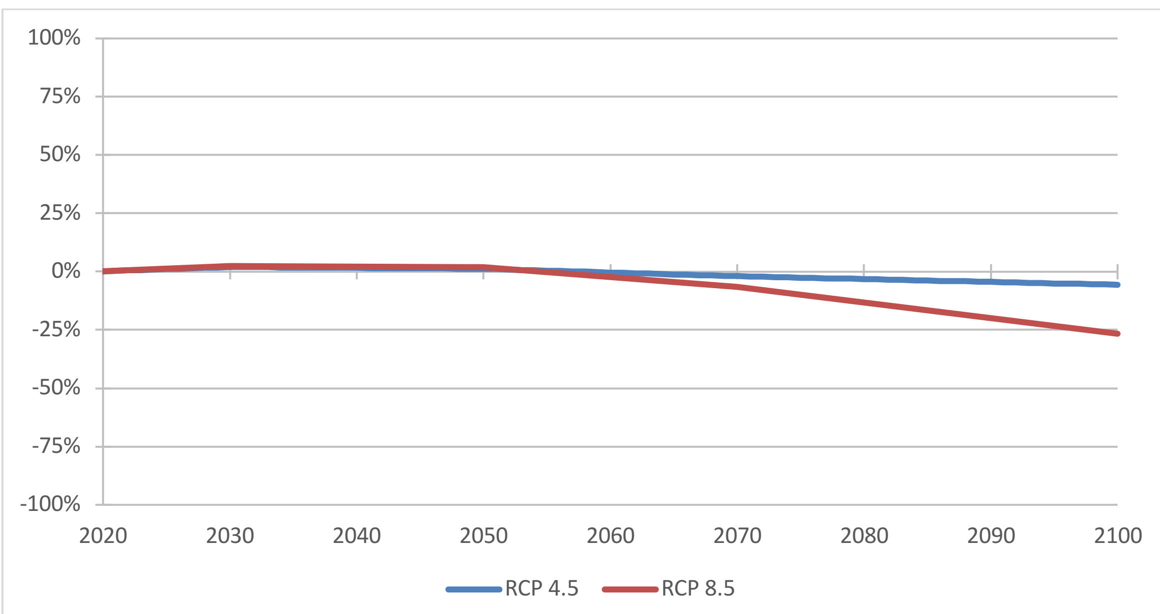

Figure 2. Projected Change in Thermally Available Habitat, American Lobster, East Coast: Five-GCM Mean

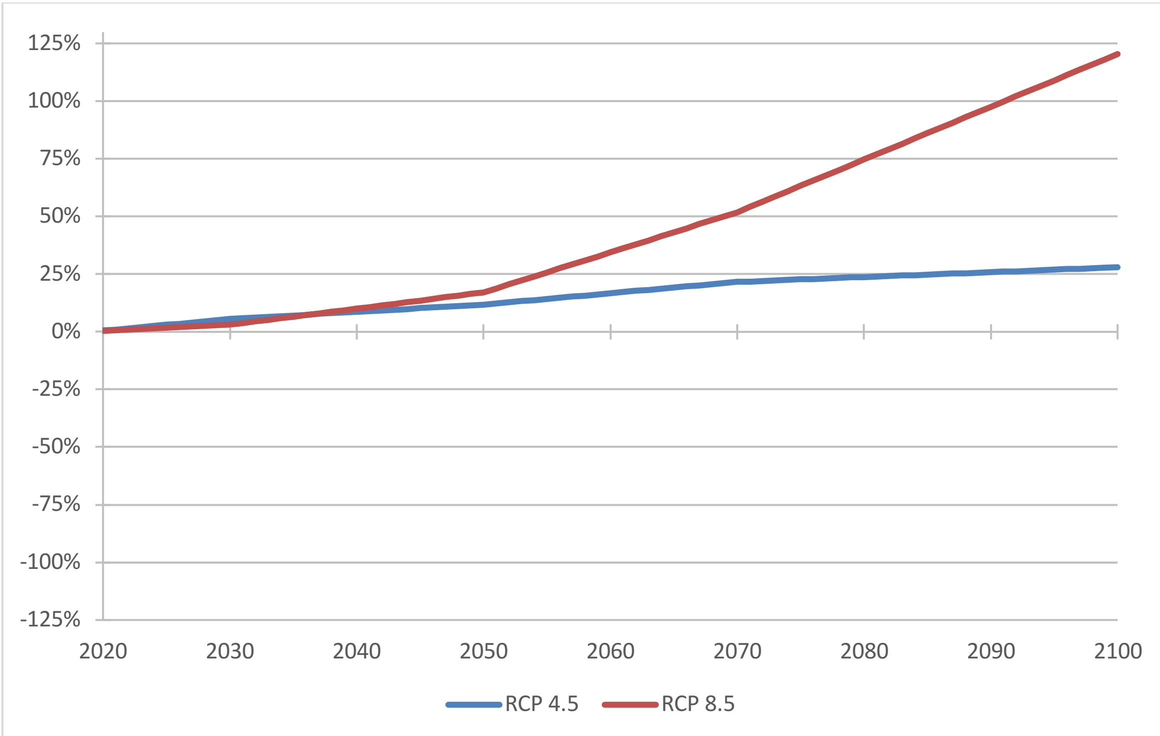

Figure 3. Projected Change in Thermally Available Habitat, Blue Crab, Gulf of Mexico: Five-GCM Mean

The implication of changes in thermally available habitat for commercial fishing landings is difficult to predict. The availability of suitable habitat clearly influences species abundance, but the abundance of any species is also a function of primary productivity, interactions with other species, population dynamics, fisheries management measures, and other factors that are difficult to model at a broad geographic scale. Similarly, commercial landings are dependent not only on species abundance but also the intensity of fishing effort, which is in turn a function of market forces, changes in technology, and fisheries management regimes at the state and national level. Our analysis does not attempt to predict the complex interactions among these variables over the course of the next 80 years. Instead, it considers the potential economic implications of predicted changes in sea temperature assuming a direct relationship over time between changes in the thermally available habitat of a species and commercial landings of that species. The analysis serves as an exploratory assessment rather than a predictive one, for assessing the direction and approximate magnitude of potential changes in landings given anticipated climate-related changes in thermally available habitat. Its findings should be interpreted and applied with this intent in mind.

As the initial step in the screening analysis, we apply our projection of the percentage change in thermally available habitat for each species in each region, as represented by the mean change in thermally available habitat predicted by the five GCMs, to our baseline estimate of annual landings, as represented by the 2007-2016 mean (2018 dollars). This generates a time series of annual landings in each region from 2021 to 2100 for each species analyzed. At this stage of the analysis we ignore the potential effect of changes in supply or changes in real income on ex-vessel prices. Our objective is to develop a first-order estimate of potential economic impacts and to identify an analytically tractable subset of species that drive the projected results. This subset will become the focus of a more rigorous analysis of potential impacts, which accounts for the effect of changes in supply and income on market prices.

To provide a general assessment of the direction and potential magnitude of impacts in each region, we compare the discounted present value of projected landings under RCP 4.5 and RCP 8.5 over the period of interest (2021-2100) to the discounted present value of landings if maintained at recent historical levels (i.e., the average annual ex-vessel value from 2007 through 2016). Consistent with other CIRA analyses, the present value calculation employs a real annual discount rate of three percent (EPA 2017). Selection of this rate is supported by the literature on valuing changes in private consumption and the treatment of intergenerational equity when discounting impacts over long time horizons (OMB 2003; Scarborough 2011).

