

## Why economics matters for understanding the effects of climate change on fisheries

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Research attempting to predict the effect of climate change on fisheries often neglects to consider how harvesters respond to changing economic, institutional, and environmental conditions, which leads to the overly simplistic prediction of “fisheries follow fish”. However, climate effects on fisheries can be complex because they arise through physical, biological, and economic mechanisms that interact or may not be well understood. Although most researchers find it obvious to include physical and biological factors in predicting the effects of climate change on fisheries, the behaviour of fish harvesters also matters for these predictions. A general but succinct conceptual framework for investigating the effects of climate change on fisheries that incorporates the biological and economic factors that determine how fisheries operate is presented. The use of this framework will result in more complete, reliable, and relevant investigations of the effects of climate change on fisheries. The uncertainty surrounding long-term projections, however, is inherent in the complexity of the system.

**Keywords:** climate change, conceptual models, economic behaviour, fisheries management.

### Introduction

Changes in climate conditions have the potential to profoundly affect marine ecosystems, of which fisheries are an integral part. The commercial fishing industry removes millions of tonnes of fish and shellfish from the marine environment annually, and recreational and subsistence harvests can be locally significant to marine ecosystems. Research on the effects of climate change on marine ecosystems is generally focused on the biological system rather than fish harvesters. Inferences from these biology-focused models have been used to predict the effect of climate change on fisheries (Klyashtorin, 1998; Köster *et al.*, 2003; Perry *et al.*, 2005; Lehodey *et al.*, 2006; Brander, 2007; Cheung *et al.*, 2010; Ianelli *et al.*, 2011b), but they often neglect to incorporate how individual harvesters respond to a variety of changing economic, institutional, and environmental conditions. These responses can significantly affect retrospective analyses and predictions.

Researchers, industry participants, and policy-makers are interested in how the distribution of fishing effort may change in relation to climate change. Potential changes include spatial and/or temporal changes in the distribution of fishing effort, the targeting of particular species, the location where harvests are landed and processed, and the composition of fishing fleets. For example,

policy-makers may be interested in the potential effects of climate change on the feedback effect of changes in harvest patterns into the population dynamics and spatial distribution of the stock, on the flexibility of policy to climate change, on the cost of fishing, or on socio-economic indicators such as income, exports, the vulnerability of communities, or food security. Each of these research objectives requires an understanding of how the drivers of fishing fleet behaviour can affect the range of potential outcomes (Fulton *et al.*, 2011).

Some of the factors that drive harvester behaviour are directly related to the biological system, such as the spatial distribution of the target species, or the total allowable catch (TAC) of a fishery, which is a function of total abundance. Other factors may be influenced by biological characteristics; for example, ocean temperature patterns may separate large and small fish, making harvested fish from certain locations more valuable, and the value of locations may shift with changing ocean conditions. Still other factors, such as fuel prices, may profoundly affect fleet behaviour but are not affected by the ecological system. To ignore how climate affects all these factors that influence a harvester's decision is to ignore the effects of basic ecosystem interactions (Davis *et al.*, 1998).

The study of social–ecological systems can benefit greatly from structural frameworks that outline the relationship between specific variables and the mechanisms that affect the complex whole (Ostrom, 2009; Reid *et al.*, 2010). In this study, we develop and describe a general but succinct conceptual framework for the investigation of the effects of climate change on fisheries. The framework recognizes that climate can affect fisheries through a variety of complex mechanisms and incorporates how climate is likely to impact the biological and the economic factors that determine how fisheries operate. Characterizing both the degree of uncertainty surrounding these mechanisms and the range of possible variation in climate and biological conditions is an essential first step in generating predictions and analysing management scenarios.

**Conceptual model**

Figure 1 is an illustrative diagram of the mechanisms through which climate factors can affect the distribution of fishing effort. The arrows represent the direction of causality.

