Ocean Warming Induced Migration of Atlantic Herring and Mackerel with Corresponding Solutions for the Scottish Fishing Industry

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Contents

1 Abstract

The Scottish fishing industry depends heavily on Atlantic Herring and Mackerel, species which have been shifting their migration patterns in recent years in correlation with global ocean surface temperature increases. We predict the movement of optimal fishing areas for Atlantic Herring and Mackerel over time and suggest strategies for Scottish fisheries based on our predictions. Our prediction uses both linear and quadratic regression models based on historical surface temperature data as well as geospatial graphical representation to model the affect of temperature changes on fishing yields.

2 Summary

The fishing industry is a major economic asset for the country, and Atlantic Herring and Mackerel consist of a considerable proportion of the market. However, since 1970, Herring and Mackerel have been steadily moving to the North and East to colder, more oxygen-rich waters, and landings have been steadily decreasing in accordance with temperature increases. This affects the livelihoods of many Scottish fishermen and fishing villages that depend largely on this single source of income. Here, we model the migration of Herring and Mackerel to predict the best locations for fishing, and suggest how small fishing businesses can adjust their operations effectively in accordance with warming induced migration.

We use linear regression to find the annual rate of ocean surface temperature increase specific to the sea-areas surrounding the British Isles, which we suspect may be different than the global temperature increase. This regression is based on historical ocean surface temperature recordings in the Scottish seas. We then use spatial ocean surface temperature data which records the temperature at each tenth of a degree of Latitude and Longitude. We use the rate of temperature increase from our regression to project this spatial temperature data out linearly 50 years. We compare this with another spatial data that records occurrence probabilities for Herring and Mackerel, and find a suitable quadratic model to represent the relationship between temperature and occurrence probability. Finally, based on this model, we use our linearly predicted temperatures to predict the occurrence probability for Herring and Mackerel over the next 50 years.

3 Introduction

Fishing industry relies on a variety of ocean-dwelling species. Any climate variability or anthropogenic change can affect the integrity of marine ecosystem resources and the fisheries. With the impact of climate change, the oceans warm up far more quickly than people previously expected; they absorb about 93 % of the heat caused by greenhouse gas emissions [1]. As a result, increasing global ocean temperatures cause certain ocean-dwelling species to migrate to more suitable habitats. The lobster population of Maine, USA, for instance, is slowly migrating north to Canada where the temperature is lower and more appropriate for the lobsters to live. Such migration, however, can seriously affect fisheries around the world and bring significant impact to the livelihood of businesses. As the population of certain species decreases in one specific sea area, fishermen may no longer be able to capture and sell fresh fish in the market as they used to. Increasing travel times and growing fuel costs would higher market prices for migrating species; fish crossing political boundaries would lead to potential trade war among countries as fishery plays a critical role in the economy of regions such as Scotland and Japan. Therefore, identifying fishery management strategies regarding potential issues caused by ocean warming are essential for fishing companies, especially the small ones with relatively scarce financial resources.

In this paper, we mainly focus on two types of pelagic species, Scottish herring (Clupea harengus) and mackerel (Scomber scombrus). Through modeling and predictive analysis, we explore the impact of their migration on small Scotland-based fishing companies who use fishing vessels without on-board refrigeration. Researchers in the past have shown the environment as the most significant factor in determining the migration route since pelagic species migrate throughout the year by seasons for feeding and spawning grounds [2] [3] [4]. In addition, each species prefers different water temperatures for habitat, and rising ocean temperature led to severe declines in boreal stenothermal species such as herring while eurythermal species including mackerel were not affected [5]. Thus, water temperature change is the main factor that causes fish populations to move.

Using the surface ocean temperature data and probability occurrence of (Clupea harengus) and mackerel (Scomber scombrus), we applied regression models and statistical method of square fit to predict the migration patterns and the most likely locations for both species over the next 50 years. To help fishermen have a better understanding of the challenges they will face due to fish migration, we thereby conducted further analysis along with practical suggestions for Scotland-based small fishing companies. Based on three different annual rates of ocean temperature increase, we analyzed the best case, worst case, and most likely elapsed time until all these populations will be too far away for small fishing companies to harvest if they continue to operate out of their current locations. Our results suggest that herring will migrate out of the Scottish Sea areas while mackerel will not have significant migraion.

In light of our model and predictive analysis, we propose the following three strategies to minimize economic and political risks in daily operations while maintaining regular business profits:

- Improve technology and fishing methods
- Switch the focus on the herring instead of mackerel, and introduce some warm water marine species
- Partner with other countries and stakeholders

As a result, our model is applicable to fishing companies around the world by inputting new data sets of ocean temperatures and probability occurrence. The strategic proposals provide insightful analysis for not only Scotland-based small fishing businesses but also the Scottish fisheries management as a whole. In addition, our results further emphasize the significant impact of temperature change and the importance of sustainable strategies fisheries management.

4 Methods and Model

4.1 Data

4.1.1 Surface temperature and environmental conditions

Herring is a north Atlantic boreal species and prefer lower optimum temperature of 4.6 $°C$, while mackere is a eurythermal species and prefer higher optimum temperature of around 12 $°C$ [5]. According to the biological definition of Atlantic herring (Clupea harengus) and mackerel (Scomber scombrus), they both dwell in the surface water [7]. Therefore, in order to predict their migration patterns overtime, we need time series datasets that include both surface temperature and spatial information in terms of latitude and longitude near Scotland.

Since temperature change is the main factor that causes migration, we utilized monthly averaged sea surface temperatures in 13 Scottish Sea Areas and annual spatial surface sea temperatures in the North-West European Continental Shelf. The former one includes 2,652 observations of temperature data for 13 Scottish Sea Areas from 1997 to 2013. The dataset combined temperatures from OISST [1], 1° (latitude and longitude) gridded dataset to make a single spatially averaged time series of monthly data for each of 13 Scottish Sea Areas (Bresnan et al, 2016). The latter dataset provides totally 10,056 observations of annual mean surface temperatures in the North-West European Continental Shelf from 1971 to 2000 as shown in Figure 3 [10].

[1] OISST represents Optimum Interpolation Sea Surface Temperature. See www.ncdc.noaa.gov/oisst for more information.

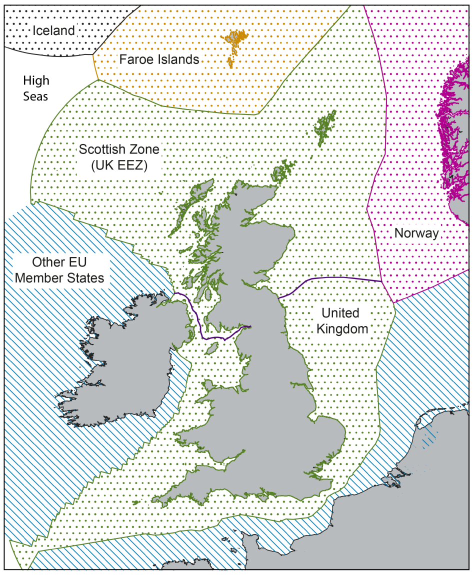

Figure 1: *Overview of territorial waters set by the EU fisheries law provided by the Scottish Parliament [8]. In addition to the UK, countries that have sea territories near Scotland are Iceland, Faroe Islands, Norway and Ireland.*

