Dynamic behaviors of Scotland Fish Populations and Its Impact on The Fishing Industry

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1. Background

Global ocean temperatures affect the quality of habitats for certain ocean-dwelling species. When temperature changes are too great for their continued thriving, these species move to seek other habitats better suited to their present and future living and reproductive success. One example of this is seen in the lobster population of Maine, USA, that is slowly migrating north to Canada, where the lower ocean temperatures provide a more suitable habitat. This geographic population shift can significantly disrupt the livelihood of companies who depend on the stability of ocean-dwelling species.

This study will focus on modeling the potential migration of Scottish herring and mackerel from their current habitats near Scotland if and when global ocean temperatures increase. This study will also estimate the business impact of fish migration since these two fish species represent a significant economic contribution to the Scottish fishing industry. Changes in population locations of herring and mackerel could make it economically impractical for smaller Scotland-based fishing companies, who use fishing vessels without on-board refrigeration, to harvest and deliver fresh fish to markets in Scotland fishing ports.

2. Modeling Fish Population Dynamics

We constructed a discrete model with one-year time steps to model herring and mackerel's yearly population dynamics. In this section, we will discuss and justify our assumptions and explain the considerations while we were constructing the fish population model.

2.1. Fisheries.

2.1.1. Locations.

To understand how the temperature change will impact the Scottish herring and mackerel fishing industry, we first need to know where these Scottish fisheries are located and how they operate.

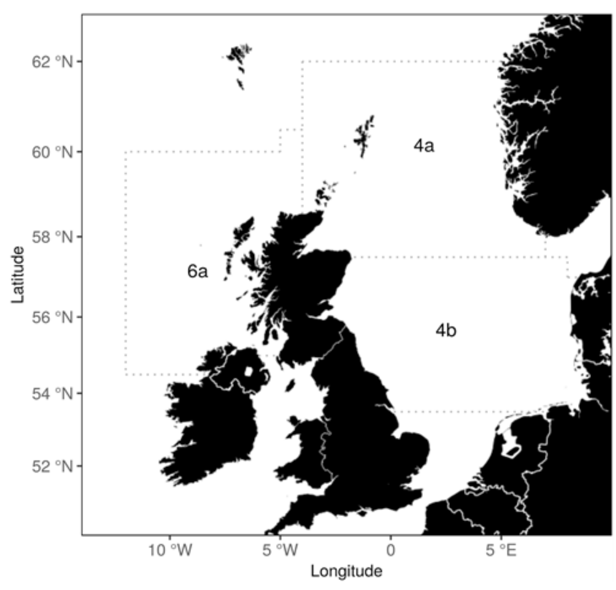


Fig. 1. ICES Divisions

According to the Scottish Sea Fisheries Statistics published by the Scottish Government, Scottish vessels were most active in three main ICES areas during 2016. These were the Northern North Sea (ICES division IVa), the West Coast of Scotland (ICES division VIa), and the Southern North Sea (ICES division IVb) shown in fig.1. We assume this is still the case today and will not change within 50 years, and thus this study will focus on the fish population dynamics in these three ICES divisions.

2.1.2. Activities.

Although we could never possibly know how many fish in the ocean, we could approximate it using the industry's total landing tonnage. We assume the fishing effort, a measure of the anthropogenic work input used to catch fish, is a constant. This means that the amount of fish that fisheries can harvest is proportional to the fish population's density in the fixed ICES division. Or, we can say, depends on the population size of the fish in that division. Let $N(t)$ and $L(t)$ denote a fish's population and the landing tonnage of that fish with respect to time, respectively. The relationship between $N(t)$ and $L(t)$ is often determined by the government's legislation and policies, which is called the harvest rate. We denote it as $h = \frac{L(t)}{N(t)*C}$, where C is the average weight of a single fish. We assume C is some constant.

2.2. Herring & Mackerel.

The next steps are to define possible factors that will cause the fish population to change over a fixed period. Before we move forward, we need to make some assumptions about the Scottish herring and mackerels' general behavior.