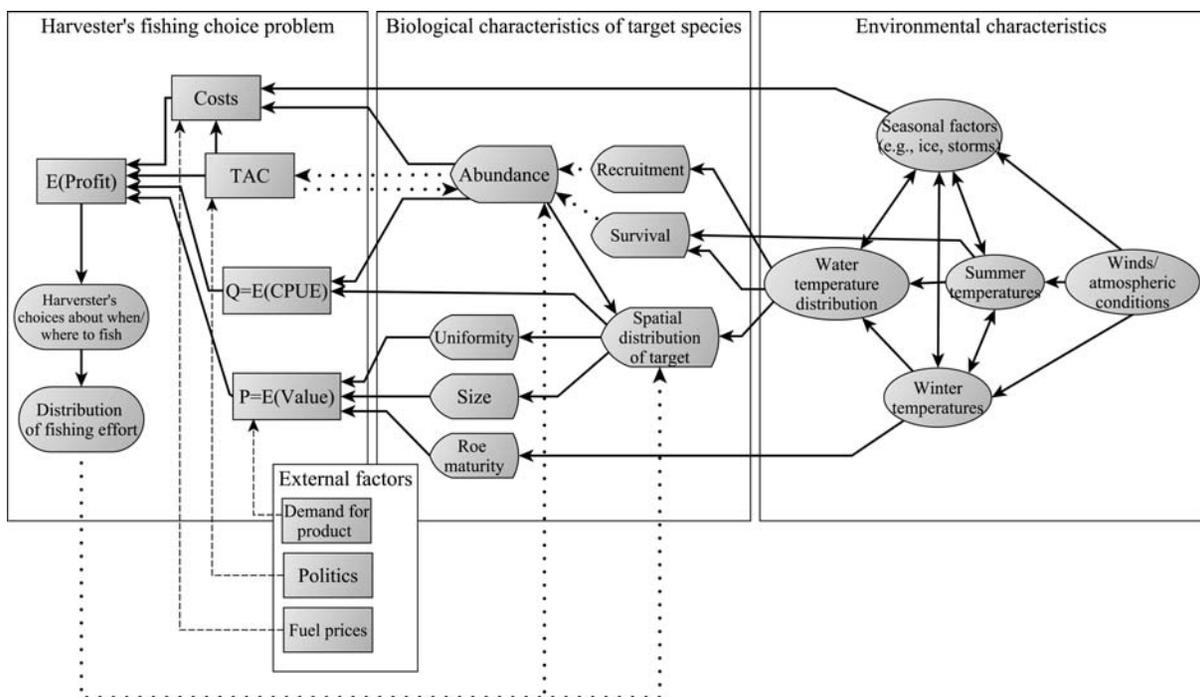
Climate change is predicted to affect many of the environmental characteristics of ecosystems, but with large regional and temporal variability (IPCC, 2007). For example, climate change may affect atmospheric circulation patterns such as the Arctic Oscillation and the North Atlantic Oscillation (Overland and Wang, 2005; Hurrell and Deser, 2010), which help to determine the extent of winter sea ice in the Arctic, and in turn affect water temperatures for the entire annual cycle (Thompson and Wallace, 1998). Environmental characteristics are likely to affect the biology of a fishery’s target species, including recruitment, survival, and spatial distribution. Finally, the biological characteristics of the target species affect the fishery through the variable components of a harvester’s decision-making process, the most general of which include expected catch (i.e. catch per unit effort, cpue), expected value of catch, the cost of fishing, and the TAC. Harvesters consider these factors when making decisions about

where and when to fish. The diagram illustrates the mechanisms linking environmental, biological, and economic characteristics of many fisheries and their ecosystems.

The solid lines connecting elements in Figure 1 represent mechanisms with relatively contemporaneous effects. For example, the extent of winter ice cover is likely to affect the distribution of water temperatures contemporaneously and throughout the rest of the annual cycle. The dotted lines represent mechanisms that are likely to arise non-contemporaneously or have both year of and lagged effects. Lagged effects are much more difficult to identify in empirical data because the correct lag structure is often not known, and the interaction of contemporaneous and non-contemporaneous factors may obscure identification. For example, fishing may affect total abundance through both the contemporaneous removal of fish from the ecosystem and through effects on recruitment. The effects through recruitment may take several years to become evident in abundance measures.

