[DRAFT] Future Scenarios for Transboundary Fisheries Management in Changing Oceans: Gauging the Biological Tides

Palacios-Abrantes, J., Sumaila R., Cheung, W.W.L.

Abstract

Climate change is driving shifts in distribution of fish stocks towards areas with cooler environment, generally in higher latitude or deeper water. Particularly, distribution shifts in fish stocks that straddle between national jurisdictions or Exclusive Economic Zones (EEZ) are challenging transboundary fisheries management. Canada and USA share numerous economically and culturally important fish stocks in both the Pacific and Atlantic coasts, with some of them managed by Regional Fisheries Management Organizations (RFMOs). In this paper, we examine the past and projected future sharing of catches of transboundary fish stocks between the EEZs of Canada and USA. We hypothesize that ocean warming has been altering the sharing of fish stocks between the two countries, and that such changes will intensify under the 'business-as-usual' carbon emission scenario. Firstly, we examine historical fisheries catches of fish stocks that straddle Canadian and USA EEZs from 1950 to 2010. Catches are divided by five sub-regions: Canada (Pacific), Canada (Atlantic), USA (Washington to California), USA (Alaska) and USA (Atlantic). We then calculate the ratio of sub-regional catches (hereafter called stock-share ratio) between Canada and USA in the Pacific and Atlantic coasts and show that the

stock-share ratio of some fish stocks such as Pacific halibut are changing in the direction as expected from the effects of ocean warming. Secondly, we analyze projections of changes in potential catch of these fish stocks under climate change from multiple earth system and species distribution models by the mid- to end of the 21st century. We calculate the projected stock-share ratio between Canada and USA under high and low greenhouse gas emission scenarios. These results highlight fish stocks, sub-regions and RFMOs that are most exposed to climate change impacts caused by shifting fish distributions and, consequently, the disturbance to transboundary fisheries management.

Introduction

First paragraph of paper summary — This paragraph is not needed.

Around 1,500 fish stocks are estimated to move ~~freely~~ between nations' maritime boundaries, but ~~in some cases successfully~~ only a subset of these stocks are co-managed by two or more countries (Caddy 1997; Miller and Munro 2002). Transboundary fisheries, are fishing activities that catch from fish stocks ~~that~~ crossing international borders, are of utmost importance for Canada and the US, as many important fish stocks such as salmon (*Oncorhynchus spp.*), Pacific halibut (*Hippoglossus stenolepis*), and Atlantic cod (*Gadus morhua*), fall into this category. New paragraph Shifts in fish species distribution has been one of the most

Start global, then follow by N. America in following paragraphs.

— Add total global catch estimates from transboundary fisheries

Add estimates, if available, no. that are co-managed.

- In the 1st paragraph, establish the global importance of transboundary fisheries. → merge with paragraph below

2nd paragraph - add topic sentence saying transboundary fisheries and their management is challenged by CC. → merge with paragraph below

documented impacts of climate change in marine populations (Poloczanska et al. 2016). Nevertheless, management rules for shared stocks (e.g. quota or spatial delimitation) are often determined based on current and historic knowledge of the stock's distribution and do not consider future shifts in distributions (Fredston-Hermann, Gaines, and Halpern 2018). Moreover, despite evidence of impacts of climate change on transboundary species like sockeye salmon (McDaniels et al. 2010), Atlantic cod (Pershing et al. 2015) and tropical tuna (Monllor-Hurtado, Pennino, and Sanchez-Lizaso 2017), many treaties do not consider climate change in their management scheme. Using North America as a case study, in the current paper, we explore the consequences of potential shifts in the distribution of co-managed stocks to fisheries management. We use mechanistic species distribution models on 37 major co-managed fish stocks between Canada and the United States. We then dive deeper into two case studies (International Pacific Halibut and Gulf of Maine treaty) to understand the consequences of such shifts in these policies. Finally, we explore similar situations around the world and suggest policy actions to mitigate the management impacts of shifting species distributions.

merge with last paragraph of the introduction

Overall on transboundary fisheries

merge with 1st paragraph

Transboundary fisheries are defined as fish stocks that move freely between (i) Countries economic exclusive zones (EEZs) and (ii) between EEZs and the high seas (also called straddling stocks) (Song, Scholtens, et al. 2017). Since 1985, when the United Nations Law of the Seas (UNCLOS) came into play, nations have been incentivized to cooperate on the management of transboundary fisheries (United Nations 1986). The management of transboundary stocks can be approached with game theory as often success depends on effective cooperation between parties

(Miller and Munro 2002). However, the participation of several fishing "players" (e.g. different countries and sometimes jurisdictions within a country), the migration patterns of the stock, and their abundance fluctuation within space and time makes these stocks extremely hard to manage (Miller and Munro 2002). Moreover, as climate change reshapes the ocean's environment worldwide (Gattuso et al. 2015), transboundary fisheries delicate governance is threatened as new migration patterns may arise (Pinsky et al. 2018), historic distribution and abundances might shift (Cheung, Lam, and Sarmiento 2010), and species basic natural traits may modify (Pauly and Cheung 2017).

merge with the paragraph on climate change

Summary impacts of climate change on transboundary fisheries

Climate change causes shift in distributions of fish stocks and impacts their fisheries.

~~The oceans have absorbed 93% of the warming produced by climate change (Rheim et al. 2013).~~ The ocean is getting warmer, less oxygenated and increasing in acidity. To cope with ~~this warming and the associated changes in oceanic physical and chemical properties~~ these changes in ocean properties, marine species have been shifting their distribution towards the poles and/or deeper waters (Poloczanska et al. 2016) including transboundary fish stocks. For example, ~~Empirical evidence of species shift has been seen for~~ straddling stocks like tropical tunas (Monllor-Hurtado, Pennino, and Sanchez-Lizaso 2017), other transboundary species that have been observed to shift in distribution following changes in ocean conditions include ~~like~~ sockeye salmon (McDaniels et al. 2010), and flounders (Pinsky and Fogarty 2012) at a more local level (between states within the US). ~~Moreover, such~~ Climate change induced distribution shifts are projected to continue towards the end of the 21st century ~~worldwide~~ (~~Cheung, Lam, and Sarmiento 2010~~ Cheung 2018; Jones and Cheung 2015) at rate of tens to hundreds of km and/or tens of metre per decade towards the pole and deeper water, respectively, although there will be regional variations. ~~While there is a general pole-ward shifting trend, projections will more likely have different regional outcomes (Morley et al. 2018). For example, in North America, climate change is expected to shift the distribution of over 600 species in the incoming years, although models suggest that some stocks will not move pole-ward~~ (Morley et al. 2018). As a result, some countries or management jurisdictions may see more transboundary stocks and their catches shifting into their waters while others will stand to lose.

describe the observation

Ocean: global

oceans: regional seas.