2.2.1. General Behavior.

Biologically, mackerel and herring are classified as migratory fish, which means that during their life cycle, anadromous long distance migratory fish will migrate from the sea into shallower water near the shore. According to Scottish Sea Fisheries Statistics, mackerel and herring are the two main pelagic fish landed by Scottish vessels. They spawn in shallow waters like estuaries, coastal waters, and offshore banks. Since herring and mackerel migrate, we assume that the natural resources necessary to support the population will not exhaust. To avoid the complexity of species interaction and competition, we assume the fish population's size will grow exponentially with the absence of commercial fishing activities.

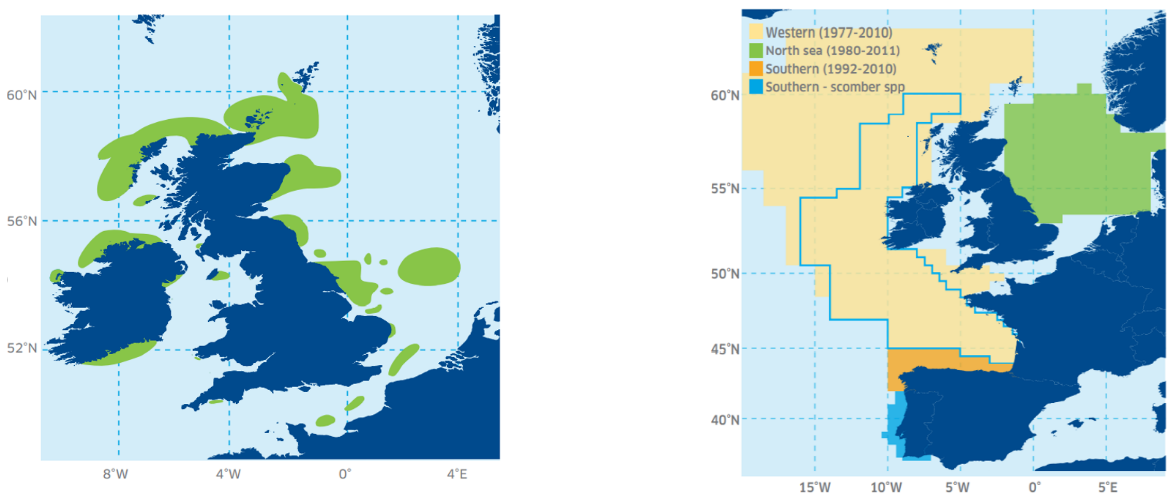
Herring According to NOAA Fisheries, herrings spawn as early as August through November. Female Atlantic herring can produce 30,000 to 200,000 eggs. They deposit their eggs on rock, gravel, or sand ocean bottom. Schools of herring can produce so many eggs that they cover the ocean bottom in a dense carpet of eggs several centimeters thick. The eggs usually hatch in 7 to 10 days, depending on temperature. According to Dodson's(1) studies, the optimal temperature for mackerel egg development seems to be 14°C. We denote f_h and p_h to be the fraction of mature females in the herring population and the average number of eggs that one female can produce in the spawning season.

Mackerel According to NOAA Fisheries, mackerel usually spawn from May to July. A female mackerel can produce around 285,000 to almost 2,000,000 eggs. The female mackerel releases their eggs in batches, between five to seven times throughout the entire spawning season. During the spawning season, eggs generally float in the surface water and hatch in four to seven and a half days, depending on the water temperature.Ibaibarriaga's(2) studies shown that the most suitable temperature for mackerel egg development seems to be 12°C. We denote f_m and p_m to be the fraction of mature females in the mackerel population and the average number of eggs that one female can produce in the spawning season.

We assume the above information is accurate and will use them in later sections to construct our model.

2.2.2. Increasing Factors.

When it comes to model population dynamics, one critical assumption we made is that the increase in population size should depend on the number of young fish that survive in spawning season to enter the adult fishery as recruits. Using the information provided by the Scottish Sea Fisheries Statistics again, we found that all three ICES division contains spawning grounds for herring and mackerel (see fig.2).