Table 5 presents the projected change in present value of ex-vessel revenues under RCP 4.5, holding ex-vessel prices constant and assuming the landings of each species analyzed change in direct proportion to projected changes in thermally available habitat. The analysis indicates a loss of approximately $1 billion, a 0.9 percent decline in the present value of landings relative to the baseline. As the table shows, the projected impacts differ by region. On a present value basis, changes in thermally available habitat off the East Coast and Gulf Coast are projected to have a positive impact on commercial landings. In contrast, changes in thermally available habitat in the Pacific waters of the U.S. EEZ are projected to have a negative impact, both in the Alaska region and off the West Coast.

Table 5. Results of Screening Analysis: RCP 4.5

		Change in Present Value of Ex-Vessel Revenues, 2021-2100: RCP 4.5 vs. Baseline, r = 3%	
Region	**Average Annual Ex-Vessel Revenues, 2007-2016 (2018 Dollars, Billions)**	**Projected Change (2018 Dollars, Billions)[1]**	**Percentage Change**
East Coast	$1.519	$0.415	0.9%
Gulf Coast	$0.567	$0.472	2.7%
Subtotal: Atlantic	$2.086	$0.887	1.4%
West Coast	$0.443	($1.327)	-9.9%
Alaska	$1.247	($0.598)	-1.6%
Subtotal: Pacific	$1.689	($1.925)	-3.8%
Total	$3.775	($1.037)	-0.9%

[1] For purposes of the screening analysis, ex-vessel prices are held constant. The projected change in the present value of ex-vessel revenues assumes that the catch of each species analyzed would increase or decrease over time in direct proportion to the projected change in the species' available habitat.

Table 6 shows a similar set of estimates for RCP 8.5. In this case the projected decline in the present value of ex-vessel revenues is $1.6 billion, a 1.4 percent loss relative to the baseline. The impact in Pacific waters remains negative, particularly in the West Coast region, but the projected impact on landings elsewhere is mixed. The analysis shows a decidedly positive impact in the Gulf region, largely due to projected increases in available habitat for blue crab and white shrimp; we note that these projections may be overstated, because the thermal niche models for these species may not effectively capture their upper temperature limits. In contrast, the impact on the East Coast is slightly negative, due primarily to projected reductions in available habitat for high value species like sea scallops and American lobster.

Table 6. Results of Screening Analysis: RCP 8.5

		Change in Present Value of Ex-Vessel Revenues, 2021-2100: RCP 8.5 vs. Baseline, r = 3%	
Region	**Average Annual Ex-Vessel Revenues, 2007-2016 (2018 Dollars, Billions)**	**Projected Change (2018 Dollars, Billions)[1]**	**Percentage Change**
East Coast	$1.519	($0.116)	-0.3%
Gulf of Mexico	$0.567	$1.130	6.6%
Subtotal: Atlantic	$2.086	$1.014	1.6%
West Coast	$0.443	($1.988)	-14.8%
Alaska	$1.247	($0.649)	-1.7%
Subtotal: Pacific	$1.689	($2.636)	-5.2%
Total	$3.775	($1.623)	-1.4%

[1] For purposes of the screening analysis, ex-vessel prices are held constant. The projected change in the present value of ex-vessel revenues assumes that the catch of each species analyzed would increase or decrease over time in direct proportion to the projected change in the species' available habitat.

Tables 7 and 8 illustrate the results of the screening analysis for the 20 highest value fisheries for which habitat projections are available. Table 7 shows that under the RCP 4.5 scenario, the present value of ex-vessel revenues is projected to increase for 11 of the 20 fisheries and to decrease for the others. The greatest absolute impact is projected for the snow crab fishery, where the present value of landings from 2021 to 2100 is projected to decline by more than $1 billion (30.6 percent) compared to the present value of landings if maintained at recent historical levels (i.e., the average annual ex-vessel value from 2007 through 2016). In contrast, the analysis suggests that the present value of landings of white shrimp could increase by more than $670 million (9.0 percent).

Table 7. Results of Screening Analysis for 20 Highest Value Fisheries: RCP 4.5

	Annual Ex-Vessel Revenues, 2007-2016 (2018 Dollars, Millions)		Change in Present Value of Ex-Vessel Revenues, 2021-2100: RCP 4.5 vs. Baseline, r = 3%	
Fishery	**Mean**	**Standard Deviation**	**Projected Change (2018 Dollars, Millions)[1]**	**Percentage Change**
American Lobster	$502.5	$111.5	$54.1	0.4%
Sea Scallop	$501.4	$72.8	$410.4	2.7%
Walleye Pollock	$390.4	$49.9	$79.9	0.7%
White Shrimp	$246.3	$30.1	$670.2	9.0%
Brown Shrimp	$216.2	$51.6	($133.3)	-2.0%
Pacific Cod	$212.1	$56.9	$13.0	0.2%
Blue Crab	$209.4	$19.6	$407.8	6.4%
Dungeness Crab	$186.1	$48.0	($800.4)	-14.2%
Pacific Halibut	$182.9	$60.3	$52.0	0.9%
Sablefish	$140.0	$27.3	$227.6	5.4%
Snow Crab	$113.0	$38.4	($1,048.4)	-30.6%
Chum Salmon	$73.3	$20.1	($210.9)	-9.5%
California Market Squid	$58.0	$22.0	$132.3	7.5%
Chinook Salmon	$51.8	$15.1	($36.3)	-2.3%
Yellowfin Sole	$49.2	$10.5	($180.4)	-12.1%
Pacific Hake	$46.6	$17.9	($51.6)	-3.7%
Ocean Shrimp	$34.2	$20.6	($185.0)	-17.9%
Summer Flounder	$31.3	$3.6	$80.7	8.5%
Longfin Squid	$29.7	$9.2	$79.3	8.8%
Florida Stone Crab (Claws)	$28.7	$5.0	($164.9)	-19.0%

[1] For purposes of the screening analysis, ex-vessel prices are held constant. The projected change in the present value of ex-vessel revenues assumes that the catch of each species analyzed would increase or decrease over time in direct proportion to the projected change in the species' available habitat.

Table 8 provides a comparable set of estimates for RCP 8.5. For 17 of the 20 fisheries, the direction of the projected impact on the present value of landings remains the same. Moreover, as might be anticipated for most of these fisheries, the magnitude of projected impacts under RCP 8.5 is greater than under RCP 4.5. For three fisheries, however, the direction of the projected impact changes. In the case of the American lobster and sea scallop fisheries, the projected impact switches from positive to negative, as small gains in habitat in the East Coast region early in the century are offset by greater losses in habitat toward the century's end. In contrast, the projected impact for Chinook salmon landings switches from negative to positive. In this case, more rapid warming in the RCP 8.5 scenario leads to an earlier and more substantial increase in thermally available ocean habitat in the Alaska region, offsetting a loss of ocean habitat along the West Coast. Note that the analysis does not consider the availability or condition of the freshwater habitat on which anadromous species like Chinook salmon depend, an important consideration in projecting changes in the future landings of such species.