This work is focused on high-latitude regions, where the effects of climate change are expected to be the most dramatic and earliest (IPCC, 2007). However, the conceptual framework applies to temperate, tropical, and subtropical regions as well. To capture the dynamics through which climate change affects fisheries, each link displayed in Figure 1 needs to be considered carefully, along with the possibility of additional links, when adapting Figure 1 for a particular fishery.

The remainder of this study is organized as follows. We first present a simple economic model of fishing behaviour, versions of which have been empirically supported in a large number of fisheries. In the subsequent subsection, we describe how environmental characteristics affect the biological characteristics of a fish harvester’s target species. Then, we explain how these biological characteristics affect fishing decisions. Finally, we discuss the implications of using this framework to guide research on the effect of climate change on fisheries. The use of this framework



**Figure 1.** Conceptual model of how the environment affects the distribution of fishing effort. Arrows represent the direction of causality, and dotted lines represent the mechanisms that may arise on a non-contemporaneous time-scale.

avoids the simplistic conclusion of “fisheries will follow fish” which is often professed without considering the complexity of economic drivers of fisheries and their constraints.

### Harvester behaviour

The foundation of the study of fish harvester behaviour is the individual harvester’s decision-making process. Harvesters have a knowledge of the potential benefits and costs of decisions about how, when, and where to fish. They weigh the potential costs and benefits of their options and must make trade-offs between, for example, fishing in one location vs. another, or fishing more intensively at the beginning than at the end of a season. Economists have put a great deal of effort into modelling fishing fleet behaviour (e.g. Bockstael and Opaluch, 1983; Eales and Wilen, 1986; Holland and Sutinen, 2000; Smith and Wilen, 2003; Haynie and Layton, 2010). (A “fleet” can be defined as the group of harvesters exploiting the resource. A group of subsistence harvesters, for example, can be considered a fleet.) Location choice models are particularly relevant because of recent policy emphasis on spatial fishing restrictions such as spatial closures, marine protected areas, and area-based fishing rights (Smith and Wilen, 2003; Wilen, 2004; Sanchirico *et al.*, 2006), and because stock dynamics may be influenced by changes in the distribution of fishing effort. Fish harvesters maximize utility (which is often assumed to be “profit”, especially for commercial fisheries, because it may be more easily measured than “utility”) by considering the characteristics of potential fishing locations, such as the quantity, quality, and species of fish they expect to catch, and the cost of travelling to different areas at different times. Choices along other dimensions, such as the timing of fishing (Brown, 1974; Kellogg *et al.*, 1988) and entry and exit decisions (Ward and Sutinen, 1994; Pradhan and Leung, 2004) have also been modelled.

A simple conceptual fishing location choice model involves a harvester choosing an area to fish that will maximize the profit from fishing. For example, consider a harvester who makes a choice between  $j$  fishing locations,  $j = 1, \dots, J$ . The harvester will receive revenues from the quantity of fish caught and the price received for the catch from the chosen location. For a recreational or subsistence harvester, a non-market valuation or other utility measure (e.g. site quality) could be substituted for cash revenue. Perfect information about the quality and quantity of fish that will be encountered is never available, so it is assumed that the harvester makes a choice based on an expectation,  $E(\cdot)$ , of revenues and the cost that will be incurred by choosing to fish in location  $j$ . The harvester must incur the cost per kilometre ( $c_j$ ) of travelling to the chosen location, which is distance  $Dist_j$  from port or from his/her previous fishing location. Travel costs vary depending on the type of fishery and location chosen and could include factors such as fuel, the time cost of travel, or safety. The harvester’s expected profit,  $E(\pi_{jt})$ , from fishing in location  $j$  at period  $t$  is