Past Conflicts

~~While~~ the shifts in distribution of transboundary fish stocks would ~~impose an~~ impact the economic ~~burden~~ of their ~~to fishers~~ fisheries (Lam et al. 2016; Pinsky and Fogarty 2012; Sumaila et al. 2011), ~~it will also~~ and causes ~~create~~ international ~~conflict as range shifts alter the~~ dispute in the sharing of fish stocks between nation's EEZs (Miller and Munro 2002; Spijkers and Boonstra 2017). ~~An estimate of over 500 conflicts events related to fishing have arisen since 1974, from simple verbal encounters to actual deadly conflicts. Since that period the US and Canada have been involved in 80 conflicts related to fisheries *(Spijkers J., International Fishery Conflict 207 Database in preparation)*.~~ ~~These conflicts have been in part linked to environmental forcing that modifies the quantity and quality of natural resources, creating conflict between groups that depend on these resources for their livelihood (Spijkers and Boonstra 2017)~~. For example, Europe is currently involved in an unsolved dispute over *Scomber scombrus* known as the "mackerel wars". The conflict erupted in 2007 when the stock shifted their distribution from the Norwegian Sea towards northern and western regions of the Nordic Seas, consequently arriving to Iceland national waters (Spijkers and Boonstra 2017). Moreover, ~~Historic~~ disputes over Pacific salmon between Canada and the United States arose in the 1990's because of climate-related changes in stock abundance and migratory behavior (Miller et al. 2013; Miller and Munro 2002; Song, Temby, et al. 2017). ~~Despite past evidence of impacts of climate change on transboundary species, and future projections of increasing conflicts (Pinsky et al. 2018)~~, International treaties ~~that rule the management of~~ for the management of transboundary species rarely consider climate change in their management scheme (Pecl, 2018). ~~It becomes crucial to oversee international fisheries management under the scope of shifting~~

As climate change alters the sharing of fish stocks between countries to extend that is beyond historical changes, existing policies and governance structure may not be able to cope with these changes. Consequently, countries may not be satisfied with the sharing or allocation of access to resources, leading to international disputes.

~~stocks if we want to achieve sustainable harvest and marine conservation~~ (Pinsky et al. 2018; Fredston-Hermann, Gaines, and Halpern 2018).

Bring it home, treaties between CA/US

Transboundary fisheries between Canada and USA offer a unique lens to understand

the extend to which climate-induced distribution shift will challenge the future sustainability of these fisheries.

~~Despite the mentioned past conflicts~~, Canada and US have a long history of fisheries cooperation (Song, Temby, et al. 2017). They participate in diverse, co-managed, commercial transboundary stocks through various fisheries management organizations (Fisheries and Oceans Canada 2016b). Cooperation schemes ~~between these nations~~ ~~differ in species composition~~ vary by fisheries stocks, regulatory areas, legal terms of agreement, and management measures, among others. In the Atlantic coast, Canada and the United States are part of the Northwest Atlantic Fisheries Organization (NAFO) that oversees the co-management of 41 species from southern Gulf of Maine to Greenland (NASCO 2018). Would be useful to have a map of RFMOs between USA and Canada Within NAFO's region 5Z, Canada and the US have a "Resource Sharing Understanding" to set catch-limits of Atlantic cod (*Gadus morhua*), Haddock (*Melanogrammus aeglefinus*) and, Yellow flounder (*Limanda ferruginea*) (Soboil and Sutinen 2006). In the Pacific coast, Pacific halibut (*Hippoglossus stenolepis*) and black cod/sablefish (*Anoplopoma fimbria*) are both managed under the International Pacific Halibut Commission (IPHC) (IPHC Secretariat and Gustafson 2016). All five salmon species (chinook, *Oncorhynchus tshawytscha*; chum, *O. keta*; coho, *O. kisutch*; pink, *O. gorbuscha*; and sockeye), are managed by the Pacific Salmon Organization (PSC 2017). Finally, under the Pacific Whiting Treaty, Canada and the United states co-manage the coastal stock of this Pacific hake species (*Merluccius productus*) (Merten 2015). ~~The different characteristics of each treaty will play an important role on the management~~

It is expected that climate-induced shifts in stock distribution will challenge the operation of these treaties.

~~impacts of climate change driven shift in species distribution and so, it is necessarily to not only approach this issue as a regional one but also at the more specific treaty level~~.

The main objective of this paper is to assess the level of exposure of international fisheries management treaties between USA and Canada to climate change impacts through shifts in stock distributions.

~~Given the robust evidence on changes in distribution of fish stocks under climate change, it is important for Canada and the US to anticipate how environmental change will affect their transboundary fisheries management~~ (Miller et al. 2013). Understanding these stocks shifts will shed a light on future conditions and inform decision makers on the paths to follow under a changing climate. ~~Hence,~~ Specifically, in this paper, we.... In the current paper we rely on a species distribution model and scenario planning to project the changes in the distribution of 37 fish stocks co-managed by Canada and US. Moreover, we use two specific treaties as case studies (IPHC and a non-official treaty in the Gulf of Maine) to explore the potential impacts that climate change will have on selected transboundary fisheries management. Finally, we identify opportunities to improve the adaptability of ~~transboundary fisheries management to climate change in North America~~.

Formulate a clear hypothesis to test here

Methods

Projecting future species distribution

study area and fisheries

We used a Dynamic Bioclimatic Envelope Model (DBEM) to project the distribution of species from 2015 to 2100 under scenarios of climate change (~~Cheung, Lam, and Sarmiento 2010~~ Cheung et al. 2016a,b.). The DBEM algorithm integrates ecophysiology, habitat suitability with spatial population dynamics of exploited fishes and invertebrates to project shifts in abundance and potential fisheries catches under climate change. The algorithm ~~uses~~ predicted current species distribute based on depth range, latitudinal range, habitat preferences and an index of species association with major habitat types to estimate changes in abundance distribution over a 0.5’ x 0.5’ grid of the world oceans. For each grid cell and time step, the model ~~simulates~~ then calculated the species’ carrying capacity ~~from~~ according sea surface temperature, salinity, oxygen content, sea ice extent (for polar species) and

as well as the species' preferences to these conditions.

bathymetry. It then incorporates the intrinsic population growth, settled larvae, and net migration of adults from surrounding cells using an advection-diffusion-reaction equation. ~~Finally,~~ the

simulated the effects of … on

model also ~~simulates how~~ changes in temperature and oxygen content ~~would affect~~ growth of ~~the~~

cheung et al. 2013 … Ultimately, the model simulated spatial and temporal

individuals (~~Cheung, Close, and Lam 2008~~). ~~In addition to population dynamics, the model~~

and calculated abundance and maximum catch

~~simulates fishing activity following a maximum sustainable yield policy for each species in each grid~~ cell.

potential (a proxy of maximum sustainable yield by applying fishing at MSY level that it calculated for each grid cell.