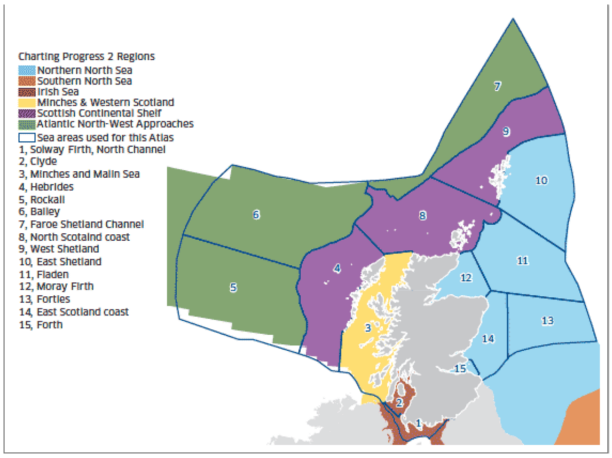

Figure 2: *Map of 15 Scottish Sea Areas, 13 of which have corresponding data in the monthly averaged sea surface temperature dataset [9]. Note that no data were available in Solway (region 1 in the figure) and Forth Sea Areas (region 15 in the figure) because of their small size and coastal nature.*

4.1.2 Population distribution

To simulate the population migration over time, we utilized the probability occurrence data for both herring (Clupea harengus) and mackerel (Scomber scombrus) in addition to the two datasets discussed above [11]. Previous researchers have used Continuous Plankton Recorder (CPR) survey to obtain spatial distribution of the larvae, and thus model mackerel's seasonal migration for spawning activities throughout the year [12]; other research has demonstrated the correlation between temperature and mackerel distribution by using mackerel catch data from both bot-

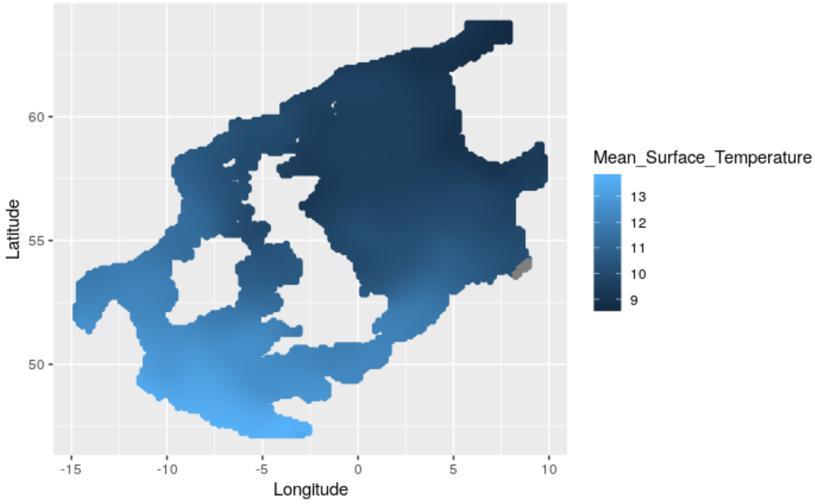

Figure 3: *Annual mean surface temperatures (in Celsius) in the North-West European Continental Shelf with a resolution of* $\frac{1}{6}$ *longitude by* $\frac{1}{10}$ *Latitude from 1971 to 2000. The original data were extracted from the International Council for the Exploration of the Sea (ICES) data centre and supplemented by additional records from the World Ocean Data Centre (WODC) and the mean annual temperatures were calculated and published by Berx et al. (2009). The lighter the color is in the plot, the higher the annual mean surface temperature is in the corresponding region. The grey color means there is no available data in the region. Map plotted in RStudio.*

tom bowl trawl surveys and fisheries commercial data [13]. All these datasets are not applicable to our model because we want to have an overview of the long-term migration pattern over the next fifty years instead of seasonal routes within a year for both species. Therefore, we decided to utilize the probability occurrence data from Aquamaps [11] [14].

The dataset from AquaMaps includes the "relative probability of occurrence" of herring (Clupea harengus) and mackerel (Scomber scombrus) overtime based on information about species-specific habitat usage from published species databases such as FishBase [15] and SeaLifeBase [16]. With the estimates of the environmental fators such as depth, salinity, and temperature, AquaMaps modeled species distribution for 22,889 species by calculating the values of relative likelihood of presence at each individual 0.5° grid depending how well its environmental attributes match what is known about herring's (Clupea harengus) or mackerel's (Scomber scombrus) habitat usage [14].

4.2 Model

Our fundamental assumption is that ocean temperature will change enough that both Scottish herring (Clupea harengus) and mackerel (Scomber scombrus) will migrate at some point in the future. In other words, surface temperature is the main factor that causes their migration. In addition, we assume that the rate of

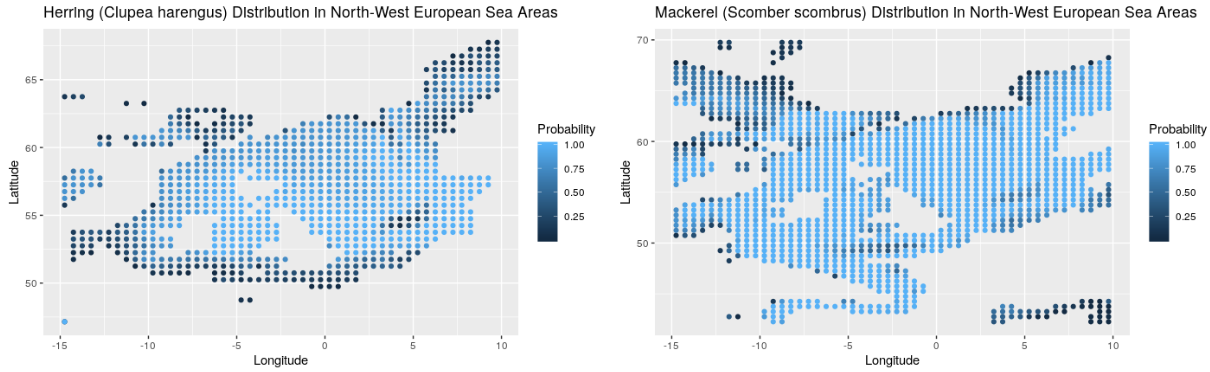

Figure 4: *Herring (Clupea harengus) and mackerel (Scomber scombrus) distribution based on probability occurrence data from AquaMaps [11]. These maps show the color-coded relative likelihood of Atlantic herring and mackerel to occur in a grid of 0.5 ° latitude / longitude cell dimensions in the North-West European sea areas. The lighter-blue areas represent more suitable habitat for herring (Clupea harengus) or mackerel (Scomber scombrus). Maps plotted in RStudio.*

temperature change is consistent throughout the next 50 years and the North-West European Continental Shelf, including the 13 Scottish sea areas.