Table 8. Results of Screening Analysis for 20 Highest Value Fisheries: RCP 8.5

	Annual Ex-Vessel Revenues, 2007-2016 (2018 Dollars, Millions)		Change in Present Value of Ex-Vessel Revenues, 2021-2100: RCP 8.5 vs. Baseline, r = 3%	
Fishery	**Mean**	**Standard Deviation**	**Projected Change (2018 Dollars, Millions)[1]**	**Percentage Change**
American Lobster	$502.5	$111.5	($219.9)	-1.4%
Sea Scallop	$501.4	$72.8	($114.3)	-0.8%
Walleye Pollock	$390.4	$49.9	$189.9	1.6%
White Shrimp	$246.3	$30.1	$1,269.8	17.0%
Brown Shrimp	$216.2	$51.6	($176.5)	-2.7%
Pacific Cod	$212.1	$56.9	$26.8	0.4%
Blue Crab	$209.4	$19.6	$649.2	10.2%
Dungeness Crab	$186.1	$48.0	($1,160.5)	-20.6%
Pacific Halibut	$182.9	$60.3	$28.9	0.5%
Sablefish	$140.0	$27.3	$403.6	9.5%
Snow Crab	$113.0	$38.4	($1,549.8)	-45.3%
Chum Salmon	$73.3	$20.1	($425.6)	-19.2%
California Market Squid	$58.0	$22.0	$205.7	11.7%
Chinook Salmon	$51.8	$15.1	$24.3	1.5%
Yellowfin Sole	$49.2	$10.5	($349.0)	-23.4%
Pacific Hake	$46.6	$17.9	($78.5)	-5.6%
Ocean Shrimp	$34.2	$20.6	($258.2)	-24.9%
Summer Flounder	$31.3	$3.6	$82.4	8.7%
Longfin Squid	$29.7	$9.2	$76.0	8.4%
Florida Stone Crab (Claws)	$28.7	$5.0	($204.3)	-23.5%

[1] For purposes of the screening analysis, ex-vessel prices are held constant. The projected change in the present value of ex-vessel revenues assumes that the catch of each species analyzed would increase or decrease over time in direct proportion to the projected change in the species' available habitat.

2.2.3 Implications for Economic Welfare Analysis

In addition to providing general insight to the potential effects of climate change on future landings of commercially harvested species, the screening analysis helped to guide the selection of fisheries considered in our assessment of consumer welfare impacts. To ensure that the welfare assessment would be analytically tractable, we limited its scope to 16 species that could be equally divided into four categories, each of which would contain commodities that consumers might consider close substitutes. Given the limited number of species the analysis could consider, we also chose to focus, to the extent possible, on fisheries that account for the greatest share of current ex-vessel landings. One exception to this selection process was snow crab, a species for which our analysis of RCP 8.5 projects a complete loss of thermally available habitat within the areas modeled by the end of the century (see Figure 4). The implication of this finding – that landings of snow crab would fall to zero by the end of the century – is analytically intractable. More importantly, the thermally available habitat for snow crab in the Bering Sea shows a strong potential to shift northward, beyond the northern boundary of our projection grid. This raises concern that the geographic limits of the habitat analysis may lead us to overstate the impact of rising temperatures on future landings. These factors led us to exclude snow crab from the welfare analysis, resulting in selection of the following species, by fishery category:

- Lobster/crab – American lobster, blue crab, Dungeness crab, and Florida stone crab (claws);
- Shrimp/mollusk – sea scallop, white shrimp, brown shrimp, and California market squid;
- High-value fish (mean ex-vessel price greater than $0.75 per pound, 2018 dollars) – Pacific halibut, sablefish, Chinook salmon, and summer flounder;
- Low-value fish (mean ex-vessel price less than $0.75 per pound, 2018 dollars) – walleye pollock, Pacific cod, yellowfin sole, and chum salmon.

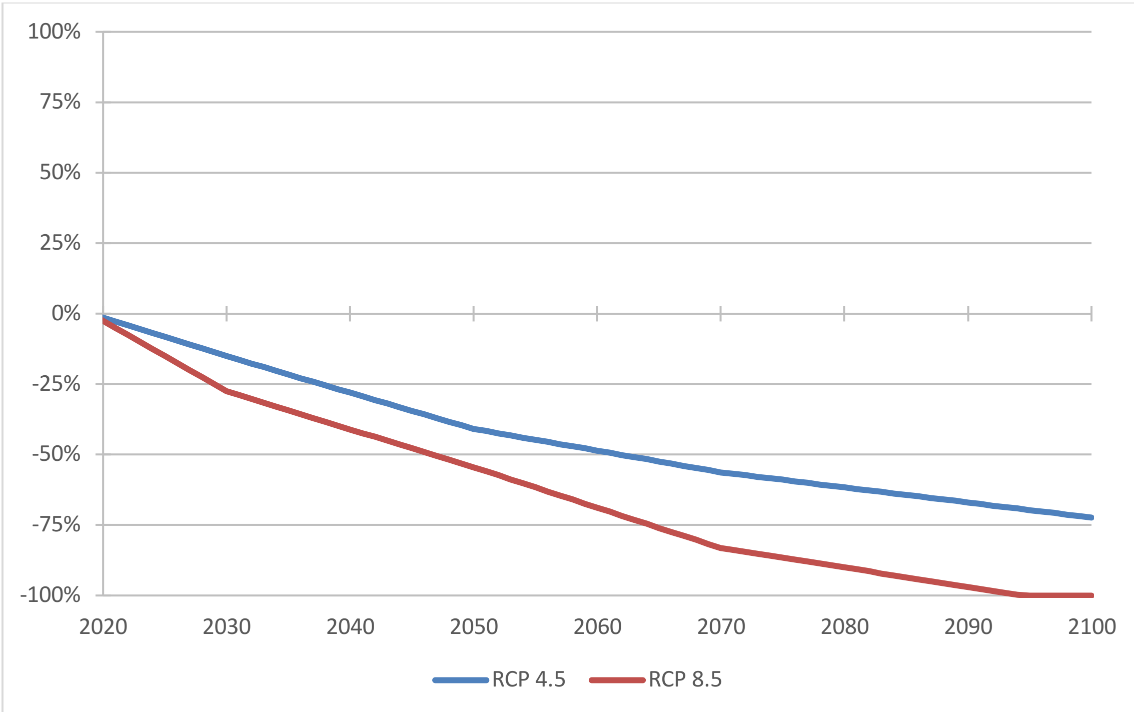

Figure 4. Projected Change in Thermally Available Habitat, Snow Crab, Alaska: Five-GCM Mean

Table 9 lists these species, noting the baseline rank of each fishery by ex-vessel value. As it indicates, the scope of the analysis includes 16 of the 20 fisheries in the screening analysis dataset with the greatest average annual ex-vessel revenues. In aggregate, the revenue associated with these 16 fisheries accounts for 82 percent of the dataset's baseline total and 56 percent of commercial landings in the four regions analyzed. Moreover, the 16 fisheries include those the screening analysis suggests might experience an increase in the present value of landings in response to warming temperatures, as well as those that might experience a decrease. Thus, the welfare analysis not only captures impacts on fisheries that are currently economically important, but also reflects expected variation in the implications of rising sea temperatures for different species.

Table 9. Species Selected for Welfare Analysis

Fishery	Annual Ex-Vessel Revenues, 2007-2016 (2018 Dollars, Millions)		Baseline Rank by Value	Fishery Group
	Mean	Standard Deviation		
American Lobster	$502.5	$111.5	1	Lobster/Crab
Sea Scallop	$501.4	$72.8	2	Shrimp/Mollusk
Walleye Pollock	$390.4	$49.9	3	Low Value Fish
White Shrimp	$246.3	$30.1	4	Shrimp/Mollusk
Brown Shrimp	$216.2	$51.6	5	Shrimp/Mollusk
Pacific Cod	$212.1	$56.9	6	Low Value Fish
Blue Crab	$209.4	$19.6	7	Lobster/Crab
Dungeness Crab	$186.1	$48.0	8	Lobster/Crab
Pacific Halibut	$182.9	$60.3	9	High Value Fish
Sablefish	$140.0	$27.3	10	High Value Fish
Chum Salmon	$73.3	$20.1	12	Low Value Fish
California Market Squid	$58.0	$22.0	13	Shrimp/Mollusk
Chinook Salmon	$51.8	$15.1	14	High Value Fish
Yellowfin Sole	$49.2	$10.5	15	Low Value Fish
Summer Flounder	$31.3	$3.6	18	High Value Fish
Florida Stone Crab (Claws)	$28.7	$5.0	20	Lobster/Crab
Total	$3,079.6			