$$E(\pi_{jt}) = E(Q_{jt}) \times E(price_{jt}) - c_{jt}Dist_{jt}, \quad (1)$$

where  $E(\cdot)$  is the expectations operator,  $Q_{jt}$  the quantity of catch in area  $j$  in time  $t$ , and  $price_{jt}$  the unit value of fish caught in area  $j$  in time  $t$ .  $Q_{jt}$  is a function of cpue and the amount of effort applied. The harvester maximizes the profit in each period  $t$  by choosing among the  $J$  location alternatives. A harvester will choose location  $j$  in time  $t$  if the expected profit from that area at that time (expected revenues minus travel costs) is greater than that from

all other alternatives. This can be rewritten as the probability that the harvester chooses alternative  $j$ :

$$P_{jt} = Pr(E(\pi_{jt}) > E(\pi_{kt})) \quad \forall j \neq k. \quad (2)$$

A harvester is less likely to travel to a more distant location because a greater travel cost would be incurred, holding other factors equal. However, an increase in  $E(Q_{jt})$  and/or  $E(price_{jt})$  would increase the probability of travelling to location  $j$  to fish, all other things being equal.

The harvester’s optimization problem is often subject to a variety of constraints defined by the management system in place for the fishery. For example, a harvester’s decision-making process is different in a rationalized fishery (a fishery with individual allocations of quota) vs. a non-rationalized fishery (no individual allocation of quota, although often entry into the fishery is limited and there is a TAC). Catch shares, fisheries cooperatives, individual fishing quotas, and individual tradable quotas are examples of rationalized fishery management systems. Rationalized management alters the harvester’s decision-making process into one of choosing areas in which to fish in each period so as to maximize the profit over the entire time available, such as a season, subject to an individual quota constraint ( $TAC_i$ ). That is, a harvester chooses a location to fish in each period  $t = 1, \dots, T$ , where  $T$  is the end of the season, so as to maximize the total profit over the season, subject to the constraint that the total quantity of fish caught must be equal to the vessel’s (denoted  $i$ ) share of the TAC, or  $\sum_t^T Q_{it} \leq TAC_i$ .

The constraints provided by the management system are important because they may lead harvesters to place differing value on prices, catch rates, travel costs, or on other factors that are not included in the model presented here. For example, in a non-rationalized fishery, harvesters place more value on quantity,  $E(Q_j)$ , than value,  $E(price_j)$ , than they would if (or when) the fishery were rationalized. This is because in a non-rationalized fishery, there is an incentive to “race” for fish, i.e. to catch the quota before others do and the fishery is closed (Levhari and Mirman, 1980). The profit-maximizing result is often the targeting of the highest catch rates. In a rationalized system, however, the individual allocation of quota allows vessels to consider the additional profit that may be gained by making trade-offs between fishing in areas with higher value, less abundant fish and areas with lower value, more abundant fish, because fish not caught now can be caught later in the season. Additionally, in a rationalized fishery, changes in the constraints (such as TAC) or alternative fishing opportunities may affect the harvester’s decisions about location choice or the timing of fishing. For example, an increase in TAC, holding other factors equal, may increase the relative importance of  $E(Q_j)$  to  $E(price_j)$  and travel costs. As the TAC increases, a harvester will be more constrained by the number of periods in the season because he or she needs to catch more fish in the same amount of time; sacrificing higher quality fish for volume may lead to greater profit. If harvesters can participate in other fisheries, it may be optimal to fish in the alternative fishery during its peak, then return to the rationalized fishery.

Expected cpue, expected prices, and travel costs are the main variable components in a harvester’s decision-making process, whereas TAC, management systems, and other factors constrain fishing. These variables can be affected by factors that are not impacted by climate variation, such as demand for the processed products, fuel prices, and politics; these are shown as external

factors in Figure 1. Demand for the products being produced from the catch affects the prices harvesters expect to receive and depends on economic and market conditions. Fuel prices affect costs. Other costs, such as crew salaries, the cost of maintenance, or the price of leased quota, could affect the profitability of fishing and alter the level of effort. For recreational and subsistence harvest, factors such as non-fishing employment opportunities, non-fishing recreational activities, or the price of alternative food sources could have a similar effect. Politics can affect the development and evolution of the management and system of regulation and may play a role in the determination of TAC, fishing days, closures, or other constraints.