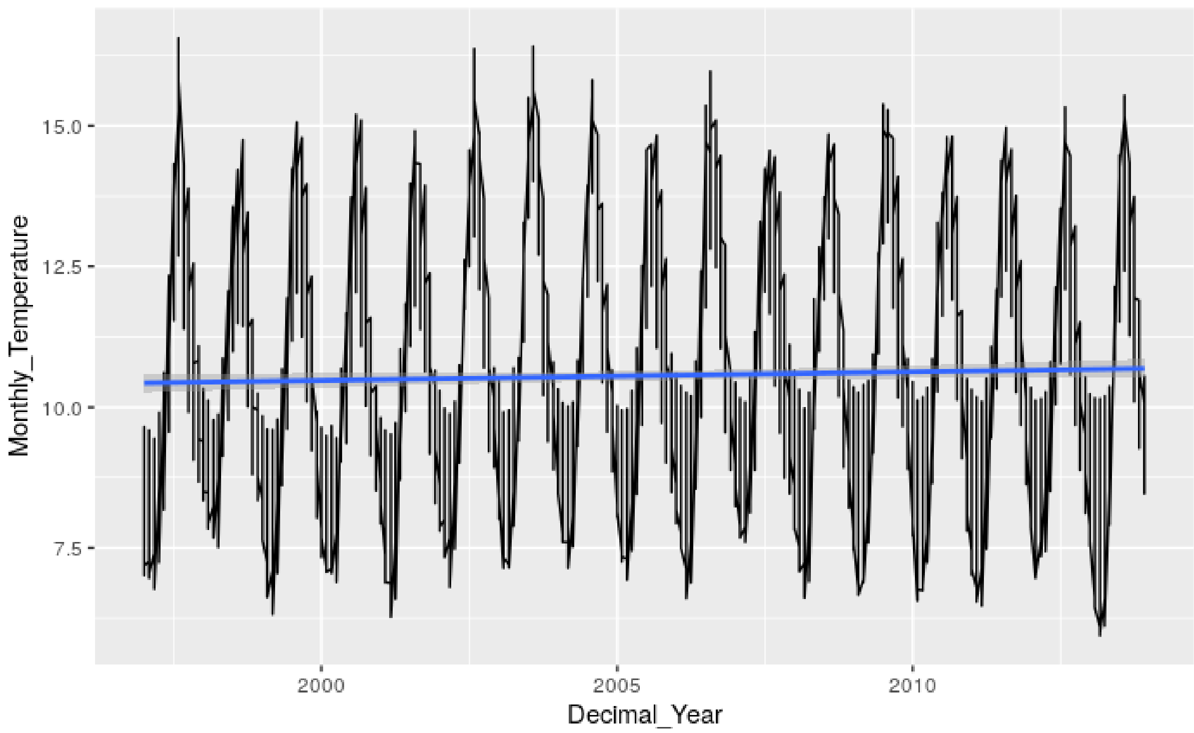

Figure 5: *Here we plot the monthly temperature data, with months on the x-axis and temperature on the y-axis in Celcius.*

To predict the migration pattern of both herring and mackerel, we first want to understand how surface temperatures change in the Scottish sea areas as well as other adjacent territorial waters over the next several decades. Using the linear

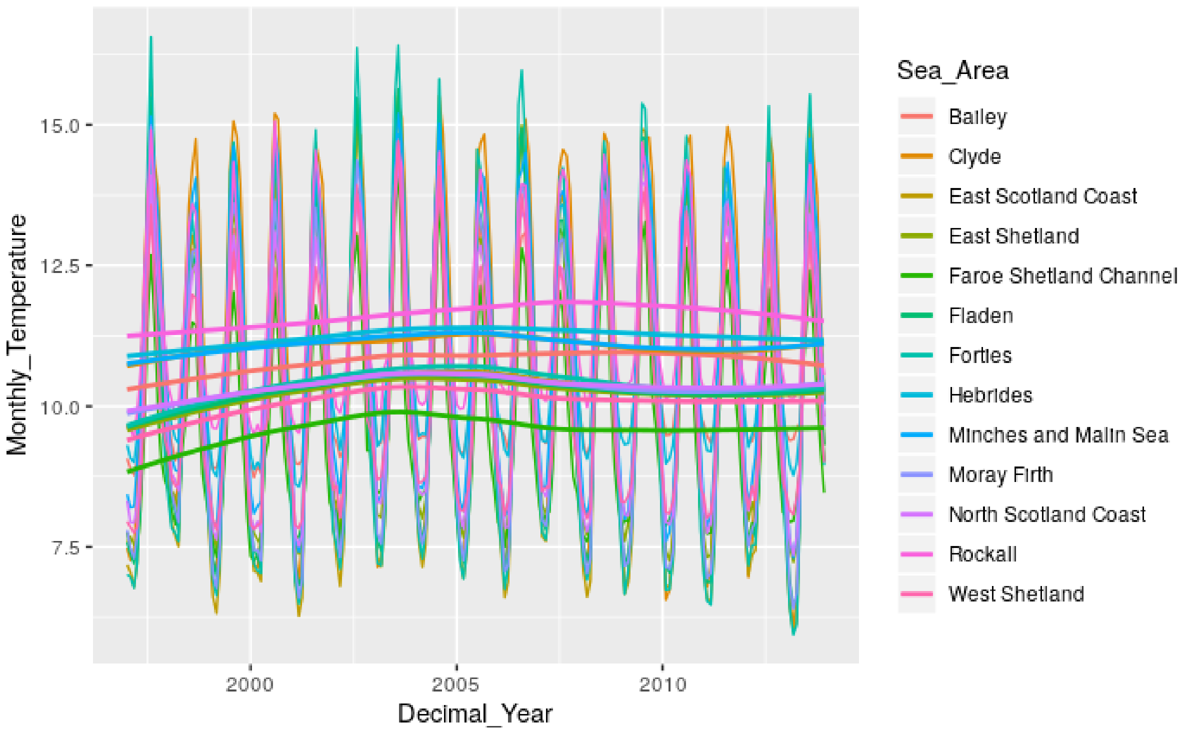

Figure 6: *Here we plot the month vs. temperature again, but sectioned into the 13 Scottish sea areas where the temperatures were measured. We see that although there is a vertical shift, the trends are relatively similar across areas, so we can assume a universal rate of temperature increase for the entirety of the Scottish seas.*

regression model and the historic data set of monthly mean ocean temperatures in the 13 Scottish sea areas, we obtained the monthly rate of temperature change from R and thus the annual rate of surface temperature change, $\alpha = 0.1816°C/year$. We then picked the mean annual temperature in 2014 from the dataset as our starting point and predicted the surface temperatures from 2020 to 2070 in Excel based on the equation below.

Define T = *Annual Mean Surface Temperature.*

T_0 *represents the mean annual temperature in 2014 and* T_1 *represents data for the next following year.*

$$T_1 = T_0 + \alpha \cdot (\textit{Year-2014})$$

Since the current dataset does not provide consistent spatial data with information about both surface temperature and population distribution, we first plotted the temperature data and probability occurrence data that we have ; we observed that there is a quadratic relationship between the annual mean surface temperature and the probability occurrence (see Figure 9 below.

We then combined both datasets by taking the intersection of them since the probability occurrence dataset includes data that covers bigger range of sea areas than the mean surface temperature dataset (See Figure 3 4). The newly constructed dataset ended up with a total of observations, and was more informative informative to predict the distribution of both species and determine suitable habitat for herring

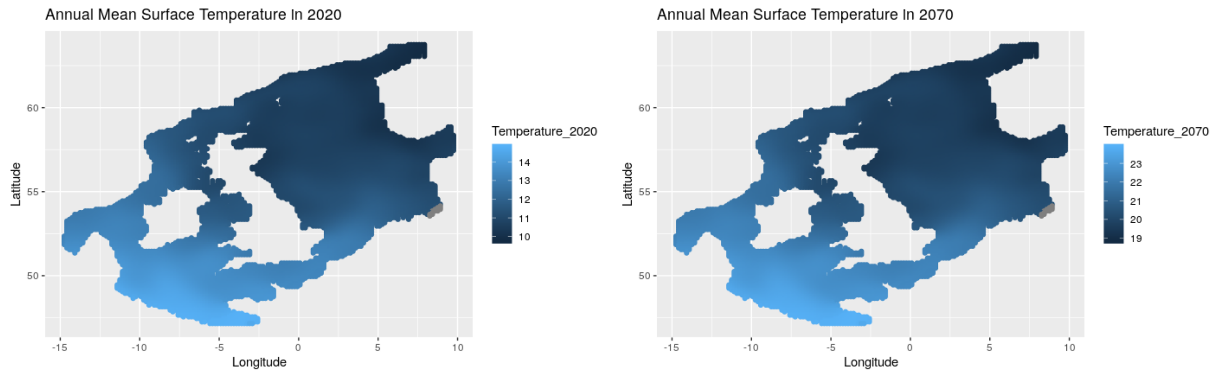

Figure 7: *Predicted mean surface temperatures in 2020 and 2070 in Celsius. Note that the color in both figures does not differ, but the scale of temperature changes significantly. The lowest mean surface temperature in 2020 is about 9.76 °C while the lowest mean surface temperature in 2070 is almost two times more than the one in 2020, that is, about 18.84 °C. Maps plotted in RStudio.*