Figures 5 through 8 present the mean projected changes in annual harvests (in percentage terms) for the 16 modeled species, with separate figures for each fishery group. There are two panels in each figure, one for RCP 4.5 and one for RCP 8.5. Tables 10 and 11 present the baseline harvests (in millions of pounds) for these 16 species and the projected harvests in 2050 and 2090 for the two climate scenarios. The tables also report the 95 percent confidence intervals around the projected change in harvest, based on a Monte Carlo simulation that considered two factors: (1) variation in annual landings from 2007 through 2016; and (2) variation in the predicted change in thermally available habitat across the five GCMs. As these tables and figures show, the projected changes in landings under RCP 8.5 are generally more rapid and pronounced than those under RCP 4.5, particularly toward the end of the century. In the high-end case, the projected increase or decrease in landings by 2090 for several species approaches or exceeds 50 percent. Changes of this magnitude suggest substantial shifts in the distribution of seafood products available to consumers. In the discussion that follows, we examine the implications of these changes for consumer welfare.

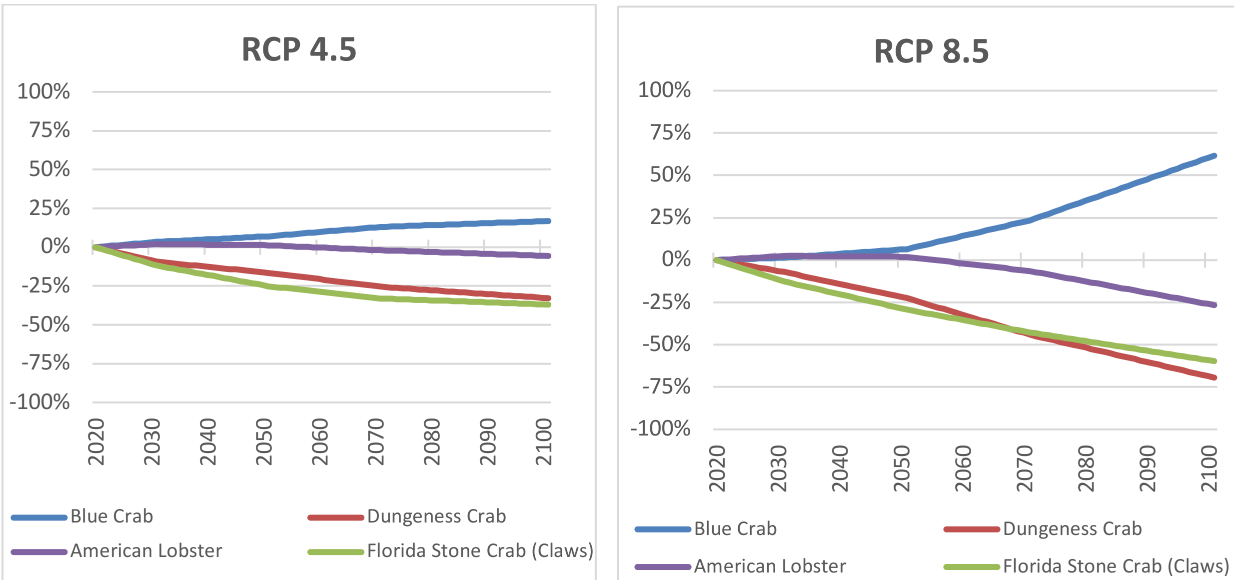

Figure 5. Projected Changes in Commercial Harvests of Key Lobster/Crab Species: Five-GCM Mean

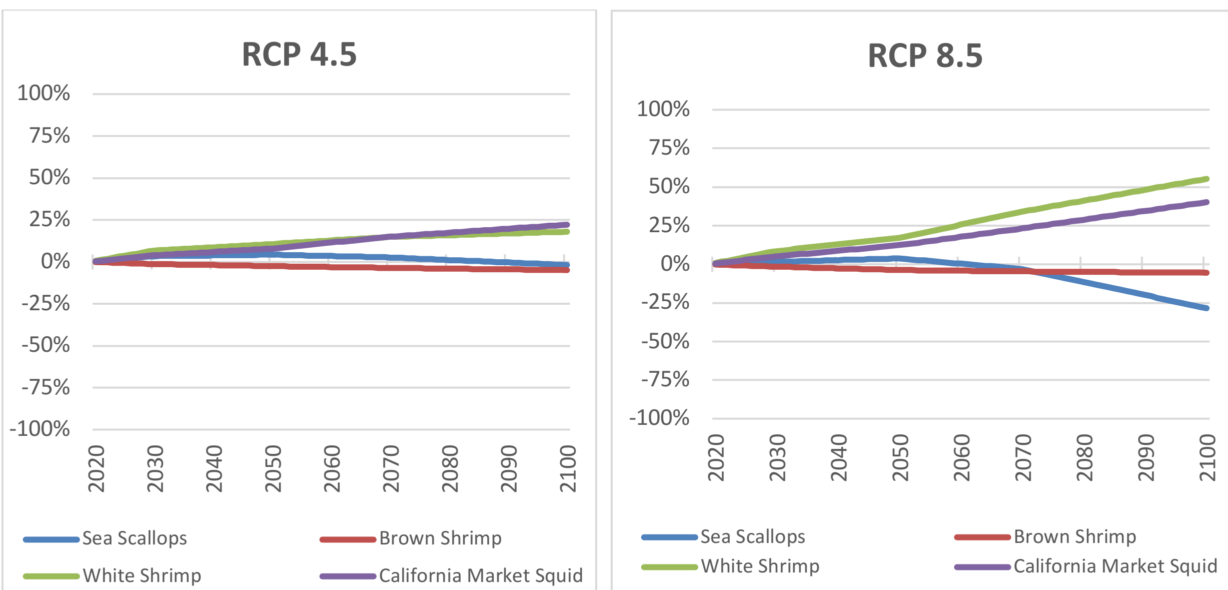

Figure 6. Projected Changes in Commercial Harvests of Key Shrimp/Mollusk Species: Five GCM Mean