Fisheries data to feed the model was gathered from Sea Around Us (Zeller et al. 2016). We used

projected changes in ocean conditions from

three ~~global circulation models for climate forcing's~~: The Geophysical Fluid Dynamics

Earth system models;

Laboratory ESM 2M (GFDL) (www.gfdl.noaa.gov), the Institute Pierre Simon ~~239~~ Laplace Climate Model 5 (IPSL-CM5) (www.icmc.ipsl.fr/), and the Max Planck Institute for Meteorology Earth System Model (MPI) (www.mpimet.mpg.de/en/science/models/). ~~Results~~

Describe preprocessing of data, e.g. regridding (spatial interpolation).

Two scenarios of

~~from the model were averaged to account for climate uncertainty~~. ~~Each model ran two~~ IPCC-Representative Concentration Pathways; 2.6 (RCP2.6) and 8.5 (RCP8.5) representing a low emission (strong mitigation) and a high emission (business-as-usual) scenario, respectively (IPCC 2014).

projected … studied

We ~~used~~ the Maximum Catch Potential (MCP) ~~output of the model~~ for each ~~of the analyzed~~

in the … total

species ~~within both~~ US and Canada's EEZ. ~~For each year~~, ~~the projected~~ MCP ~~of each species was~~

in each

~~aggregated~~ ~~by~~ grid cell ~~and RCP~~ as follows:

$$X_k = \sum_{i=1}^{n} MCP_{iyk}$$

This is 11 years, why not 10 years?

projected

where X is the ~~aggregated~~ MCP for each grid (k) ~~per year (y)~~, and species (n). We then estimate the percentage change in MCP relative to present dates (average of 2004-2014). ~~Instead of using the last fisheries data year (2014) as "today", we average X between 2004 and 2014 ($\bar{X}$) to reduce the effects of inter-annual variability of projected MCP in the analysis.~~ The percentage change in MCP relative to $\bar{X}$ was calculated ~~estimated~~ as ~~follows~~:

n - total no. of spp.

$$\Delta\bar{X} = 1 - \frac{X_{fn}}{X_{nk}} * 100$$

f i

i

but you said 2014 earlier.

where f is ~~equals~~ year~~s~~ between 2015 and 2100. Thus, $\Delta\bar{X}$ reflects the percentage change in maximum catch potential relative to the average of 2005 - 2014. Finally, to estimate the proportion change in MCP at the country level, we aggregated X by EEZ (by summing X across ~~instead of~~ grid cell) and divided each country's MCP by the total projected MCP of each year for all three EEZs). — why?

Finally, for each treaty, we estimated the change in the proportion of MCP for each country relative to the mean MCP of 2005-2014. Then, for each consecutive year after 2014 we divided each EEZ's projected proportion of the MCP by that of 2005-2014.

Need to explain what you mean exactly here in terms of the calculation

The current project focused on the transboundary fisheries of Canada and the United States for both the Atlantic and the Pacific coasts. The analysis was carried within the 200 nautical miles of both nation's EEZ from the Gulf of Mexico to The Labrador Sea in the Atlantic, and from California to Chukchi Sea, in the Pacific coast. Subsets of the total area were done for both the IPHC and NAFO-5Z. For the IPHC, we used the most updated spatial regulatory data (IPHC Secretariat and Gustafson 2016). For this specific case we considered Alaska as a separate entity, the Lower United States (Washington, Oregon and California), and British Columbia (Canada).

move this to the 1st paragraph on "study area"!

move up

For the NAFO-5Z we used NAFO's regulatory area within latitudes 46.2°N and 41.5°S, and longitudes -72°W and -64°E.

The species analyzed were selected based on five treaties in both the Atlantic and Pacific coast of north America (Table 1). All species under the IPHC, PSC, WT and NAFO were analyzed as these treaties are strictly managed under Canada and US's EEZ. However, in the case of NAFO, its governance extends to international waters and the EEZ of Greenland (*ST1*). Therefore, a subset of the **31** species reported was made based on those fished strictly on Canada and US regions (NAFO subareas 2's,3's with the exception of 3N and 3M,4's,5's and 6 A,B, and C.) (Northeast Atlantic Fisheries Commission, n.d.).

Add a table:

	Pacific US	Pacific CA RCP2.6 RCP8.5	Atl US	Atl CA
increase				
no change				
decrease				

no. of species (mean, min, max) across ESMs.

Results

All species

need a topic sentence

Focus on describing the new table I suggested at the beginning

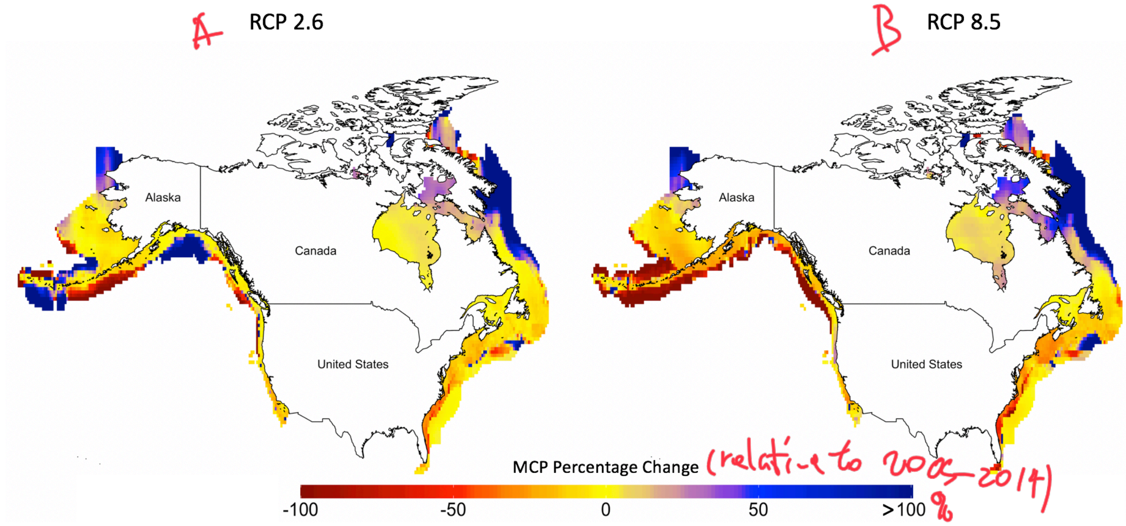
Under a low emission scenario (RCP 2.6), transboundary species of the Atlantic coast of North America are expected to shift their distribution towards higher latitudes, increasing their MCP of the northeast coast of Canada and decreasing in the northeast of US. The Pacific coast shows a less clear trend with a considerable increase in the coast of the Gulf of Alaska but a decrease in British Columbia and northwestern areas of Alaska's EEZ (Fig. 1 - RCP 2.6). These results will become more accented and, in some areas inverse, if carbon emissions are not reduced and the *status quo* is maintained. Under the RCP 8.5, reductions of MCP in the US Atlantic coast will be higher than 2.6 while Canadian waters will more likely increase captures even more. For the

what do you mean?