When attempting to identify the effects of climate factors using retrospective data, it is important to consider how these other factors (those not directly related to climate variation) may have affected what happened. It is also important to consider future variation when making predictions. For example, a major increase in fuel prices could cause a change in the spatial distribution of fishing effort by making travel more expensive. If the fuel price increase happened to be correlated with a change in climate conditions, the change in effort could be incorrectly attributed to climate. In addition, species targeting in a multispecies fishery is affected by the value of each species caught. For example, in a fishery where two abalone stocks occur in the same area near Japan, harvesters selectively target the more-valuable species at the opening of the season. As the cpue of that species declines through fishing, harvesters begin to target the other species (Matsumiya and Matsuishi, 1989). An assumption of simultaneous exploitation could lead to erroneous conclusions about the dynamics of the fleet, which, if related to climate in some way, could result in erroneous climate-related projections. Similarly, using retrospective data from before a significant management change to predict a distribution of effort after the management change could be seriously misleading, because constraints and trade-offs of harvesters' decisions are likely to have been affected by the management change (Homans and Wilen, 2005). Incorporating a model of harvesters' decisions is an important step in testing the statistical relationship between climate change and observed variation in a fishery.

### Environmental characteristics of an ecosystem affect biological characteristics

Climate-related changes in the environment such as increases in temperature, decreases in snow and ice-extent, and changes in hydrological systems have been observed to the greatest degree in northern latitudes (IPCC, 2007). Global climate models predict continued changes in the long-term means and variability of atmospheric conditions and the environmental characteristics they affect. For example, changes in the Arctic Oscillation and weaker northerly winds over the Pacific Arctic have caused decreases in seasonal sea-ice cover and warmer ocean temperatures (Thompson and Wallace, 1998; Overland and Wang, 2005, 2007). These changes are projected to continue, affecting many environmental characteristics of marine ecosystems that, in turn, affect biological processes (Overpeck *et al.*, 1997; Marshall *et al.*, 2001; Attrill and Power, 2002; Hunt *et al.*, 2002; Beaugrand, 2004; Grebmeier *et al.*, 2006).

In general, the environmental characteristics of an ecosystem interact in complex ways to affect the biological characteristics of the target species of the fishery. Evaluating the precise mechanisms of these interactions is well beyond the scope of this paper, but

Figure 1 illustrates them on the most basic level. For extreme latitudes, winds and atmospheric conditions create an environment characterized by a distribution of ice cover, and air and water temperatures that vary at many scales.

The distribution of water temperatures is an important determinant of marine species' locations; many species have "climate envelopes"—bands of temperature that they prefer as a result of physiological factors and the location of important food sources (Box, 1981; Guisan and Zimmermann, 2000; Parmesan and Yohe, 2003). Changes in the distribution of temperature bands may result in changes in the distribution of species. Many studies of the effect of climate change on species' ranges rely on this climate envelope approach. For example, Richardson and Schoeman (2004) find that sea-surface warming in the Northeast Atlantic is associated with changes in phytoplankton abundance that propagates up the foodweb. Atkinson *et al.* (2004) find that sea-ice algae are an important food source for Antarctic krill, and their recruitment and survival are positively correlated with the extent of winter sea ice. Larger species such as penguins, albatrosses, seals, and whales depend on Antarctic krill. Antarctic salps occupy the warmer and lower productivity regions of the Southern Ocean, and increases in their abundance are related to decreases in winter sea ice. Perry *et al.* (2005) find that the distributions of many North Sea fish have shifted north in response to increases in sea temperatures.

Other climate factors may also affect characteristics of target species that are important to the fishery (Walther *et al.*, 2002); for example, temperatures may affect the phenology of marine species (Beaugrand *et al.*, 2003; Edwards and Richardson, 2004; Yoneda and Wright, 2005; Bellier *et al.*, 2007), as well as food availability and the probability of overwinter survival (Beaugrand *et al.*, 2003; Hunt *et al.*, 2011; Mueter *et al.*, 2011). Many other species and ecosystem-specific examples are possible (several are reviewed in Brander, 2010).