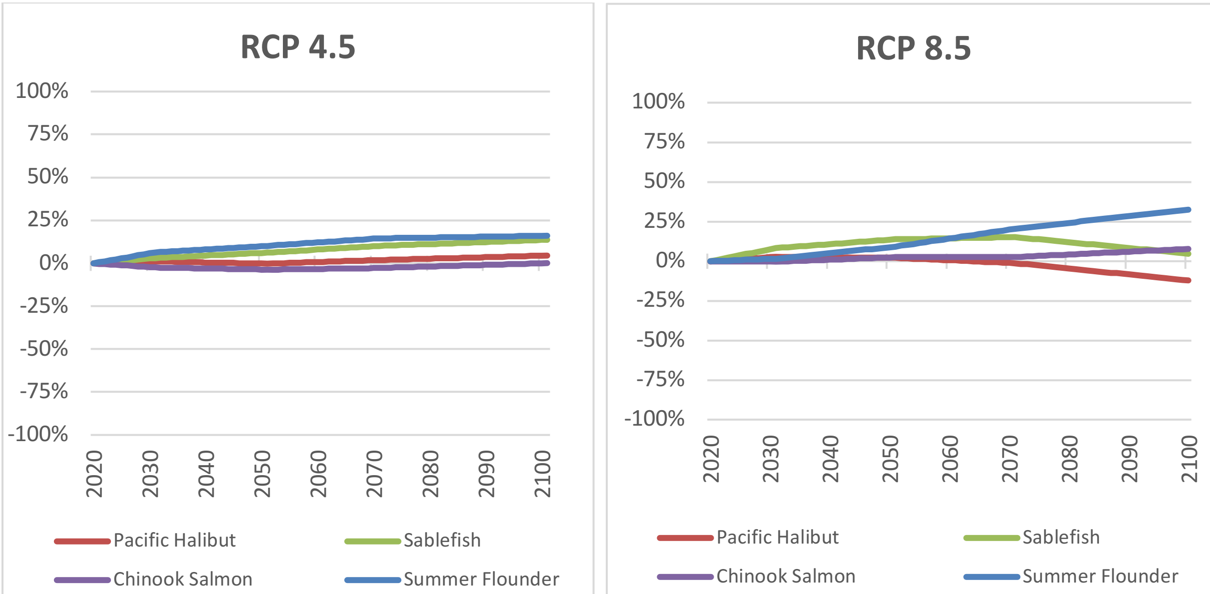

Figure 7. Projected Changes in Commercial Harvests of Key High Value Fish Species: Five-GCM Mean

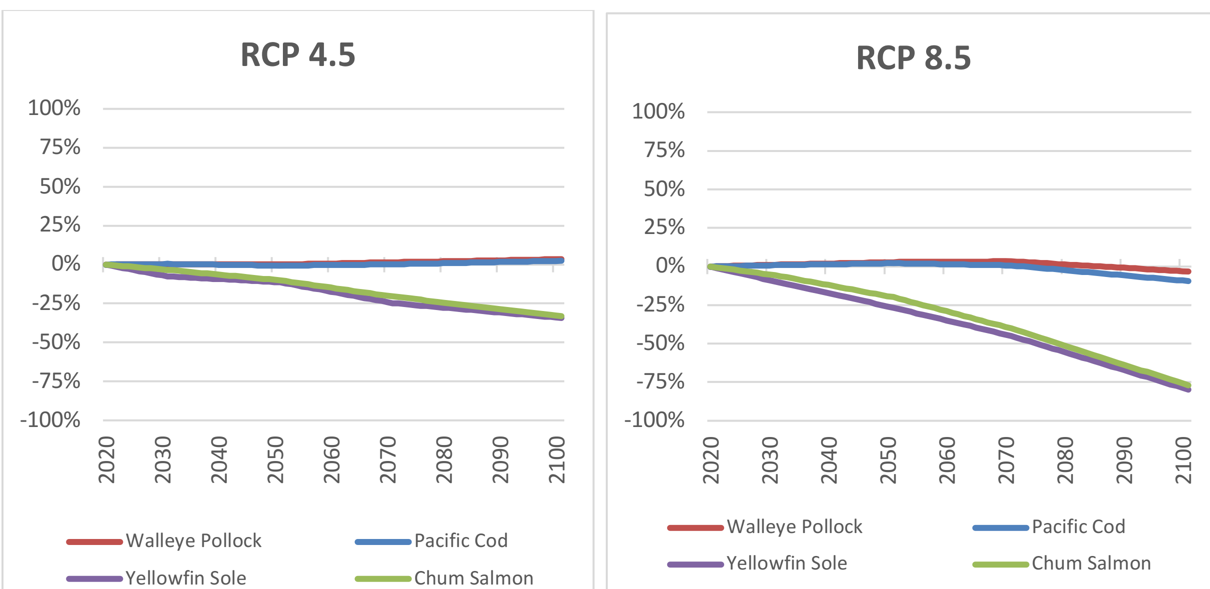

Figure 8. Projected Changes in Commercial Harvests of Key Low Value Fish Species: Five GCM Mean

Table 10. Projected Change in Commercial Harvests for the 16 Modeled Species, RCP 4.5

		Annual Average 2007-2016	2050 Projection[1]			2090 Projection[1]		
Fishery Group	**Fishery**	**(MM lbs.)**	**Landings (MM lbs.)**	**Percent Change**	**95% Confidence Interval**	**Landings (MM lbs.)**	**Percent Change**	**95% Confidence Interval**
Lobster/Crab	Blue Crab	168.3	180.1	7.1%	2.4% - 12.7%	194.5	15.6%	4.4% - 28.1%
	Dungeness Crab	58.9	49.2	(16.5%)	(25.2%) - (7.1%)	41.0	(30.4%)	(41.9%) - (18.6%)
	American Lobster	126.7	128.3	1.3%	(3.1%) - 5.1%	121.1	(4.4%)	(11.3%) - 2.1%
	Florida Stone Crab (Claws)	4.6	3.5	(25.1%)	(34.6%) - (13.3%)	3.0	(35.6%)	(48.7%) - (20.1%)
Shrimp/Mollusk	Sea Scallop	49.3	51.5	4.3%	0.4% - 9.2%	49.2	(0.3%)	(4.9%) - 3.9%
	Brown Shrimp	107.4	104.8	(2.5%)	(5.6%) - 0.2%	102.7	(4.4%)	(9.6%) - 0.4%
	White Shrimp	109.1	120.8	10.7%	5.8% - 15.2%	127.7	17.0%	9.0% - 24.1%
	California Market Squid	179.4	193.9	8.0%	6.1% - 10.4%	215.0	19.8%	15.6% - 26.1%
High Value Fish	Pacific Halibut	43.2	43.1	(0.2%)	(1.8%) - 1.7%	44.8	3.6%	1.9% - 5.8%
	Sablefish	39.6	42.1	6.2%	(1.9%) - 15.0%	44.6	12.5%	5.7% - 21.5%
	Chinook Salmon	14.5	13.9	(3.7%)	(8.6%) - 1.3%	14.3	(0.8%)	(6.5%) - 5.1%
	Summer Flounder	11.2	12.4	10.2%	2.1% - 19.4%	13.0	15.6%	3.3% - 29.4%
Low Value Fish	Walleye Pollock	2,760.6	2,765.1	0.2%	(1.4%) - 1.1%	2,840.3	2.9%	1.1% - 4.5%
	Pacific Cod	620.2	616.4	(0.6%)	(1.8%) - 0.6%	631.2	1.8%	(1.6%) - 5.1%
	Yellowfin Sole	290.6	257.7	(11.3%)	(21.9%) - 0.0%	200.4	(31.0%)	(44.4%) - (19.0%)
	Chum Salmon	118.7	106.8	(10.1%)	(18.0%) - 0.6%	84.5	(28.8%)	(38.0%) - (20.1%)

[1] The projected change in commercial harvests assumes that the catch of each species would increase or decrease in direct proportion to the projected change in the species' thermally available habitat.