Herring Probability Occurrence V.S. Mean Surface Temperature

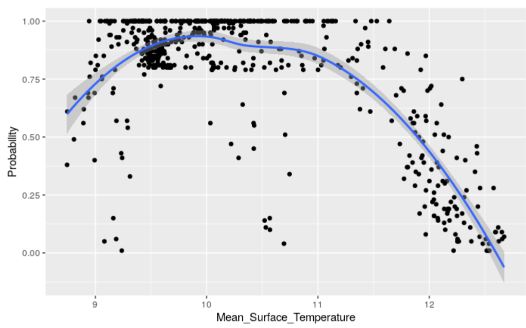

Figure 8: *Observation Plots for herring, which shows a quadratic relationship between its probability occurrence and annual mean surface temperature*

Mackerel Probability Occurrence V.S. Mean Surface Temperatrue

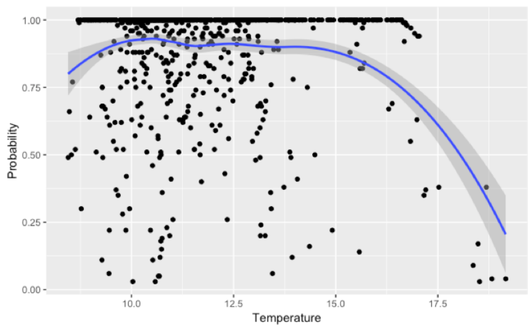

Figure 9: *Observation Plots for mackerel, which shows a quadraquadraticdic relationship between its probability occurrence and annual mean surface temperature*

and mackerel. Based on this dataset, we then built the following model in R to best fit all the observations and predict future migration patterns:

$$\textit{Future Probability Occurrence for Herring} = -14.18 + 2.98 \cdot T_{now} + (-0.15) \cdot T_{now}^2$$

$$\textit{Future Probability Occurrence for Mackerel} = -0.17 + 0.18 \cdot T_{now} + (-0.007) \cdot T_{now}^2$$

4.3 Results

4.3.1 Where do herring and mackerel end up over the next 50 years?

Herring (Clupea harengus):

Based on the quadratic model presented earlier and the probability occurrence data for herring, we predicted relative likelihood of herring's presence in the north-west European sea areas over the next 50 years. We generated the following maps in R, which showed us how herring's population move over time. From the maps in Figure 10, we can observe that the herring stocks will be mostly likely to leave Scottish sea areas and migrate abroad by 2030; they will completely move out of Scotland before 2040. Based on the pattern of population movement from 2020 to 2030, we conclude that herring (Clupea harengus) is most likely migrate to the territorial water in Norway.

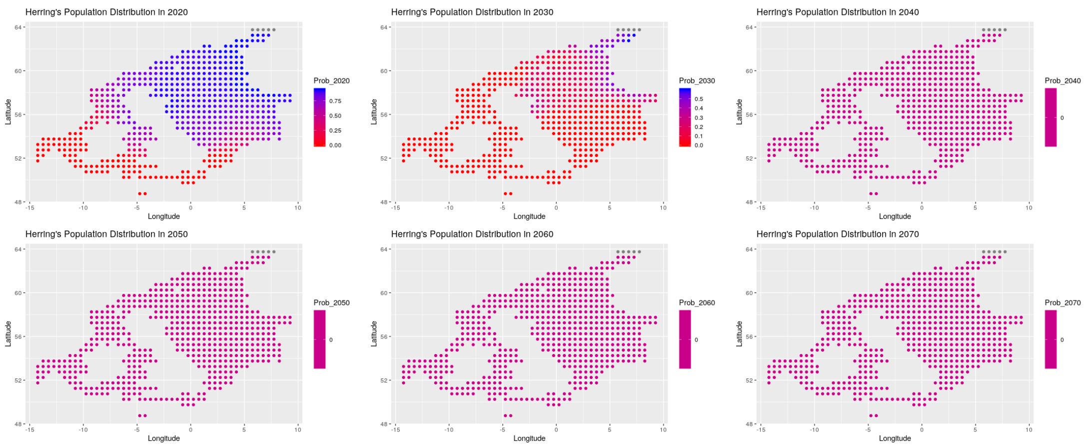

Figure 10: *Maps of herring (Clupea harengus) migration for each decade from 2020 to 2070. The darker dots in the map indicate a more suitable environment for most herring populations to dwell in and thus the locations they end up with throughout the year; the grey dots represent unavailable observations. Note that by 2040, the probability occurrence is 0 for all areas near Scotland.*

Mackerel (Scomber scombrus):

We went through similar steps as we did above to determine the most likely locations for Mackerel (Scomber scombrus)over the next 50 years. First, we used the quadratic model for mackerel to predict the probability occurrence data in the north-west European sea areas. We then generated the maps in R. Based on the migration patterns shown in Figure 11, we found that in contrast to the migration patterns of herring, mackerel does not completely leave the Scottish sea areas and gradually move in the direction of North-east. Thus, the most likely locations for mackerel in 2070 is the north-eastern Scottish sea areas as well as the sea areas that are adjacent to it in Norway.

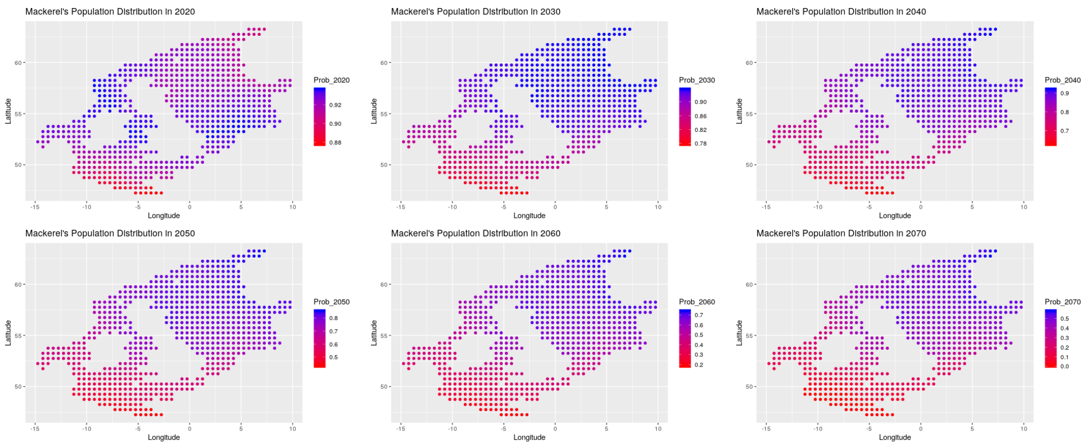

Figure 11: *Maps of mackerel (Scomber scombrus) migration for each decade from 2020 to 2070. They indicate how Mackerel (Scomber scombrus) migrate near Scotland over time. The darker dots in the map indicate a more suitable environment for most herring populations to dwell in and thus the locations they end up with throughout the year; the grey dots represent unavailable observations.*

4.3.2 Predictive analysis

We now discuss the elapsed times for each species until the populations will move too far away for small fishing companies to harvest if they continue to operate out of their current locations in three different scenarios. Based on the annual rate of surface temperature change and its 80 % confidence interval, (0.003774064, 0.02649963), we used the upper bound as the worst case and the lower bound as the best case since we assume that the temperature is the main factor that affects the migration of both herring and mackerel. To make our model most useful and informative for small fishing companies in Scotland, we identify three different cases of elapsed times for each species.