Whereas the environmental characteristics of an ecosystem affect the harvester's decision-making process through biological and ecosystem effects on the target species, Figure 1 shows how some environmental variables, such as ice cover, for example, can directly affect the harvester's decision-making process. Variables such as ice cover or the frequency of storms can affect harvester costs. These factors may make travel to some areas difficult or impossible, and climate-related changes in weather or ice conditions can open or close areas to fishing seasonally.

### Biological characteristics of a species affect the fishery

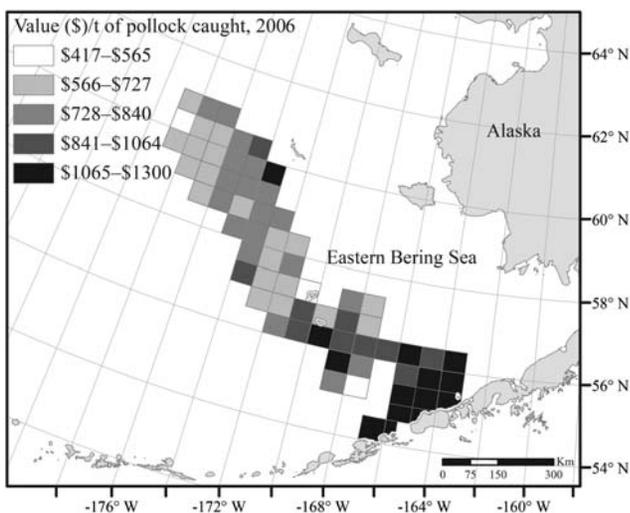
Figure 1 illustrates several mechanisms by which the environmental characteristics of an ecosystem are likely to affect the biological characteristics of the target species, and how those biological characteristics are likely to affect the factors that matter to fish harvesters.

Non-contemporaneous factors such as recruitment, survival, or the effect of fishing on the spatial distribution of the target species in subsequent years (those represented by dotted lines connecting the elements) are likely to be more difficult to identify in empirical data. For example, the survival rate of juvenile fish affects the total biomass, but will not affect the fishable biomass until they have recruited into the fishery, which can be many years later. Ocean temperature and current patterns can affect the degree of spatial overlap between juvenile and adult Alaska pollock; adults may cannibalize young pollock, resulting in a contemporaneous benefit for adult pollock, but a lagged cost on future biomass

(Wespestad *et al.*, 2000). These effects can be extremely difficult to identify, especially with spatially and temporally limited biological data, because of multiple and overlapping lags. As our focus here is on providing a framework to recognize the relationships that may characterize how climate change may affect fisheries, not the details involved in identifying these relationships, we focus the discussion on contemporaneous factors, although non-contemporaneous factors are also likely to impact the fishery.

Figure 1 portrays a number of contemporaneous biological factors that have the potential to affect the fishery. The spatial distribution of the target species affects harvesters' expectation of the quantity of fish they are likely to catch,  $E(Q)$ , in each potential fishing location. Additionally, the spatial distribution of the population can affect the expected value of the catch,  $E(\text{price})$ , if it varies by fish size, age class, and other factors that affect the quality of the fish and the value of the harvest, or if it affects the uniformity of fish size or species composition in schools, which may increase the efficiency of harvest or post-harvest processing.

Figure 2 provides an example. It shows the average processed value of 1 t of Alaska pollock catch from the eastern Bering Sea catcher-processor fleet in 2006 by  $0.5^\circ \times 1^\circ$  grid. Clearly, the average value of pollock caught in the southern regions of the fishing grounds is significantly higher than the average value in the north. This is because in winter, high-value roe is removed from prespawning female pollock, processed, and sold to Asian markets. The rest of the fish is processed into fillets and other products, so the harvest of roe represents a 50–200% bonus on regular fish prices. Spawning is concentrated in the southern region of the fishery, causing the spatial value differences shown in Figure 2. However, roe-harvesting is done almost exclusively in winter, so this spatial price premium is absent in summer. Ignoring the spatial and temporal differences in the value of pollock and focusing only on cpue as an indication of how the fishery will change would lead to serious inaccuracies in the prediction of the distribution of fishing effort.