Pacific coast, the 2.6-MCP gain will be completely inverted with important reductions in the

- start with describing total MCP change in US and Canada and difference between scenarios
- then differences between sub-regions

whole area from Washington to the Aleutian Islands, and potential increase only in the Chukchi Sea (Fig. 1 - RCP 8.5).



(relative to 2005-2014) %

Percentage Change of MCP for Transboundary Fisheries of North America. RCP 2.6 (A) *represents a low emission scenario (high mitigation).* (B) *RCP 8.5 represents a high emission scenario (status quo)*

~~Regional results allow to understand trends in species distribution and future landings of such species. However, to understand the implications of shifting stocks to transboundary fisheries management such shifts have to be seen at the treaty level. Treaties have different management areas, rules placed and species regulated, all factors that will have different outcomes under a changing climate.~~

Projected changes in MCP of Pacific Halibut

~~International Pacific Halibut Commission~~

we projected a small decrease (x% - x%) of Pacific Halibut?

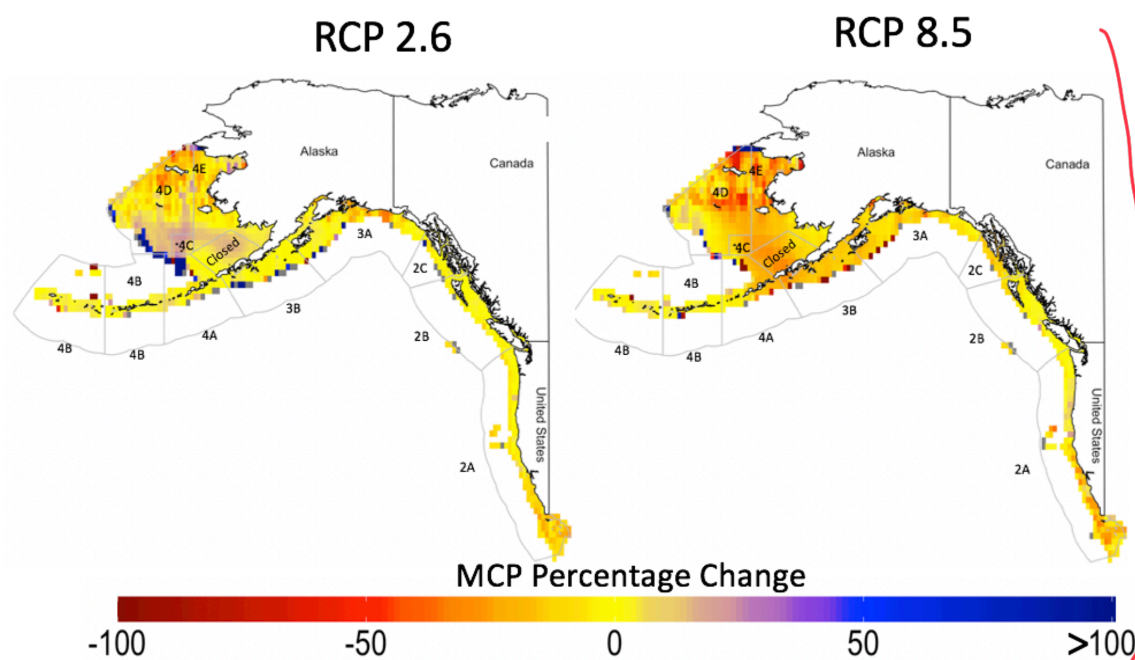
For the International Pacific Halibut Commission regulation area, MCP ~~is overall expected to suffer small changes~~ except for specific areas. Lower US waters of the coast of California (Area

statistical areas where larger decrease of up to x% was projected

PTO

Across the xx statistical area, x of them is projected to have a decrease of <-x% under both RCP 2.6 and 8.5. However, in ...

2A), east of the Gulf of Alaska (Area 3A) and northern Bering Sea (Areas 4DE) ~~are expected to~~
were projected to decrease by xx, xx, and xx% respectively,
~~suffer reductions in~~ MCP. ~~In the other hand~~, most of the Bering Sea ~~is expected~~ to gain MCP, as
In contrast, under RCP 2.6 ... statistical areas in were projected
well as some areas southern (deeper) of the Gulf of Alaska ~~(Areas 3AB)~~ (Fig. 2). ~~This gain/loss~~
However, under RCP 8.5, only area xx, and xx
~~trade-off is reverse under high emission scenario as no gain was projected for the area except for~~
were projected to gain in RCP. Specifically under RCP8.5
~~very punctual, small, zones.~~ ~~The previous~~ decrease in areas 2A and 4DE intensifies ~~and the gain~~
projected RCP 2.6 MCP was projected to while
~~seen~~ in the Bering Sea under ~~a low emission scenario~~ becomes a ~~reduction~~ in MCP. ~~Interestingly,~~
MCP along the coast of loss under RCP8.5,
~~under both scenarios the coast of~~ British Columbia ~~does not seem to win nor loos~~ MCP, ~~probably~~
was projected to remain relatively stable
~~due to a southern gain and northern loss to the neighbouring areas~~. Such results only intensify by
BC? under both RCPs,
the end of the century with loses over most of the territory under the high emissions scenario.



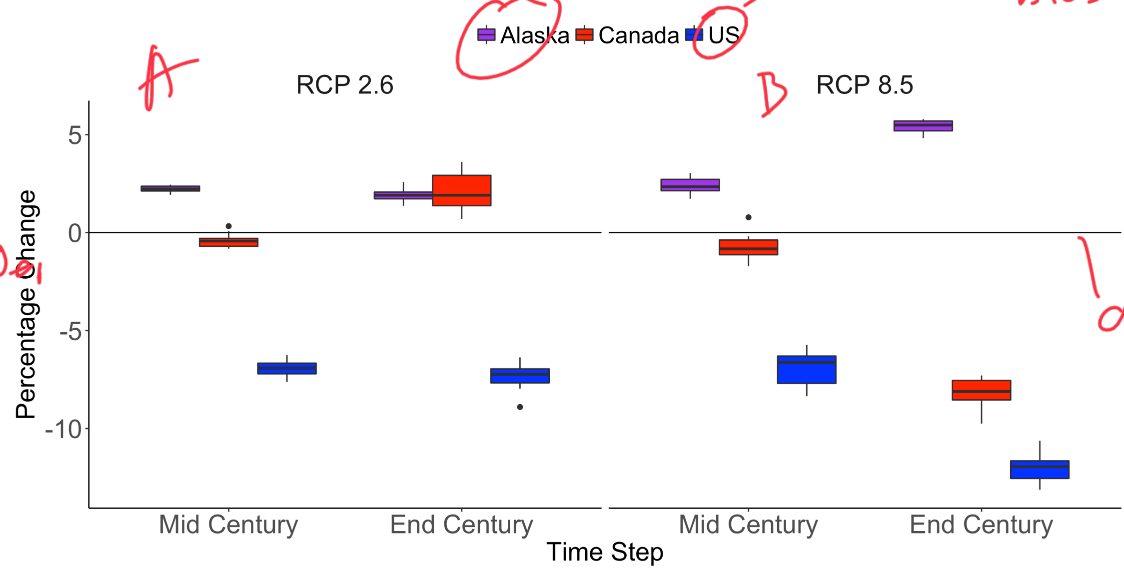
can you aggregate by statistical area? It would be better.