Herring (Clupea harengus):

1. Most-likely Case:

Using the annual rate of surface temperature change from our linear regression model, we predicted the mean surface temperature for each year over the next 50 years and and combining the data original model to determine the most likely elapsed time for herring. Since Figure 10) suggests that herring will move out of Scottish sea ares by 2040 , we specifically looked into the distribution of herring between 2020 and 2030 and plotted the maps shown in Figure 12 in R. We found that the probability occurrence of herring in the Scottish sea areas will be very low by around 2029.

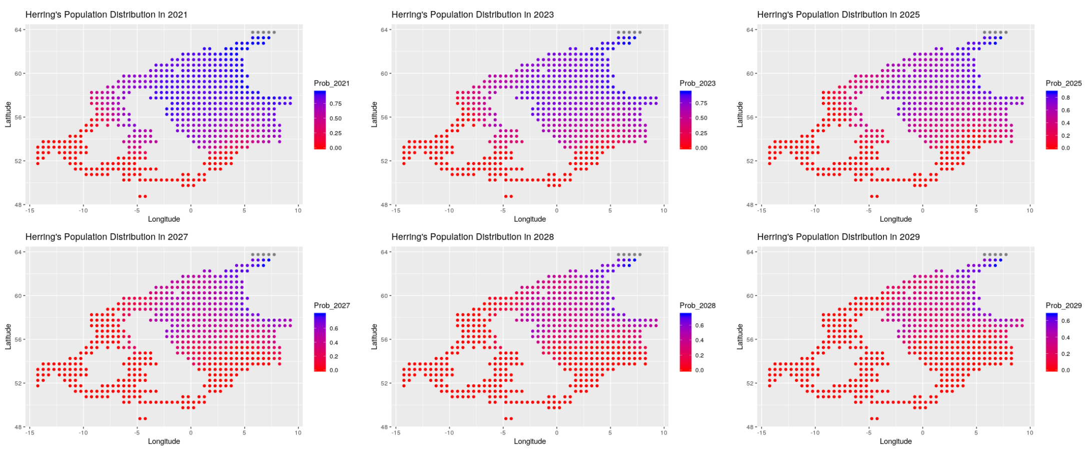

Figure 12: *Snapshots of Herring's (Clupea harengus): population distribution between 2020 to 2030. The darker dots in the map indicate a more suitable environment for most herring populations to dwell in and thus the locations they end up with throughout the year; the grey dots represent unavailable observations. Note that by 2029, the probability occurrence is 0 for all areas near Scotland.*

2. Best Case: herring's migration will mostly not affect small fishing companies. As the maps in 13 indicate, herring will move in the north-east direction but not far enough for the Scottish fishing companies to catch them.

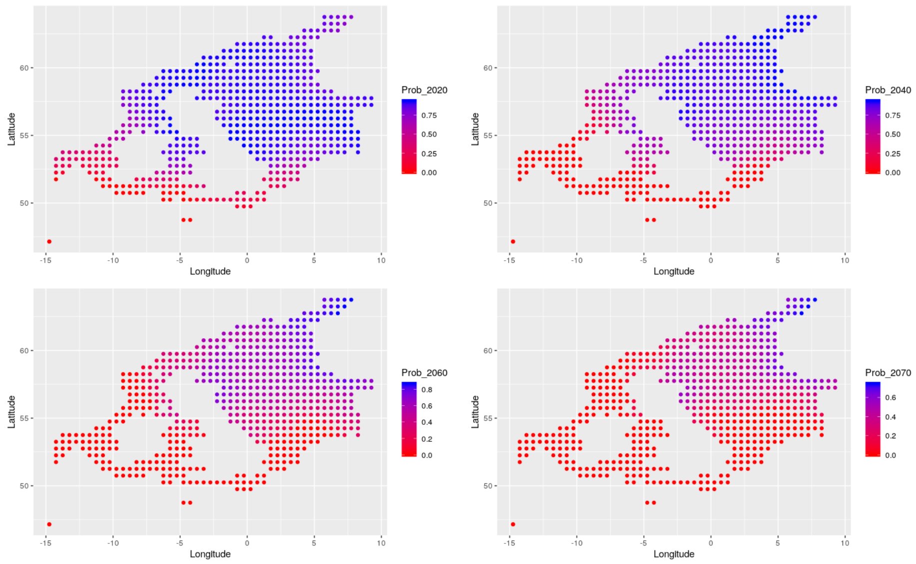

Figure 13: *Snapshots of Herring's (Clupea harengus): population distribution between 2020 to 2070. No significant impact to Scottish fishermen over the next 50 years.*

3. Worst Case: based on the 0.026 $°C$ increase per year, herring will mostly disappear from the Scottish sea ares by around 2027 if in fact, the temperature change is much faster than what the model predicted. The maps in Figure 14 show the overall migration pattern over the first next decade.

Mackerel (Scomber scombrus):

1. Most-likely Case: Based on the results generated by our model (see Figure 11), we found that the mackerel populations will not migrate far away to make the fishing companies have a hard time catching them. The main reason is that unlike herring, mackerel generally prefers higher water temperature. Thus, the increasing surface temperature as a result of climate change does not affect mackerel as much as it does to herring.

2. Best Case: Similar to the most-likely case discussed above, there is no significant change but a slight migration of the majority of mackerel stocks. For this to be said, fishing companies do not need to worry about mackerel's migration affecting their harvest. See Figure 15 below for the maps generated in R.

3. Worst Case:overtime, mackerel move from the south-west to the north-east in the north-west European sea areas. By around 2070, the probability occurrence values for mackerel in the Scottish sea areas are mostly below 0.5. Thus, fishing companies may need to spend extra time and cost on catching mackerel if the temperature increases faster than our prediction in the most-likely case.

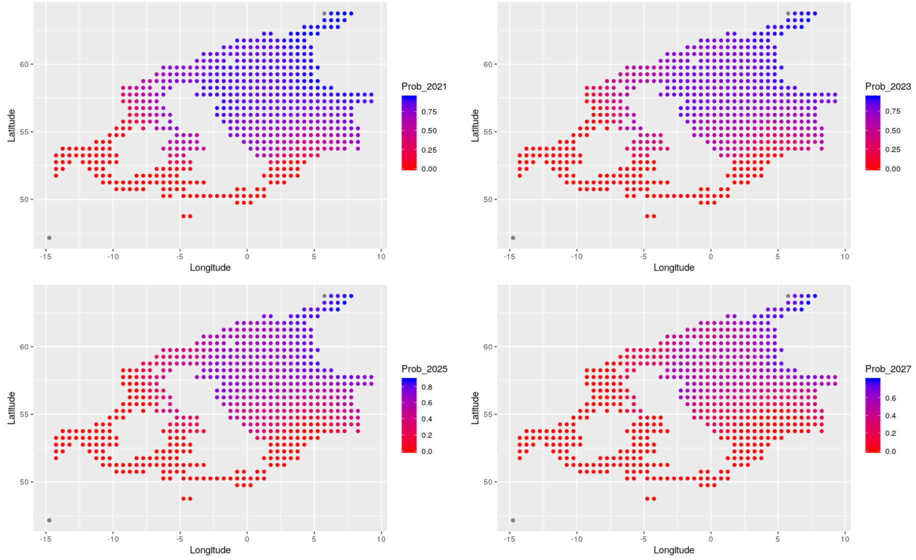

Figure 14: *Snapshots of Herring's (Clupea harengus): population distribution between 2020 to 2030. Note that by 2029, the probability occurrence is 0 in all the Scottish sea areas.*