**Figure 2.** Estimated average value of processed product per tonne of pollock caught by the catcher processor sector of the eastern Bering Sea pollock fishery, by  $0.5^\circ \times 1^\circ$  grid, for the 2006 fishing year (as an example). Grids with three or fewer vessels fishing in them are censored for confidentiality. Data are from the National Marine Fisheries Service Observer Program Database.

The total abundance of the target species also affects many characteristics of the fish harvester's economic trade-offs. Abundance affects travel costs because when total fishable biomass is larger, less time and travel are expended on the search for acceptable quantities of fish. In other words, the travel distance between fishing hauls is likely to be smaller. Abundance affects the TAC constraint because the estimated abundance is used to set the annual TAC. Abundance also affects expectations about the quantity of catch and cpue. Although generally increased abundance is expected to increase the expected catch, it may not increase uniformly, which is why there is a link in Figure 1 from abundance back to the spatial distribution of the target species. For example, if increases in abundance result in an expansion of a species' range, then the resulting increase in cpue may be greater on the expansionary edges of the range than in the areas where the species is always present (Holt *et al.*, 1997).

Vessel size, horsepower, the ability to process fish on board, or harvester preferences may lead to different harvesters making different decisions under changing conditions. For example, Loomis and Ditton (1987) find that recreational anglers who fish in tournaments have very different preferences from those who fish for sport. Tournament anglers prefer trips where they catch larger fish, whereas sport fishers prefer to catch a greater number of fish. Differentiating these two types of recreational fishers would be important in predicting changes in effort resulting from, for example, climate-induced changes in growth rates or biomass.

## Discussion and conclusions

This paper has presented a general conceptual framework for the study of the effects of climate change on fishing and argued why it is essential to include economics in this framework. The framework applies to all types of fishing: commercial, subsistence, or recreational. Disregarding the economic behaviour of fish harvesters can lead to serious mistakes in retrospective analyses or when making predictions about the effects of climate change on the ecosystem and the spatial distribution of fisheries, just as ignoring any important interaction could make the resulting predictions unreliable, incorrect, or irrelevant (Davis *et al.*, 1998). For example, a simple error is to assume that one size fits all, merely focusing on abundance and ignoring how harvesters may target certain sizes or species of fish with different values, as illustrated by the examples in the previous section.

The conceptual framework of Figure 1 illustrates that the effect of a change in a climate variable on the distribution of fishing occurs through many physical, biological, and economic mechanisms. For example, a decrease in winter ice cover in a polar region may be expected to decrease the cost of fishing (harvesters have the opportunity to fish in previously ice-covered waters), increasing the expected profit in areas affected by the change, and potentially changing the spatial distribution of fishing effort. However, ice cover may also affect recruitment, which will affect the total abundance in future years. Total abundance affects the TAC constraint, the cost of fishing, and expected cpue. The extent of winter ice cover may also affect the distribution of water temperature, affecting the spatial distribution of a harvester's target species, which can affect expected cpue in different locations and various components of expected value. By following the links in the diagram, it is clear that each variable affects many other variables in the system, and ultimately has the potential to affect the distribution of fishing in many ways.