Table 11. Projected Change in Commercial Harvests for the 16 Modeled Species, RCP 8.5

			2050 Projection[1]			2090 Projection[1]		
Fishery Group	**Fishery**	**Annual Average 2007-2016 (MM lbs.)**	**Landings (MM lbs.)**	**Percent Change**	**95% Confidence Interval**	**Landings (MM lbs.)**	**Percent Change**	**95% Confidence Interval**
Lobster/Crab	Blue Crab	168.3	179.1	6.4%	3.1% - 9.7%	250.5	48.9%	28.3% - 69.9%
	Dungeness Crab	58.9	45.6	(22.5%)	(35.2%) - (11.3%)	23.0	(60.9%)	(74.4%) - (44.9%)
	American Lobster	126.7	129.2	1.9%	(3.2%) - 6.1%	101.5	(19.9%)	(30.5%) - (12.2%)
	Florida Stone Crab (Claws)	4.6	3.3	(29.3%)	(39.7%) - (16.2%)	2.1	(54.0%)	(68.9%) - (34.7%)
Shrimp/Mollusk	Sea Scallop	49.3	51.2	3.8%	(6.1%) - 12.8%	39.5	(20.0%)	(32.5%) - (6.9%)
	Brown Shrimp	107.4	103.4	(3.7%)	(7.7%) - 0.3%	101.9	(5.2%)	(12.7%) - 2.4%
	White Shrimp	109.1	127.8	17.1%	13.2% - 20.6%	161.8	48.2%	35.6% - 60.7%
	California Market Squid	179.4	201.6	12.3%	10.1% - 15.3%	241.4	34.6%	27.2% - 46.2%
High Value Fish	Pacific Halibut	43.2	44.1	2.1%	(1.3%) - 5.2%	39.4	(8.7%)	(23.1%) - 3.0%
	Sablefish	39.6	45.1	13.8%	7.9% - 20.1%	42.8	8.1%	(10.4%) - 23.7%
	Chinook Salmon	14.5	14.8	2.5%	(6.7%) - 13.8%	15.4	6.2%	(14.6%) - 35.0%
	Summer Flounder	11.2	12.3	9.2%	2.2% - 16.9%	14.5	28.8%	12.2% - 44.2%
Low Value Fish	Walleye Pollock	2,760.6	2,840.4	2.9%	1.0% - 4.7%	2,733.3	(1.0%)	(10.1%) - 7.9%
	Pacific Cod	620.2	633.9	2.2%	(0.4%) - 4.6%	582.8	(6.0%)	(18.5%) - 6.5%
	Yellowfin Sole	290.6	213.3	(26.6%)	(37.2%) - (18.0%)	92.5	(68.2%)	(84.4%) - (52.7%)
	Chum Salmon	118.7	95.1	(19.8%)	(30.7%) - (9.9%)	41.9	(64.7%)	(68.3%) - (61.1%)

2.2.4 Limitations of the Economic Models

As previously noted, this analysis excludes many factors that may influence species abundance and commercial landings, such as potential changes in primary productivity, species interactions, population dynamics, or fisheries management. In addition, because the approach focuses on potential changes in landings of species that are already commercially harvested, it does not account for the possibility that an increase in the abundance of other species could lead to the development of new fisheries. This type of development would help to offset potential losses in economic welfare attributable to a decline in the productivity of established fisheries.

An additional limitation of the analysis concerns our ability to characterize the uncertainty around the projected changes in landings. The confidence intervals presented in Tables 10 and 11 are based on a Monte Carlo simulation that considered two factors: (1) variation in annual landings from 2007 through 2016; and (2) variation in the predicted change in thermally available habitat across the five GCMs. These confidence intervals do not reflect other sources of uncertainty in the GCMs' projections of changes in thermally available habitat, nor do they account for the impact of the considerations noted in the previous paragraph.

Finally, it is important to note that while we are examining consumer surplus, the quantity and value data we use to estimate our model are taken from domestic dockside transactions. The supply chain from the fishing vessel to the consumer's table is complex. The US imports the majority of its seafood and an increasing fraction is produced in aquaculture. Given some imported seafood and aquaculture are close substitutes for domestic wild harvest, omitting them from our analysis could affect our elasticity and welfare estimates. To the extent that the data we use in our analysis is generated in markets that include imports and aquaculture, our demand responses to changes in domestic wild harvest are consistent so long as we assume those other supplies are held constant. The effects of climate change on imported seafood and the emergence of aquaculture are not addressed in this paper; we simply recognize them as limitations to a more holistic analysis.

3. Analysis of Welfare Impacts

3.1 Modeling Approach

Given expected changes in annual harvests for the 16 modeled species, the welfare analysis proceeds in several steps. The first is to estimate parameters of a utility function that describes how consumers will be affected by changes in supply. We begin by assuming consumers are maximizing their utility based on current supply and that, as harvests change, they will reoptimize. We specify a form for the utility function and use historical data to estimate its parameters. Projected changes in supply and real income are then plugged into the utility function to predict how consumers will respond. The estimated utility function tells us if consumers are better or worse off after the change and allows us to express the utility change in monetary terms.

Our model must be able to capture interactions between the demands for different species. If supply in one fishery falls over time, causing price to increase, species with a stable or increasing supply become relatively cheaper and consumers are likely to substitute toward them. In this way, price effects and welfare impacts ripple through the system of demands. Modeling such interactions with a simultaneous system of demand equations becomes intractable as the number of species increases. To address the high dimensionality of the problem, we model demand in the 16 fisheries as a two-stage process in which consumers first allocate expenditures among groups of related species, then further allocate expenditures among species within those groups (Table 9).

Moore and Griffiths (2018) demonstrate how to estimate price changes and consumer welfare impacts in a multi-stage inverse demand system; we apply their approach to our projected changes in harvest.

In a two-stage model, prices are determined by consumers first allocating expenditures to fishery groups based on aggregated supply in each, then among the individual species modeled in the second stage. A supply change in one fishery can affect the price of a species in a different group through the first stage expenditure allocation. Consumer welfare impacts are found by measuring the distance between optimized consumption bundles in utility-space before and after the change in supply. The distance is then monetized using forecasted expenditures on each fishery group. Real incomes are expected to grow through the end of the century; as their wealth increases consumers will allocate some of that wealth to purchase the 16 modeled species, which will put upward pressure on prices. Our model captures this demand shift using an income elasticity for seafood from Cheng and Capps' (1988) analysis of demand for seafood in the U.S. and forecasts of changes in real income.

The scope of our analysis prevents us from collecting the data and developing the models required to forecast the change in harvest effort in response to stock changes and estimate producer surplus. While there are examples in the literature of studies that perform such analyses, they tend to focus on single fisheries. Edwards' 2005 study of the Atlantic sea scallop fishery and Tan and Jardine's 2019 analysis of the horseshoe crab fishery in the Delaware Bay are two examples. Performing that type of analysis on 16 different species for the entire US harvest is far beyond the scope of this paper. Markowski et al. (1999) limit their welfare analysis to consumer surplus when estimating the impact of climate change on the US commercial fishing industry for the same reason, as do Speers et al. (2016) in their analysis of coral reef dependent fisheries under climate change and ocean acidification.

The assumption of an exogenous supply is not uncommon and has a long tradition in the agricultural and fisheries economics literatures (Moschini and Vissa 1992; Eales and Unnevehr 1994). Lacking production and cost functions to predict responses of harvesters, we make the simplifying assumption that harvest changes in proportion to thermally available habitat. This implies that in each fishery the fishery management authority imposes management measures, based on stock assessments, which aim to constrain the annual catch to a sustainable level, either directly through means of binding quotas or indirectly through limits on fishing effort.   The fishery stocks we examine here are managed by various regional councils, and the restrictions governing harvest are complex. Nonetheless, based on a review of the management measures currently in effect for all 16 species, we find strong empirical support for constraints on catch or effort set according to biological criteria. The fishery management plans for 15 out of the 16 species we model are designed with the goal of maintaining either maximum sustainable yield, optimum sustainable yield, or some other biological benchmark. This empirical support for our assumption of constraints on catch that will adjust with stock assessments allows us to estimate the change in harvest level independent of the economic details of each fishery.

3.2 Estimation

The specific functional form we choose for the demand system is the inverse almost ideal demand system (Moschini and Vissa 1992, see appendix for estimating equations). It is derived in a utility theoretic framework and estimated to satisfy adding-up and homogeneity restrictions. Seemingly unrelated regressions (SUR) are used to estimate the demand systems because there are no cross-equation restrictions on the estimated parameters but the error terms within a demand system are likely correlated. Data to estimate the model is the same as that which was used to perform the screening analysis, 2007-2016 NMFS Commercial Fishing Statistics; however, the original monthly observational units were maintained to capture seasonal variation in harvest and dockside price.