Percentage Change of MCP for Species under IPHC - RCP 2.6 represents a low emission scenario (high mitigation). RCP 8.5 represents a high emission scenario (status quo). IPHC regulatory areas in grey (Time frame?)

Topic sentence should focus on shifts in proportion.

The overall IPHC trend suggests that landings will decrease in Alaska and maintain the same in British Columbia, however, landing values might still be higher in Alaska than in the other regulatory areas. This can be seen when the proportion of the total catch of each EEZ. Under both scenarios Alaska is expected to be the big winner of the Pacific coast with the proportion of the total MCP projected for the area increasing in more than 5%. In the other hand, the lower US is projected to be the big loser with a proportion decrease over 10% by the end of the Century, if climate change is not mitigated (Figure 4). Maintaining emissions to lower levels would potentially increase the MCP of Canada by the end of the 21st century, although uncertainty in the result is higher than other cases. Failing to achieve this target would lead to a potential reduction of MCP of almost 10% for Canada.

USA (Alaska) USA (exclude Alaska)



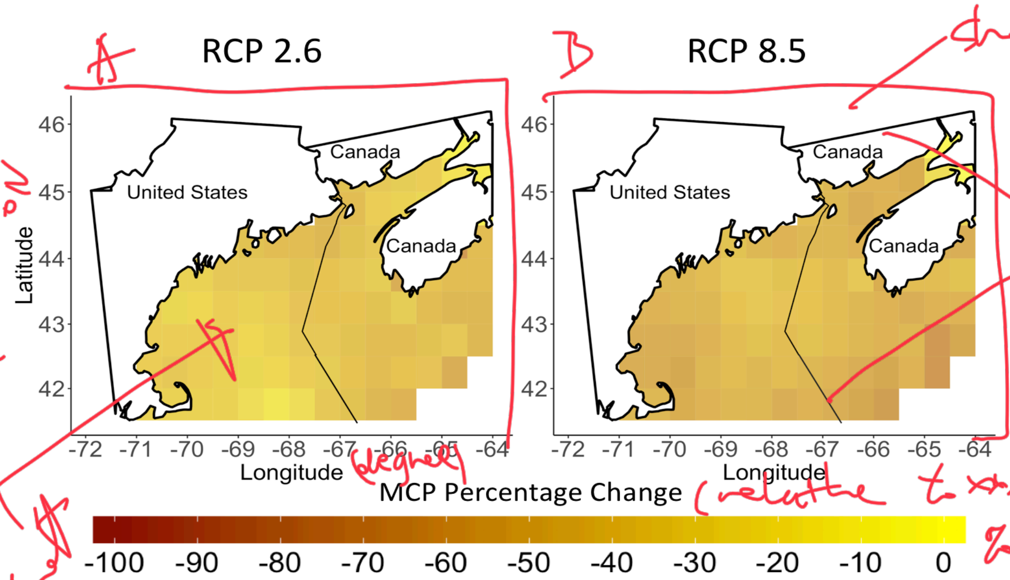
dotted line

Changes in proportion of total-EEZ MCP for IPHC under two RCPs for ~~M~~ m id-century (2046-2055) and ~~E~~ e nd of the century (1990-1100) (A) ... (B) ...

The Gulf of Maine Understanding

Show map by spp, then total in different panels.

While the species managed by the IPHC will see some increment in some areas, the results for the Gulf of Maine (NAFO area 5Z) do not present such a positive scenario. Our results suggest that the aggregated MCP of Cod (*Gadus morhua*), Yellowtail Flounder (*Limanda ferruginea*), and Haddock (*Melanogrammus aeglefinus*) will decrease within the whole Gulf with no apparent win for any country (Fig. 4). However, there is a benefit of achieving a low emission scenario, specially for the United States.



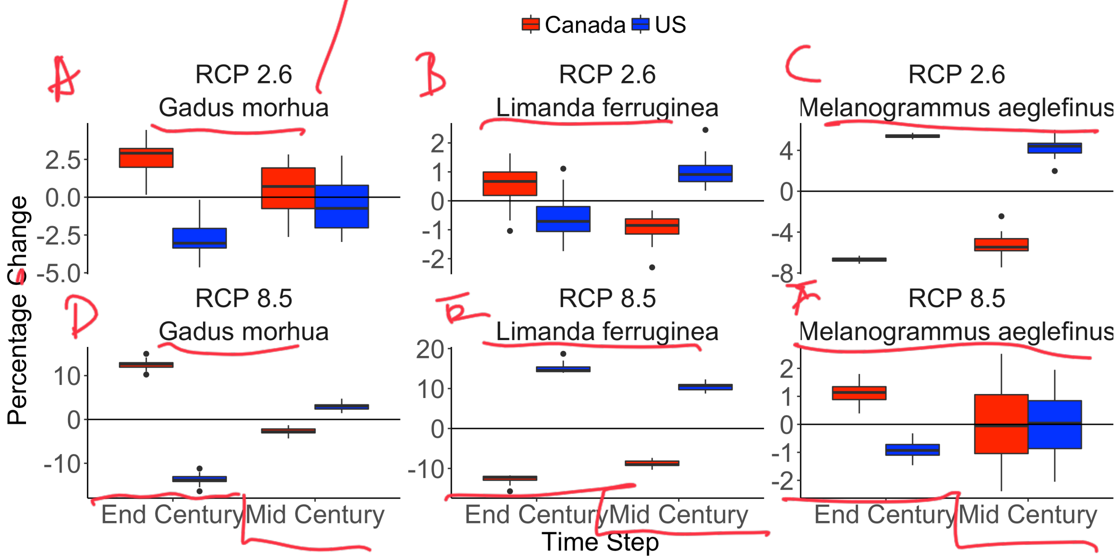
Percentage Change of MCP for Species under GMGA - ~~RCP 2.6~~ (A)... (B)...