It is essential that the researcher examines the details of the environment that are unique to individual fisheries, including the characteristics of the ocean dynamics, region, species, harvesting fleet, and management structure to determine which of these mechanisms are likely to have the most important effects. The researcher must also carefully consider mechanisms that may occur simultaneously and may have compounding or negating effects. A decrease in winter ice cover is likely to be simultaneous with an increase in winter water temperature, for example. Although their main effects may be different (ice cover directly affects costs, whereas winter temperatures directly affect the maturation rate of roe and therefore the expected value), their effects on the spatial distribution of effort will be confounded. For example, are the pollock harvesters depicted in Figure 2 travelling to newly opened areas to fish because they can (less ice) or because they expect to find high-value roe-bearing fish (higher expected price)? Alternatively, consider a change in the distribution of fish biomass resulting in more fish being located farther from a main port that happened simultaneously with an increase in fuel prices. This may result in no change in the distribution of effort, although holding either variable constant, a change in the distribution of effort would have been predicted. The researcher must consider carefully how to separate these effects in empirical data and must be extremely cautious in drawing conclusions from short time-series where there is little information available for understanding the causal mechanisms. Therefore, establishing correlations between fish populations and climate variables while omitting economic factors can generate completely erroneous explanations of causal relationships.

Even in fisheries and ecological systems with a relatively large amount of observational data, separately identifying the effects of various climate factors can be challenging. Environmental conditions that are determined to be important drivers, and are expected to change, increase the data demands required to identify separate effects. For example, in the eastern Bering Sea Alaska pollock fishery, both the spatial distributions of the stock and the total biomass are expected to change as a result of climate change (Wyllie-Echeverria and Wooster, 1998; Mueter *et al.*, 2011). However, since 1990, all years characterized by warm ocean conditions in the eastern Bering Sea have also had a relatively high total pollock biomass due to large lagged recruitment events. Cold years have been observed with both high and low abundances (Ianelli *et al.*, 2011a). Therefore, there have been no recent observations of warm, low abundance years in the Bering Sea with which to empirically identify fishery behaviour under conditions that we are most concerned about predicting. Predictions under warm, low-abundance conditions would be “out of sample” and are subject to significantly greater uncertainty.

The researcher must also recognize that there are likely to be uncertain, ignored, inestimable, or unknown elements in the ecosystem and that these may influence findings and predictions about the impact of climate change on fisheries. Long-term projections are often desired because they will potentially allow for better management adaptation to a changing climate. However, long-term projections require strong assumptions about the degree to which these other factors are held constant.

Finally, the degree to which the scientific community has information about the magnitude, certainty, or even the sign of each mechanistic link in Figure 1 varies widely. It has been noted that human behaviour is a key source of uncertainty in fisheries management (Fulton *et al.*, 2011). Figure 1 illustrates part of the

reason. Human participants in fisheries respond to a variety of economic incentives, but each incentive is affected by ecological mechanisms that are not completely understood. In each mechanism represented in Figure 1, there are varying degrees of uncertainty. When an economic model of fish harvester behaviour is added to other uncertain models or predictions, the resulting uncertainty is potentially compounded. Models to forecast fuel prices, consumer demand for the fish, or labour costs, for example, may be relevant. These would add multiple additional dimensions to the modelling process and, rather than narrowing the possible outcomes or the surrounding uncertainty, expand them. This is still preferable to ignoring or only superficially considering the effects of human behaviour. When a large number of factors affect behaviour with a large degree of uncertainty (which characterizes much of the research on climate effects on marine ecosystems), expecting a precise prediction of the effect of a particular climate factor, or climate change as a whole, on aggregate fishing effort can be unrealistic. In fact, recognizing when there is too much uncertainty surrounding the mechanisms or drivers of the system to generate reliable predictions and characterizing the causes of that uncertainty are extremely valuable contributions to the state of knowledge. They can serve to direct research towards the areas of uncertainty, spur data collection and analysis efforts, clue managers in to possible unintended effects of policy, and generate entirely new topics of research. More modelling that includes environmental, biological, and economic elements across a range of fisheries and ecosystems will help improve our understanding of how climate change can impact fisheries.

Beyond the role that this conceptual framework has in helping researchers understand the effects of climate change on fisheries, an important contribution of this study is in providing fisheries managers with additional insight about the implications of climate change for management. Management can be designed to be resilient to changing ecosystems, as well as impart upon harvesters the flexibility to adapt to changing conditions. A careful examination of how economic, biological, and environmental characteristics of fisheries interact with management institutions under a changing climate is an important topic for further research.

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