In the first stage estimation of demand equations for the fishery groups there are 12 estimated parameters; an additional 12 are identified by the utility theoretic restrictions and found using the estimated parameters. These parameters do not have a straightforward or intuitive interpretation; instead, we present the own-price elasticities for each fishery group (Table 12; cross-price elasticities are shown in the appendix). An own-price elasticity tells us how much, in proportional terms, demand for a good is expected to change given a change in its price, assuming all other prices are held constant. Given downward sloping demand curves, we expect these elasticities to be negative, providing a useful check on our model. The elasticities are non-linear functions of the estimated utility parameters; given a sufficiently large sample to assume normality of the means, we employ the delta method to find the inner 95^{th} percentiles as an indication of statistical significance. The first stage price elasticities are all negative, of reasonable magnitude, and precisely estimated. All cross-price elasticities and the formula we use to find them are reported in the appendix.

Table 12. First Stage Own-Price Elasticities

Fishery Group	Price Elasticity	Inner 95^{th} Percentile	
Lobster/Crab	-.554	-.615	-.493
Shrimp/Mollusk	-.754	-.793	-.714
High Value Fish	-.302	-.344	-.259
Low Value Fish	-.921	-.939	-.902

Estimation of the second stage demand systems proceeds exactly like the first stage. In the second stage we estimate four separate demand systems via SUR using total expenditures and harvest data for the constituent species of each fishery group (Table 13). As with the first stage, all own-price elasticity estimates are negative and, with the lone exception of Pacific Halibut in the high value fishery group, all 95-percent confidence intervals lie entirely below zero.

Table 13. Second Stage Price Elasticities

Fishery Group	Species	Price Elasticity	Inner 95th Percentile	
Lobster/Crab	Blue Crab	-.290	-.357	-.224
	Dungeness Crab	-.263	-.324	-.203
	American Lobster	-.630	-.664	-.596
	Florida Stone Crab (Claws)	-.717	-.733	-.701
Shrimp/Mollusk	Sea Scallop	-.461	-.532	-.390
	Brown Shrimp	-.418	-.495	-.342
	White Shrimp	-.418	-.476	-.361
	California Market Squid	-.995	-1.008	-.982
High Value Fish	Pacific Halibut	-.081	-.217	.056
	Sablefish	-.363	-.457	-.268
	Chinook Salmon	-.290	-.356	-.222
	Summer Flounder	-.878	-.886	-.868
Low Value Fish	Walleye Pollock	-.590	-.646	-.533
	Pacific Cod	-.699	-.725	-.672
	Yellowfin Sole	-.335	-.489	-.182
	Chum Salmon	-.760	-.791	-.730

3.3 Forecast of Total Expenditures

Real income is expected to grow through the end of the century (Chen et al., 2015). As consumers become wealthier their demand, and thus willingness to pay, for normal goods increases. This has the effect of magnifying welfare impacts of changes in supply, whether positive or negative. To capture the effect of growing real income in our model we take an estimated income elasticity of demand for seafood from the literature and forecast the change in total expenditures on the modeled fisheries to the end of our time horizon. Cheng and Capps (1988) estimate an income elasticity of demand for seafood of 0.11. Using the CIRA 2.0 gross domestic product (GDP) forecast produced by the MIT EPPA6 model (Chen et al. 2015), we project real expenditures on the modeled species to grow by 16.5 percent by the end of the century (Table 14).

Table 14. Forecast of Total Expenditures on Modeled Species

Year	Gross Domestic Product (2018 Dollars, Billions)	Expenditures on Modeled Species (2018 Dollars, Millions)
2007-2016 average	$16,674	$3,080
2020	$19,090	$3,088
2030	$23,859	$3,165
2040	$29,253	$3,237
2050	$35,051	$3,302
2060	$41,589	$3,364
2070	$48,864	$3,424
2080	$56,849	$3,482
2090	$65,477	$3,536
2100	$74,688	$3,588

3.4 Forecast of Price Changes and Consumer Welfare Impacts

Prices for each of the modeled species are forecasted by simulating the two-stage budget allocation process represented by our economic model. The first stage demand system provides forecasts of expenditure shares among the fishery groups, which are multiplied by the total expenditures in Table 14 to simulate budget allocation among those groups. The estimated second stage demand systems then provide the means to further allocate group expenditures among species which, when divided by forecasted harvests, provide prices for each species. Table 15 shows the expected percent change in prices under the two modeled climate scenarios. Tables 10 and 11 show that projections for species harvest changes are mixed and one might expect the impact on prices to be similarly mixed given supply and price tend to be inversely related. The expectation that real expenditures will grow over time, however, puts upward pressure on all prices; as a result, prices are expected to increase under the RCP 4.5 scenario, and all but one price is expected to increase under the RCP 8.5 scenario. Additionally, because we explicitly model substitution, when an increase in the supply of one species makes it relatively cheaper, consumers will substitute toward that species, increasing demand and dampening the downward pressure on price in economic equilibrium. For example, in the shrimp and shellfish group, white shrimp harvests are expected to increase by nearly 50 percent in the high emissions scenario, while their price is expected to stay about the same. This can be explained by observing that the share of shrimp and shellfish expenditures allocated to white shrimp grows from 27 percent to 37 percent, squeezing out some expenditures on scallops as their harvest falls by 20 percent. This one example shows how important demand interactions can be when modeling consumer welfare impacts.

Table 15. Projected Changes in Prices

Fishery Group	Species	Baseline Price (2018 dollars)*	Percent change in price by 2100	
			RCP 4.5	RCP 8.5
Lobster/Crab	Blue Crab	$1.17	33.35%	35.57%
	Dungeness Crab	$3.32	31.65%	21.47%
	Lobster	$5.49	31.42%	62.07%
	Florida Stone Crab (Claws)	$5.59	55.83%	69.18%
Shrimp/Mollusk	Sea Scallop	$9.35	19.4%	14.08%
	Brown Shrimp	$2.95	22.5%	21.46%
	White Shrimp	$2.87	14.72%	0.59%
	Market Squid	$0.30	5.75%	-5.30%
High Value Fish	Pacific Halibut	$2.96	26.61%	18.99%
	Sablefish	$2.79	16.64%	2.24%
	Chinook Salmon	$3.18	25.01%	5.98%
	Summer Flounder	$2.93	17.21%	5.09%
Low Value Fish	Walleye Pollock	$0.14	5.06%	56.72%
	Pacific Cod	$0.32	4.69%	58.32%
	Yellowfin Sole	$0.08	32.21%	204.18%
	Chum Salmon	$0.51	19.35%	57.38%

*Baseline prices represent the average monthly price (2018 dollars) for each species from 1996-2016.

We estimate consumer welfare impacts using a distance function approach (Moore and Griffiths 2018; Kim 1997, see appendix). The distance function is dual to the expenditure function and measures how the consumption bundle must be scaled to reach a reference level of utility. If we benchmark utility using current harvest levels, we can find the change in consumer utility when harvest levels change over time and monetize those changes using expenditure forecasts. Forecasted prices are not used in the welfare calculation directly, but they embody much of the same information. Since our model explicitly accounts for substitution possibilities among the 16 modeled species, the net price elasticity reflects how changes in relative prices among goods affect consumers' willingness to pay for a given year's harvest. Likewise, welfare impacts of a decline in harvest of one species can be mitigated if a substitute for that species experiences an increase in harvest. As such, there are some cases in which the change in harvest and the change in price have the same sign, despite all own-price elasticities being negative. Table 16 shows the net present value of consumer welfare impacts through the end of the century for each of the fishery groups. Total welfare impacts are found by summing across groups and amount to a loss of $2.1 billion or $4.2 billion, depending on the climate scenario, when discounted at 3 percent. Table 17 and Figure 9 show total annual consumer welfare impacts at ten-year intervals through the end of the century. In the year 2050, predicted annual consumer welfare losses reach $76 million in the low emissions scenario and $110 million in the high emissions scenario. By 2100 those losses reach $278 million in the lower emissions scenario and $901 million in the high emissions scenario.