Despite an expected decrease in MCP relative to 2014's values for the region, changes in the proportion of MCP for the Gulf of Maine shows different outcomes depending on the species in question. For mid-century, under the low emission scenario Canada's MCP proportion of Cod and Y. Flounder will likely increase with US increasing in Haddock. If emissions follow a

① Subdivide into mid-century and end of century.
② talk about gain in Canada and US
③ talk about loss.

business as usual path, Canada will gain Cod and Haddock but lose proportion of the Y. flounder stock (Fig 5.).

italic



widen & make the small box visible.

Changes in proportion of total-EEZ MCP for GMGA under two RCPs for Mid-century (2046-2055) and End of the century (1990-1100).

by 21st

e

21st

(A)... (B)...

Discussion

First paragraph - answer the question: does the result support or not the hypothesis posed.

Species shifting towards the poles

each subsection explain how the results support/not the hypothesis.

Global projections suggest that climate change will make marine species move towards the poles and deep water in search for colder waters ~~to satisfied their ecological needs~~ what matches their ecological niche. (Cheung, Lam, and Sarmiento 2010; Poloczanska et al. 2016). Our results are consistent with such projections as well as regional-based modeling approaches that measured species shifts in relation to climate velocity (Pinsky et al. 2013), and projected shifts in centroids for species in north America (Morley et al. 2018). For the Atlantic coast, a north-ward shift in species MCP by 2050 with an increase in intensity under the high emission scenario will benefit Canadian fisheries (Morley et al. 2018). In consequence, an overall reduction of MCP for US is expected by mid-century under both scenarios, intensifying under a high emission scenario. This shift has been already recorded for American lobster, summer and yellowtail flounder, and red hake (Pinsky and Fogarty 2012). Achieving the 2.6 target will most likely reduce the impact of climate change on landings of the 31 transboundary-species managed by NAFO and analyzed in the present study. However, as the impacts of climate change will continue to manifest, even with high mitigation from countries, it is recommend that NAFO starts to consider these dynamics on the management of key north American stocks. move to a section on implications for management.

In the Pacific coast, shifts in species distributions under a low emission scenario will likely occur from British Columbia's coast to the Gulf of Alaska, to the western Aleutian Islands, as the direction and magnitude of species' centroids shift can be of up to 500km in this region (Morley et al. 2018). The increase of MCP west of the Aleutian Islands could be a response to a temperature gradient shift (Pinsky et al. 2013), rather than latitudinal, as fish in this region can only migrate northward into the Arctic Ocean through the Bering Sea and Bering Strait (Cheung et al. 2015). Our results reflect the importance of mitigating climate change as an overall reduction of MCP within the EEZ of lower US, Canada and Southern Alaska is expected. Under this scenario, the centroids of 303 species are projected to shift more than 1500 km from their averaged 2007–2020 origin for both the lower US and Canada waters (Morley et al. 2018). Under these predictions, fish could be moving outside the EEZ's 200 nautical miles in search of colder waters and into the high seas (Morley et al. 2018), representing a potential lost for both nations.

The International Pacific Halibut Commission

In terms of management, the International Pacific Halibut Commission has a set of rigorous regulations to manage the halibut and sablefish fishery. The fishery is managed under a quota system that is determined every year by a biological sampling of the whole regulatory area (Fig 2.). From the total harvestable biomass estimation, a percentage is first separated for by-catch of other fisheries, indigenous communities and sports fishing, then, commercial quota is allocated my regulatory area accordingly. In addition, video-monitoring is required in 100% of the vessels, the fishing season is arbitrary, and fishing gear is restricted to a special "j" hook trolling (IPHC, 2016a). While these methods have proved to be ecologically successful in recent years (IPHC, 2016b), climate change could potentially compromise their performance if not addressed in time.

It is possible that the dynamic method of allocating the catch will cope with the shift in species distribution (Pinsky et al. 2018; IPHC, 2016). However, socio-economic consequences of such shift should not be discarded. Currently, the most abundant area is 3A (**XX**% of total commercial catches). A reduction of catch in this area will consequently imply a bigger economic loss than the lost in, let's say, area 2A (the lower one with only **XX**% of commercial landings). Understanding the economic loss of the present shifts can help stakeholders in the management of the resource. Moreover, while quota on the halibut fishery is transferable within countries, it is not between nations (IPHC, 2016). This characteristic could be a source of conflict as Canadian fishers see their fish move to areas controlled by Alaska. Especially if the biomass loss to area 2C and 3A is not being offset by a poleward shift of area 2A. (Fig 3). Allowing quota trade between Canadian and US fishers, as considered to some extent by NAFO, could be a potential solution for this (Pinsky et al. 2018), although more studies should be done to full understand the implications of such policy.

To mitigate the projected imbalance in landings, the IPHC could adopt a strategy known in game theory as “side payment”. With a side payment, a player receives a compensation from the other player, with the idea that keeping cooperation is still better than playing solo (Bjørndal and Munro 2012). Side payments are already used in other Canada-US treaties. The Pacific Salmon Commission, currently integrated by Canada and US has a side payment in form of a “conservation fund”. This fund was key in the conflict resolution over Pacific Salmon species in 1989 (Miller et al. 2013; Miller and Munro 2002; Song, Temby, et al. 2017).

The implementation of a “j” hook in the halibut fishery reduces bycatch in the fishery by **XX**% of total landings by year (IPHC, 2016), however, by-catch of halibut by the ground fish trawl, hook-and-line, and pot fisheries happen mostly on areas 3A and 4B (NOAA 2013). According to our projections, such area is expected to increase its MCP by mid-century increasing the potential for by-catch by trawlers in the same region. A potential increment in such impact is possible if the target species for trawling and hook and line also increase in the area. Taking stricter management measurements to manage these fisheries would likely reduce potential loss of sustainable harvest. However, conflicts between fleets already exists and could be extrapolated if the situation is not foreseen (Van Der Voo 2016).

The shift in pacific halibut might also increase pressure in the closed area. Currently, an area south of the Bering sea (Fig.2) is closed to fishing for research and conservation of the species (IPHC, 2016). Impacts of climate change on marine protected areas (MPA) tend to explore the lost in biodiversity within the MPA (Bruno et al. 2018), situation that would occur here, under the high emission scenario. Hypothetically, a reverse situation could happen under a low emission scenario as fish move out of fishing ground and into the protected waters resulting in an increase in fishing pressure form the industry.