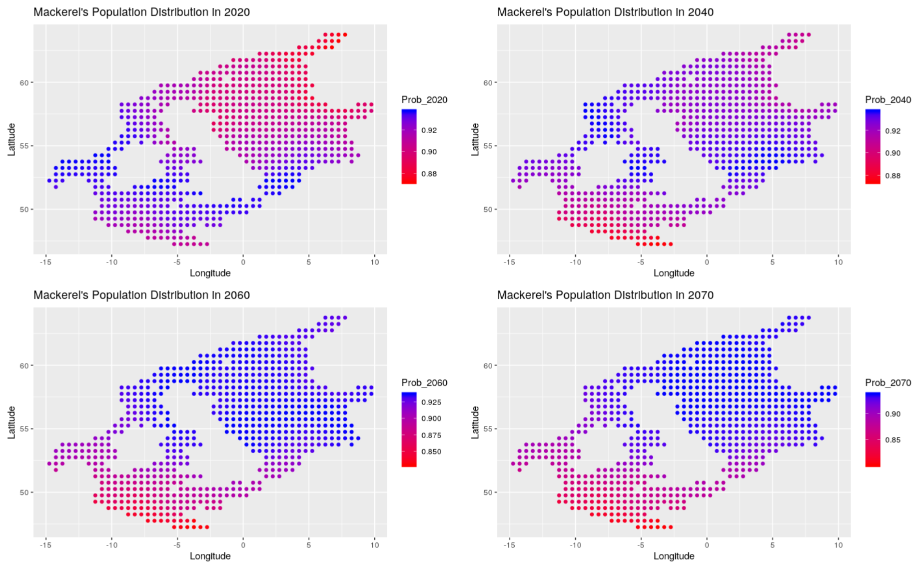

Figure 15: *Snapshots of Mackerel's (Scomber scombrus) population distribution between 2020 to 2070. The darker dots in the map indicate a more suitable environment for most herring populations to dwell in and thus the locations they end up with throughout the year; the grey dots represent unavailable observations. Note that the major populations move toward the north-east of the region*

5 Business Proposal

The Scottish fishery is an important economic component for the country, and fish stocks are an invaluable national asset. Since 1970, global ocean surface temperatures have increased by around 1 degree F [20]. The ocean is warmer today than

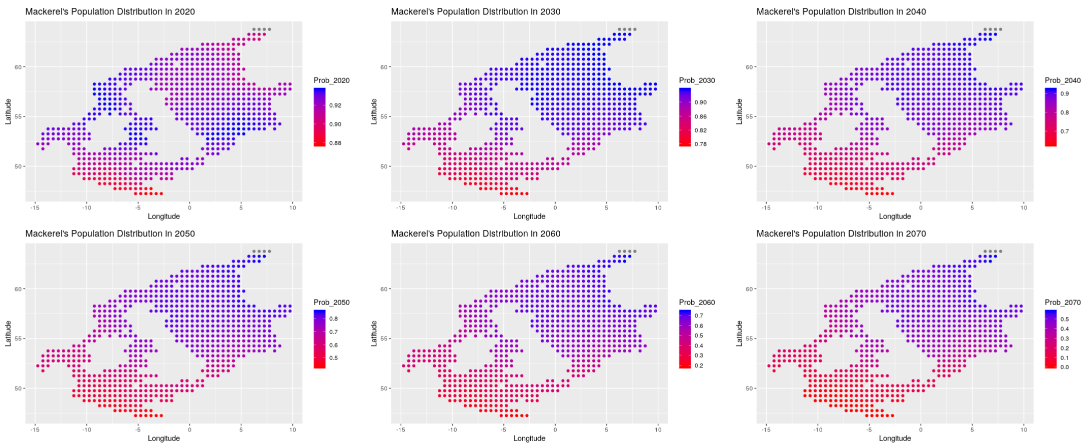

Figure 16: *Maps of mackerel (Scomber scombrus) migration for each decade from 2020 to 2070 in the worst case if the surface temperature increases faster than what our model predicted.*

at any time since record-keeping began in 1880. Steadily rising ocean temperatures are forcing fish to abandon their historic territories and move north to get more oxygen in cooler waters. Scottish fishermen's livelihoods are being disrupted, as fisheries regulators scramble to incorporate climate change into their planning. Our final goal of this paper is to address potential issues related to migration of Scottish herring and mackerel due to increasing sea temperatures as well as how small fishing businesses can adjust their operational strategies most effectively.

Mackerel remains the most valuable stock to the Scottish fleet, accounting for 29 percent (£163 million) of the total value of Scottish landings. In 2018, Scottish registered vessels landed 15 percent less mackerel by weight (153 thousand tonnes), in line with a fall in available quota. The value of mackerel landings only decreased by 1 percent in real terms compared to 2017, reflecting strong mackerel prices above £1,000 per tonne on average. One effective practice is that the Scotland government must, in partnership with stakeholders, develop a management system that supports this quota and can work in practice. Using ring-fencing[2]quota is a good way to help fishers to operate legally within such a system, as well as using it to reward and/or encourage best practice in innovative fishing techniques or methods[19].

Besides, many individuals, communities, and nations continue to rely on fish and other aquatic life as a source of food and raw materials. To maintain fish stocks, we need to reduce overfishing and bycatch through fisheries management. Managing fish populations is no easy task. It requires cooperation at all levels of government, from local communities to nations across the globe.

Fishing businesses, especially the small businesses, will be affected hugely by the change of fish migration. They are going to face the increasing international imports of fish, the higher oil price, and the expensive shipping and boarding fees. The decrease of export of herring and mackerel will also affect their business. Fully half of the catch was cured for exportation to the Continent, but considerable quantities were shipped in a lightly salted state to Stornoway, where most of them were gutted and cured, and exported to the Continent, under the name of Stornoway herrings. The herring were in considerable demand for fresh markets and also for curing. If the herring will migrate to other countries, the cured herring business line will be cut out which is a great loss for Scottish fishing business. The fishing grounds varied from 6 miles north to 20 and up to 50 mils in a north-east direction. The barrels cost will also change from 2s. 10d. (2 shillings and 10 pennies) to 3s. (3 shillings) each. And the cost of per barrel of from 18 to 20 fish in the barrel will increase from 40s. to 50s [21]. The increase price will significantly influence the small fishing businesses and might lead them go bankrupt. In this case, the small businesses might want to ask for help from government, banks, private equities, or high-tech companies in policy-making, bank loan, mortgage loan, or investing new business line.

5.1 Government policy and agreement

The temperature rises in waters have significant effects on fish distributions and impact commercial fisheries. Based on our model, Scottish herring is going to land in Norway by 2030, and by 2040 it will migrate completely out of Scotland to Norway. The mackerel will not completely move out of Scotland by 2030 because it more adapt warm water. However, if the worst case happens which the probability of occurrence of mackerel in Scotland will decrease to 0.5 around 2070, then the mackerel will move to at least north-east Scotland and a past of Norway by 2070. We still have to consider the possibility of partner with Norway government and their fishery management to deal with the problem.