Table 16. Present Value of Consumer Welfare Impacts (r = 3%)

Fishery Group	RCP 4.5 (2018 dollars, millions)	RCP 8.5 (2018 dollars, millions)
Lobster/Crab	-$2,126.0	-$2,848.2
Shrimp/Mollusk	$265.7	$1,469.7
High Value Fish	-$585.1	$441.2
Low Value Fish	$355.8	-$3,292.0
Total	-$2,089.7	-$4,229.2

Table 17. Annual Consumer Welfare Impacts, RCP 4.5 vs. RCP 8.5

Year	RCP 4.5 (2018 dollars, millions)	RCP 8.5 (2018 dollars, millions)
2020	-$1.18	-$0.55
2030	-$14.21	-$7.29
2040	-$44.21	-$56.45
2050	-$75.82	-$109.59
2060	-$118.90	-$215.36
2070	-$164.22	-$329.27
2080	-$200.60	-$504.22
2090	-$238.51	-$693.10
2100	-$277.94	-$901.25

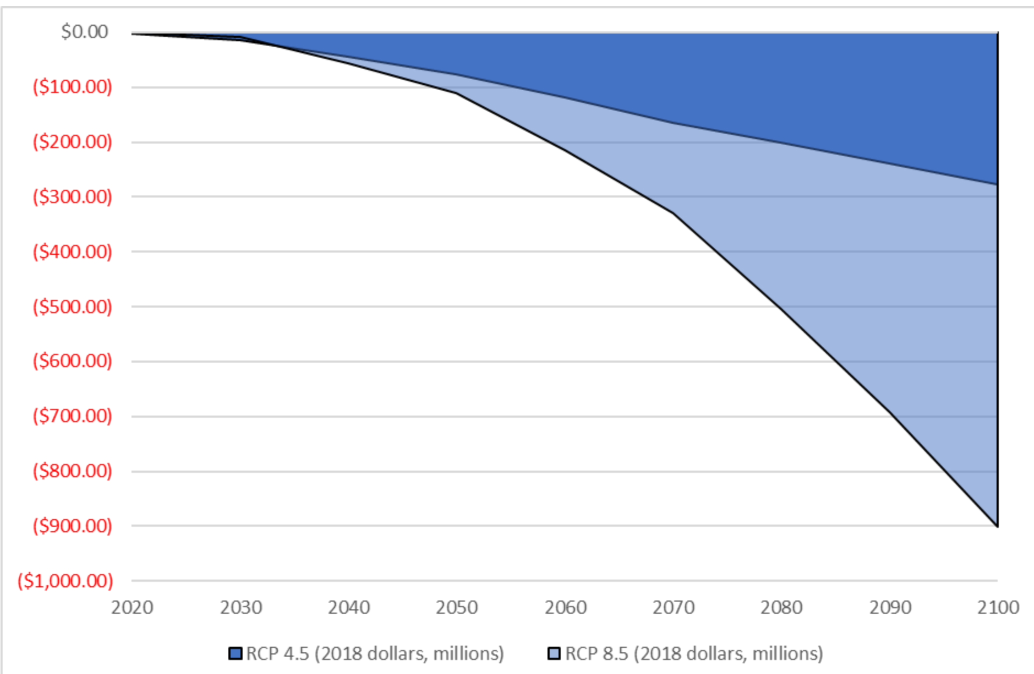

Figure 9. Annual Consumer Welfare Impacts, RCP 4.5 vs. RCP 8.5

4. Summary and Conclusions

Projections of changes in thermal habitat for marine species on the North American continental shelf predict major shifts in distribution by the end of the 21st century (Morley et al. 2018). Changes in the extent of thermally available habitat are not necessarily predictive of changes in the absolute biomass of any stock; a variety of other factors – such as changes in ocean circulation patterns, ocean acidity, or nutrient loads – may affect population productivity. Nonetheless, changes in thermally available habitat for commercially harvested species are an important indicator of potential changes in abundance and, by extension, potential changes in commercial harvest and landings.

The analysis presented here relies on projected changes in thermally available habitat for marine species within the U.S. EEZ to examine the implications of climate change for landings in 16 fisheries that together account for 56 percent of U.S. commercial fishing revenues. It suggests that for some species (e.g., blue crab, white shrimp, California market squid, summer flounder) rising sea temperatures are likely to have a positive effect on landings, while for others (e.g., Dungeness crab, Florida stone crab, yellowfin sole, chum salmon) the effect will be negative. The projected changes in landings under RCP 8.5 are generally more pronounced than those under RCP 4.5, particularly toward the end of the century; for some species, the projected increase or decrease in landings by 2100 exceeds 50 percent. Shifts of this magnitude suggest substantial changes by the end of the century in the distribution of species the U.S. commercial fishing industry will harvest.

To estimate the consumer welfare impacts of projected changes in commercial landings, we employ a two-stage inverse demand model, building on work previously conducted by Moore and Griffiths (2018). This approach captures interactions between the demand for different species, recognizing consumers' ability to adapt to changes in market conditions and optimize their utility by reallocating their expenditures. The analysis suggests a positive impact on consumer welfare in the shrimp/mollusk sector but negative effects overall, particularly in the market for lobster and crab. The present value of the loss in consumer surplus from 2021 to 2100 is estimated at approximately $2.1 billion (2018 $US) under RCP 4.5 and $4.2 billion under RCP 8.5. The projection of annual losses grows with time and ranges from $278 million to $901 million by the end of the century.

This analysis extends the CIRA project's body of work on the economic impacts of climate change and enhances our understanding of the effects of projected shifts in species distribution on substantial segments of the commercial fishing industry. Additional research is needed, however, to develop a more comprehensive assessment. Areas of potential focus include consideration of additional species; expansion of the geographic scope of the analysis to include higher latitudes, particularly off the coast of Alaska; development of improved thermal niche models for species like white shrimp and blue crab, which at present may not effectively capture the species' upper temperature limits; analysis of the potential impact of changes in ocean conditions (e.g., ocean acidification) on species productivity; and evaluation of the potential effects of changes in fisheries management (Kennedy 2016; Gaines et al. 2018). Other dynamics, such as growth in aquaculture or in international trade, may also have an important effect on the supply of seafood available to U.S. consumers and are factors worth considering in subsequent assessments.

Beyond these considerations, it may be important to examine the cost to the commercial fishing industry of adapting to shifts in the distribution and abundance of target species. Changes of the magnitude projected in this analysis suggest that future generations of commercial fishermen may find themselves in waters very different from those fished by their predecessors. Adapting to these changes will challenge their knowledge and skills and may affect their capital and operating costs in ways that are difficult to predict, potentially affecting the vessels they operate, the gear they use, the fuel they consume, and the amount of time they spend at sea (Rogers et al. 2019;). It may also require additional investments in the infrastructure that supports the industry and processes its catch. This could prove to be particularly important if the shift in species distribution prompts demand for development or expansion of ports and processing facilities in more northern areas of Alaska. It also suggests that the importance of the industry to regional economies could change substantially over the next 80 years, and that the distribution of landings within and across regions could look quite different when the next century begins.

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