Transboundary conflicts, consequence of the shift in the distribution of pacific halibut, could also arose within the US, as historically seen in States along both coasts. As fish move poleward, individual fishers from California, Oregon and Washington will have to follow the fish, changing the primary port they use for landing fish (e.g. to Alaska), or travel further from their current ports, what could potentially increase fishing cost (Pinsky and Fogarty 2012; Lam et al. 2016). In addition, an increase in fishing effort from southern fishers, as well as the migration of the stock to new areas could threatened the sustainability of the stock (Pinsky and Fogarty 2012). In the Atlantic coast for example, Blue line tilefish (*Caulolatilus microps*), historically caught and managed south of the Virginia–North Carolina border, was harvested nearly a decade without regulation when the stock shifted poleward (Pinsky et al. 2018). The shifts in pacific halibut do not only have the potential to create regional and international conflict, but also compromise the sustainability of the resource.

The Gulf of Maine Understanding

Unlike the IPHC where rules are plenty, management is collaborative, and the negotiations happen at a high level of government, the agreement of the Gulf of Maine to manage Cod, Haddock, and Yellowtail flounder is limited to catch limits. Every year, Canada and the US both undertake sampling efforts in the Gulf in order to set catch limits for all three species. However, other aspects of the fishery remain responsibility of each party (Soboil and Sutinen 2006). It has been suggested that agreements that make cooperation the preferred strategy for all players are stronger (Barrett 2003). In this sense, the level of government at which negotiations are held can directly impact this outcome, as low level agreements might lack proper penalties for non-cooperative behavior. The negotiation of a more structured treaty at the federal level could be a first step to adapt to the future changes in the Gulf of Maine (Miller et al. 2013).

While the overall reduction in MCP for flounder, haddock and cod of the Gulf of Main suggest a loss for both nations, there is an important difference between climate change scenarios (Fig4.) This situation is not particular of this region of the world. From global analysis (Cheung, Raymonde, and Frölicher 2016) to regional (Morley et al. 2018) to local, mitigating the effects of climate change will have positive results on fisheries. Moreover, despite the overall reduction, lacking cooperation between both nations will most likely result in unsustainable harvest of Cod, increasing pressure on an already pressured stock (Soboil and Sutinen 2006).

In some cases, our projections suggest that the US could gain more proportion of total MCP of Y. flounder and haddock (Fig 5.). Such gain US could be the result of species shifting their distribution from lower latitudes and towards the GoM, naturally reaching the US (lower) region first. Although considered a slow migration species, in recent years Maine has seen its landings of Y. flounder increased while southern states decrease (Pinsky and Fogarty 2012). Moreover, previous studies have found that under the low emission scenario, haddock is expected to stay at lower latitudes, contrary to what would happen under a high emission scenario (Morley et al.

2018). This pattern could explain the gain in proportion of the US against Canada as fish migrates from southern latitudes and into the Gulf of Maine.

Between 1991 to 2001 the proportion of the stock for Canada and US was 69%-31% for Cod, 28% - 72% for Haddock, and 53 - 47% for Y. flounder, respectively (Soboil and Sutinen 2006). Regardless of the RCP scenario, both countries are expected to change the proportion of the total catch within their EEZ for each species (Fig. 5). Changes in quota proportion have previously caused conflict between these nations over Pacific salmon (Miller et al. 2013). Moreover, in 1980 the IPHC changed the quota estimation from static to dynamic to address shifts in the stock at the lower US-Canada border (IPHC, 2016). Whether the change in proportion is positive or negative to an specific country will depend on the species, scenario and time step. This particular situation can be addressed by adopting quota swaps within regulatory areas as Norway and Russia due trough the establishment of the Russian-Norwegian Fisheries Commission (Joint Fish, 2018). The two northern nations share cod, haddock and capelin stocks in the Barents Sea. Implementation of this agreement resulted in a Capeling-Herring quota swap in 2011 with Norway receiving extra 30 thousand tons of capelin and Russia 10 thousand tons of Norwegian spring spawning herring (Northern Seafood, 2012). The adaptation of a similar agreement could ease the reduction of certain stocks as these three species managed under the groudfish fishery.

Conclusion

Shifts in species distribution due to climate change have the potential of creating local extinction of economically important species (Cheung et al. 2015) while rising fisheries in areas where they were not present before (Pinsky et al. 2018). Exploring such dynamics at the species level is important as differences in species response are likely to exist (Pinsky et al. 2013; Morley et al. 2018). However, fisheries represent a complex socio-ecological system, thus other aspects of the fishery such as the legal framework, rules placed, and level of compliance should be considered (Allison et al. 2009). These variables become even more critical when discussing issues of climate change and transboundary fisheries (Pinsky et al. 2018; Miller et al. 2013). Our study provides an assessment of the potential impacts that the shift of 37 species will have in the management implementation of different cooperation treaties. We found that in north America stocks are likely to shift north in the upcoming years changing the proportion of the catch of different co-managed stocks. Lessons from other countries and cases studies can provide solutions to such challenges. More specific, side payments, dynamic quota allocation, and interchangeable quotas were identified as potential solutions for the regions of North America.

Acknowledgments

References

Allison, Edward H, Allison L Perry, Marie Caroline Badjeck, W Neil Adger, Katrina Brown, Declan Conway, Ashley S Halls, et al. 2009. “Vulnerability of national economies to the impacts of climate change on fisheries.” *Fish and Fisheries* 10 (2): 173–96.

Barrett, Scott. 2003. “Environment and Statecraft: The Strategy of Environmental Treaty-making.” *Management of Environmental Quality: An International Journal* 14 (5): 622–23.

Bjørndal, T, and G Munro. 2012. “The economics and management of world fisheries.”

Bruno, John F, Amanda E Bates, Chris Cacciapaglia, Elizabeth P Pike, Steven C Amstrup, Ruben van Hooidonk, Stephanie A Henson, and Richard B Aronson. 2018. “Climate change threatens the worlds marine protected areas” 506 (April): 1–6.

Caddy, J F. 1997. “Establishing a consultative mechanism or arrangement for managing shared stocks within the jurisdiction of contiguous states.” *Taking Stock: Defining and Managing Shared Resources*.

Cheung, William W, Richard D Brodeur, Thomas A Okey, and Daniel Pauly. 2015. “Projecting future changes in distributions of pelagic fish species of Northeast Pacific shelf seas.” *Progress in Oceanography* 130 (C): 19–31.

Cheung, William W, C Close, and V Lam. 2008. “Application of macroecological theory to predict effects of climate change on global fisheries potential.” *Marine Ecology Progress Series*.

Cheung, William W, VIckey WY Lam, and J L Sarmiento. 2010. “Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change.” *Global Change Biology* 16: 24–35.

Cheung, William W, G Reygondeau, and T L Frölicher. 2016. “Large benefits to marine fisheries of meeting the 1.5 C global warming target.” *Science*.

Fredston-Hermann, Alexa, Steven D Gaines, and Benjamin S Halpern. 2018. “Biogeographic constraints to marine conservation in a changing climate.” *Annals of the New York Academy of Sciences* 367 (February): 49–13.