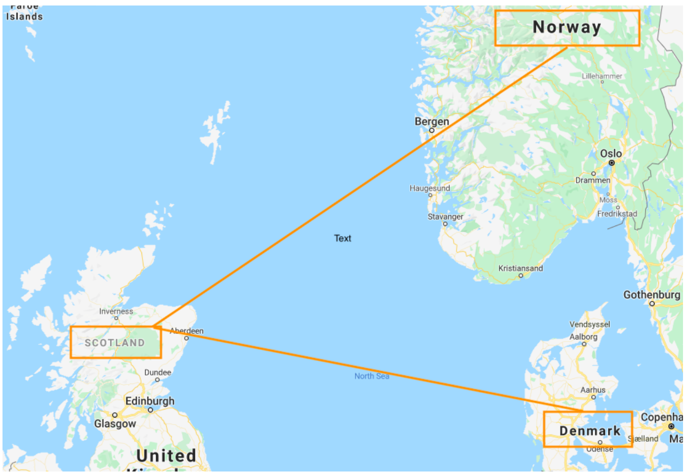

Figure 17: *Scottish mackerel and herring are increasingly landed in Norway and Denmark.*

In 2017, Scottish vessels landed £70M mackerel abroad (95,000 tonnes) which represents over half of the value and tonnage of the Scottish mackerel fisheries[6]. Despite increases in the prices paid for mackerel landed into Scottish ports, Scottish pelagic processing plants struggle to access sufficient tonnages of pelagic stocks to ensure they remain economically viable. The amended economic link condition will mean that Scottish fishing vessels must either:

- Land at least 55 percent of catches into Scottish ports
- Provide quota gifts (similar to the system currently in place in which gifted quota is distributed by the Scottish Government to vessels registered in Scotland)

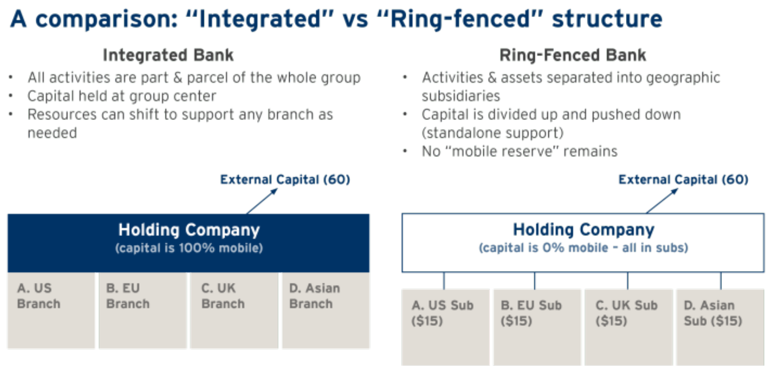

Figure 18: *A comparison with integrated bank and ring-fenced bank.*

There are also many international agreements in place. There are 17 Regional Fisheries Management Organizations (RFMOs), composed of nations that share economic interests in a particular area. When member nations agree to RFMO regulations, they are bound by these rules, which may include catch limits and specifications on the types of gear used. Evidence suggests these regulations have led to decreased bycatch (such as dolphins in tuna nets), but maintaining healthy fish stocks has remained a challenge. Enforcing fishing regulations on the high seas is extremely difficult, but member nations have worked to address the problem of illegal fishing and prevent illegally caught seafood from being imported.

5.2 Fishing method

Mackerel is a very important species for the Scottish fleet and is by far the most abundant pelagic species landed. In order to continue relying on the ocean as an important food source, economists and conservationists say we will need to employ sustainable fishing practices. Since about that time, commercial fishers have caught fish using purse seining and longlining.

[2]Many reform ideas have focused on the structure of big banks, and recommend some form of 'ring-fencing' to make banking safer. Some push for product segregation, such as UK 'ring-fencing' to protect retail activities or calls to renew Glass-Steagall walls in the U.S. Others advocate splitting banks on a geographic basis. Geographic 'ring-fencing' has become popular of late, with initiatives like the Intermediate Holding Company (IHC) rule for foreign banks in the U.S. and a mirror-image rule recently proposed by the EU for foreign banks operating there, among others. These 'ring-fencing' proposals all require dedicated capital and liquidity resources that are subject to local control [17].

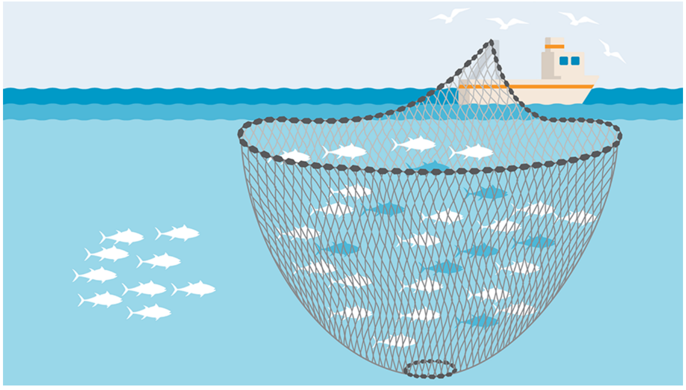

Figure 19: *Purse seines are used in the open ocean to target dense schools of single-species pelagic (midwater) fish like tuna and mackerel.*

Purse seine fishing uses a net to herd fish together and then envelop them by pulling the net's drawstring. The net can scoop up many fish at a time, and is typically used to catch schooling fish or those that come together to spawn. Longlining is a type of fishing in which a very long line—up to 100 kilometers (62 miles)—is set and dragged behind a boat. These lines have thousands of baited hooks attached to smaller lines stretching downward. Both purse seining and long-lining are efficient fishing methods. These techniques can catch hundreds or thousands of fish at a time. However, Purse seining, longlining, and many other types of fishing can also result in a lot of bycatch, the capture of unintended species. Longlines intended to fish, for instance, can ensnare birds, sea turtles, and other fish such as swordfish.

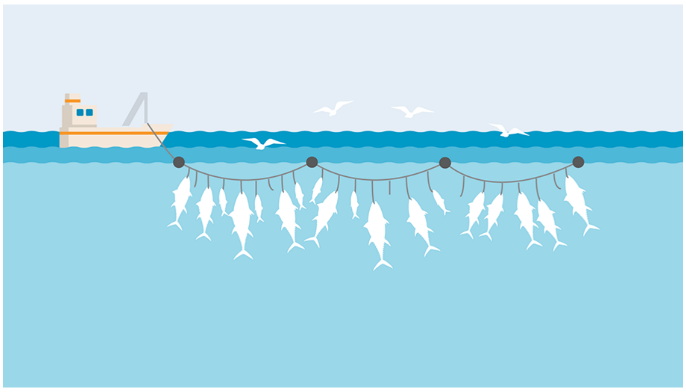

Figure 20: *Without careful management, longline fisheries can have unintended interactions with non-target fish, seabirds, and other marine life. Because of this, to become MSC, The Marine Stewardship Council, certified, they are often required to make improvements to their monitoring programs, and to mitigate interactions with non-target species.*

Instead, using hook-and-line methods to catch only what they need to feed themselves and their communities, which become entangled in more modern fishing gear like nets and traps. This method can also protect other species. Their most common historical fishing practices were hook and line, spearfishing, and cast nets. Hooks constructed of bone, shell, or stone were designed to catch specific species. Fishers would also craft 2-meter (6-foot) spears. They would dive underwater or spear fish from above, again targeting specific animals. Cast nets were used by fishers working individually or in groups. The nets could be cast from shore or canoes, catching groups of fish. All of these methods targeted fish needed for fishers' families and local communities.

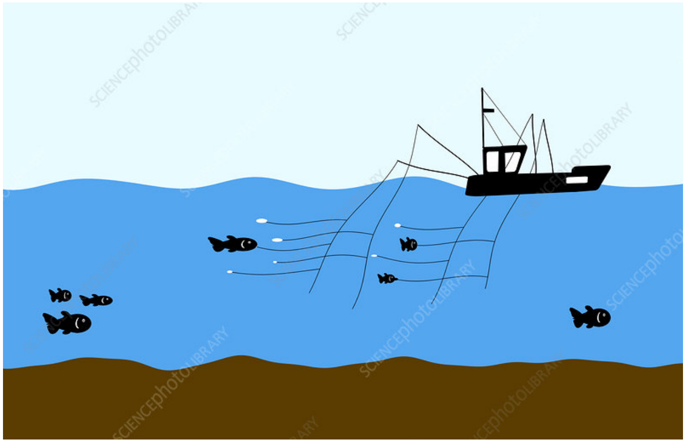

Figure 21: *Hook-and-line fishing method. Illustration of a fishing boat (upper right) catching seafood using the hook-and-line fishing method. Lines and hooks attached to rods are used to catch fish. This method is less intensive than fishing methods that use nets. The exact form of hook and line used depends on the conditions and the fish being caught.*

If you have ever gone fishing, chances are you used a rod and reel. Rod-and-reel fishing is a modern version of traditional hook-and-line. Rods and reels come in different shapes and sizes, allowing recreational and commercial fishers to target a wide variety of fish species in both freshwater and saltwater. The different types of rods and reels, coupled with different locations and bait, mean fishers can catch pelagic fish like sailfish, bottom-dwellers like flounder, and freshwater species such as catfish and trout. Rod-and-reel fishing results in less bycatch because non-targeted species can be released immediately. Additionally, only one fish is caught at a time, preventing over-fishing. For commercial fishers, rod-and reel-fishing is a more sustainable alternative to long lining.

5.3 New species

Back to our model, although mackerel travels miles away to north, it is still more adaptable in the warm water than herring. In this case, we suggest Scottish fishery could consider invest more on mackerel than herring. The aggregate of mackerel is close to the surface, so purse seine and rod-and-reel are preferred techniques for capturing it.

In addition, there are some exotic warm water marine species, such as anchovy, bluefin tuna, stingray, and thresher shark. The predicted increase in warm water-species represent a potential opportunity to increase catches of these species, thus potentially compensating the loss of cold-water species. The fishing industry could potentially mitigate the loss of catch potential of traditional species such as herring and mackerel by exploiting emerging species.

5.4 Other ideas

- A few scientists claim that fish can evolve by themselves and adapt to live in warm water. Some species have learned to survive where it's very hot. Things like tube-worms, bacteria, crabs, mussels and clams live in the hot water, so the fish might have enough nutrition and food.

- An alternative way to prevent overfishing and bycatch is to simply abstain from eating fish and other seafood. Dr. Sylvia Earle, renowned marine scientist and National Geographic Explorer-in-Residence, suggests people need to take a break from eating seafood until we learn better how to maintain healthy fish and wildlife populations. However, for people whose main protein resource is fish, this recommendation seems not likely for them.

- Generally, people living in tropics might be extremely affected by the fish migration because the main food resource for them are fish. The migration of fish will impact and even jeopardise their lifestyle. It may cause a human migration.

- As consumers, we can choose seafood from well-managed, sustainable fisheries to help fishing companies. To do so, we should educate ourselves about where our fish comes from and how it is caught.

- Introducing new species in Scotland would require new markets yielding similar profit which is not guaranteed. Most importantly, catching emerging species will only be possible if fishing quotas are granted. Given these two conditions, whether the fishing industry will be able to successfully adapt under future climate change effects remains uncertain.

6 Discussion

6.1 Variable relationships

The main assumption of our model is that the surface temperature in a location is directly correlated with the occurrence probability in that location. The reason for this assumption is that we see a correlation between ocean surface temperatures and occurrence probability in both Herring and Mackerel at a single given time. Biologically, this could be due to the oxygen levels in the water, which are generally higher in cooler water. Whatever the biological reason, the relationship between the temperature of an individual location and occurrence probability is significant, and thus we assume that this is a direct correlation.

However, this introduces a limitation into our paper in that it does not consider the affect of overall ocean warming. There may be factors acting on the Pelagic migration that are related to the mean temperature for the entire Scottish territory longitudinally, but that are not correlated to the temperature of an individual ocean location at a single point in time, like the type of relationship we assumed in our second quadratic regression between surface temperature and occurrence probability at a given location.

For example, another possible reason that temperature and occurrence probabilities are correlated could be that the organism on which pelagic fish feed somehow react adversely to warmer water. Pelagic fish, including Mackerel and Herring, feed on zooplankton and small fish that feed on plankton. The spatial relationship between plankton and pelagic fish populations is so pronounced, that plankton levels can actually be used to estimate the population levels of the fish that feed on them, such as Herring and Mackerel (REFERENCE). It is unclear whether plankton and other food source populations are directly affected by the temperature of the water at a specific location, but there is evidence that planktonic levels are correlated to overall global ocean temperature trends.

This being said, there could be other confounding factors between the ocean temperature of a location and , the example here being plankton levels, that would reduce the accuracy of our predictions.

6.2 Population Redistribution

The main place we need to improve our model is in modeling where the population that is displaced resettles. This was challenging because we only found reliable data about the Scottish seas as opposed to the North Sea and Arctic sea to the North and East of the British Isles. We successfully showed the places (in red) where it is most likely unsuitable for Herring and Mackerel to live, but we were unable to show where these populations then resettle. Namely, for both Herring and Mackerel, our model predicts that the Western stocks will be completely displaced because of warmer temperatures to the West of Scotland. However, our model does not account for the likely possibility that for Mackerel, the Western stock will mix into the longer lasting Eastern stock and relocate on the Eastern side of Scotland in the North Sea. For this reason, we suggest that the maps above be taken more as population suitability graphs, where blue shows places that are more likely suitable for pelagic fish, and red the places that have similar temperature conditions to where, in the past, these fish have not lived.

6.3 Linear Temperature increase

Another major assumption in our model is that global ocean temperature increase is linear. This seems to be the standard in the literature, but may not be the best assumption. We know, for example, that carbon dioxide levels, which are closely related to air temperature trends, are increasing exponentially. However, since the ocean has a high heat capacity and temperature changes slowly, this assumption is probably reasonable since we are only predicting out 50 years.

6.4 Limited Data

The final limitation of our model is that it is highly dependent on the accuracy of the data we used. The occurrence probability data in particular is potentially problematic. Firstly, these data are more accurate in highly fished areas, and have greater variance in less commonly fished areas. Additionally, it would be better to have spatial population estimation data, because these data show no information about biomass. An area where the average catch is half the biomass of that in another area, but where catches have the same frequency appears the same in these data. For the Mackerel data, this was especially limiting because a high proportion of the data were at P=1 (probability of occurrence is 100%).

7 Conclusion

Here we explore ways to use historical data projected onto spatial data, and apply this method to the Herring and Mackerel movements in the Northeast Atlantic. We find that both Herring and Mackerel follow the trends already set in recent years, moving both Northward and Eastward. We predict an Estimated timeline for both of these migrations, and see that for both Mackerel and Herring, the Western stocks disappear. For Mackerel, this will occur much more slowly due to the higher heat tolerance of Mackerel. We also see that while Western Herring stocks disappear quickly, the Western stock of Mackerel lingers at least until 2080, and will most likely be re-enforced by migrating Mackerel from the Eastern stock. Thus, we recommend that West coast fisheries (of both Mackerel and Herring) switch to a different type of fish, or if they are Mackerel fisheries, they may relocate to the east. For East cost fisheries, we recommend preparing for incoming competition for the shrinking Mackerel grounds that will concentrate Mackerel populations off the Northeast coast.

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