Gattuso, J P, A Magnan, R Billé, W W L Cheung, E L Howes, F Joos, D Allemand, et al. 2015. "Contrasting futures for ocean and society from different anthropogenic CO2 emissions scenarios." *Science* 349 (6243): aac4722–aac4722.

IPCC. 2014. *Climate Change 2014 Impacts, Adaptation, and Vulnerability: Summary for Policy makers*. Edited by Christopher B Field, Vicente R Barros, David Jon Dokken, Katharine J Mach, and Michael D Mastrandrea. Working Group Ii Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

IPHC Secretariat, and Katherine Gustafson. 2016. "Annual Report 2016, Established by a Convention between Canada and the United States of America." Seattle, Washington: IPHC.

Joint Fishing. 2018. Joint Russian-Norwegian Fisheries Commission, History- Available at: http://www.jointfish.com/eng/THE-FISHERIES-COMMISSION/HISTORY.html

Lam, Vicky W Y, William W Cheung, Gabriel Reygondeau, and U Rashid Sumaila. 2016. "Projected change in global fisheries revenues under climate change." *Nature Publishing Group*, August, 1–8.

McDaniels, Tim, Sarah Wilmot, Michael Healey, and Scott Hinch. 2010. "Vulnerability of Fraser River sockeye salmon to climate change: A life cycle perspective using expert judgments." *Journal of Environmental Management* 91 (12): 2771–80.

Merten, Wessley. 2015. "International Agreements Concerning Living Marine Resources of Interest to NOAA Fisheries." Silver Spring, Maryland.

Miller, K, and G Munro. 2002. *Cooperation and Conflicts in the Management of Transboundary Fishery Resources*. Monterey, California: Proceeding of the Second World Conference of the Second World COngress of the American; European Associations of Environmental; Resource Economics.

Miller, Kathleen A, Gordon R Munro, U Rashid Sumaila, and William W Cheung. 2013. "Governing Marine Fisheries in a Changing Climate: A Game-Theoretic Perspective." *Canadian Journal of Agricultural Economics/Revue Canadienne d'agroeconomie* 61 (2): 309–34.

Monllor-Hurtado, Alberto, Maria Grazia Pennino, and José Luis Sanchez-Lizaso. 2017. "Shift in tuna catches due to ocean warming." *PLoS ONE* 12 (6): e0178196.

Morley, James W, Rebecca L Selden, Robert J Latour, Thomas L Frölicher, Richard J Seagraves, and Malin L Pinsky. 2018. "Projecting shifts in thermal habitat for 686 species on the North American continental shelf." *PLoS ONE* 13 (5): e0196127.

NASCO. 2018. "North Atlantic Salmon Conservation Organization. Conserving and Restoring Wild Atlantic Salmon." http://www.nasco.int/.

NOAA. 2013. "Reducing Bycatch in Alaska." https://www.npfmc.org/wp-content/PDFdocuments/bycatch/Bycatchflyer913.pdf.

Northeast Atlantic Fisheries Commission. 2018 "Northeast Atlantic Fisheries Commission Objectives."

Northern Seafood. 2018. Arctic Species is Thriving. Norway exports. Available at http://www.norwayexports.no/sectors/articles/arctic-species-is-thriving/

Pauly, Daniel, and William W Cheung. 2017. “Sound physiological knowledge and principles in modeling shrinking of fishes under climate change.” *Global Change Biology* 24 (1): e15–e26.

Pershing, A J, M A Alexander, C M Hernandez, L A Kerr, A Le Bris, K E Mills, J A Nye, et al. 2015. “Slow adaptation in the face of rapid warming leads to collapse of the Gulf of Maine cod fishery.” *Science* 350 (6262): 809–12.

Pinsky, Malin L, and Michael Fogarty. 2012. “Lagged social-ecological responses to climate and range shifts in fisheries.” *Climatic Change* 115 (3-4): 883–91.

Pinsky, Malin L, Gabriel Reygondeau, Richard Caddell, Juliano Palacios-Abrantes, Jessica Spijkers, and William W Cheung. 2018. “Preparing ocean governance for species on the move.” *Science* 360 (6394): 1189–91.

Pinsky, Malin L, Boris Worm, Michael J Fogarty, Jorge L Sarmiento, and Simon A Levin. 2013. “Marine Taxa Track Local Climate Velocities.” *Science* 341 (6151): 1239–42.

Poloczanska, Elvira S, Michael T Burrows, Christopher J Brown, Jorge García Molinos, Benjamin S Halpern, Ove Hoegh-Guldberg, Carrie V Kappel, et al. 2016. “Responses of Marine Organisms to Climate Change across Oceans.” *Frontiers in Marine Science* 3 (28): 515–21.

PSC. 2017. “Pacific Salmon Commission: About the Commission.” http://www.psc.org/about-us/.

Rheim, M, S R Rintoul, S Aoki, E Campos, D Chambers, R A Freely, S Gulev, et al. 2013. “Foreword.” In *Climate Change 2013 - the Physical Science Basis*, edited by IPCC, T F Stocker, D Quin, G K Plattner, M Tigor, S K Allen, J Boschung, et al., v——vi. Cambridge: Cambridge University Press.

Soboil, Mark Lucas, and Jon G Sutinen. 2006. “Empirical analysis and transboundary management for Georges Bank multispecies fishery.” *Canadian Journal of Fisheries and Aquatic Sciences* 63 (4): 903–16.

Song, Andrew M, Joeri Scholtens, Johny Stephen, Maarten Bavinck, and Ratana Chuenpagdee. 2017. “Transboundary research in fisheries.” *Marine Policy* 76 (C): 8–18.

Song, Andrew M, Owen Temby, Gail Krantzberg, and Gordon M Hickey. 2017. “Institutional Features of U.S.-Canadian Transboundary Fisheries Governance,” April, 1–24.

Spijkers, Jessica, and Wiebren J Boonstra. 2017. “Environmental change and social conflict: the northeast Atlantic mackerel dispute.” *Regional Environmental Change* 17 (6): 1835–51.

Sumaila, U Rashid, William W Cheung, Vicky W Y Lam, Daniel Pauly, and Samuel Herrick. 2011. “Climate change impacts on the biophysics and economics of world fisheries.” *Nature Climate Change*, November, 1–8.

United Nations. 1986. “United Nations Convention on the Law of the Sea (UNCLOS) - Part V.”

Van Der Voo, Lee. 2016. “Conflict threatens to close Bering Sea halibut fishery.” https://www.adn.com/business/article/conflict-threatens-close-bering-sea-halibut-fishery/2014/12/11/.

Zeller, D, M L D Palomares, A Tavakolie, M Ang, D Belhabib, W W L Cheung, V W Y Lam, et al. 2016. “Still catching attention: Sea Around Us reconstructed global catch data, their spatial expression and public accessibility.” *Marine Policy* 70 (August): 145–52.