(a) Herring spawning grounds

(b) Mackerel spawning grounds

Fig. 2. Herring and mackerel spawning grounds.

Assuming the information is still valid, we further assumed that each division's population dynamics depends on the survival rate of fish eggs in the spawning grounds they contain. That is, the number of young fish hatched from eggs and capable of joining the fish population. This leads us to consider the various conditions of the spawning grounds. However, since our interest lies in the impact of increasing sea surface temperature, we assume the effects of all other factors on the survival rate are negligible. Let $T(t)$ denote the sea surface temperature.

To model the impact of temperature on egg survival/hatch rates, we approach with experimental results from lab reports. Presented in fig.3, Mendiola's(3) study has shown the mackerel eggs have a survival rate around 30% in the temperature range 11-15°C in the lab, we take the 30% as the base hatch rate.

In the resulting chart, we also observed that the cumulative survival rate dropped from 30% to 20% when the temperature rose to 17.8°C. We assume the eggs' survival rate would decrease exponentially due to increasing temperature to model the relationship between the temperature change and survival rate. To solve the exponential equation's base, we fitted it to two data points (13, 0.3), and (17.8, 0.2). The resulting function is $tf_m(T(t)) = 0.93^{T(t)-12°C}$, we call this the temperature

NEA mackerel	T (°C)	Z (d^{-1})	Cum Z	Cum S	A%
	8.6	0.32	3.31	0.03	96
	11.1	0.17	1.17	0.33	67
Embryos	13.2	0.22	1.14	0.27	73
	15.1	0.24	0.99	0.30	70
	17.8	0.38	1.23	0.20	80

Fig. 3. Lab Report

factor, where $12°C$ is the critical temperature for mackerel eggs to hatch. We further assume the impact of temperature on herring's hatching process is the same, meaning that the temperature factor for herring is $tf_h(T(t)) = 0.93^{T(t)-14°C}$, where $14°C$ is the critical temperature for herring eggs to hatch. Be aware that we only consider the case that water temperature exceeds the critical temperature. If not, we say the base hatch rate will not change: $tf(t) = 0$.

We also assume that fish eggs' survival rate in the wild (not the actual survival rate) follows this pattern. However, since the wild conditions are more challenging than in the lab, we should take a survival factor into account. Let s_h and $s_m$denote the constant proportion of fish eggs for herring and mackerel that get chances to hatch. We call this the survival factor in the wild.

Collecting all the statements above, we say the population will increase in a rate calculated by: proportion of female fish)(# of eggs produced per female fish)(survival factor)(temperature factor) Which can be written in a mathematical expression as:

$$r(t) = f * p * s * tf(t)$$

Where $r(t)$ is the overall survival rate.

2.2.3. Decreasing Factors.

For population dynamics, a common factor to take into account is the natural death rate. This rate is defined as when the fish died of illness, or other predators eat the fish. Stokesbury's(4) study suggested a progressive decrease in herring's instantaneous natural mortality with age, and the death rate for herring less than 1-year-old is about 10%. To be conservative, we assumed the death rate would be a constant d=10% for both herring and mackerel.

Commercial fishing is another activity that will significantly reduce the fish population size. According to a Vic News report, Canada has reduced the harvest rate of herring down to 20%. Since this is the only report we can find, we assume that the Scotland Government has a higher harvest rate than Canada. We assume the harvest rate $h = 30\% = 0.3 = \frac{L(t)}{N(t}$, where L(t) is the landing amount and N(t) is the fish population. We also assume the harvest rate is the same for herring and mackerel and will stay constant in the next 50 years.

Since herring and mackerel are migratory fish, we assumed they could find new suitable spawning grounds. Let $m(T(t)) = m(t)$ denote the migration rate. When sea surface temperature increases, the fish will migrate to another division on the north at a rate of $m(T(t)) = m(t)$, to find new spawning grounds. We will experiment with different functions for$m(T(t))$ in the simulation section.

We also assumed fish could only migrate from division VIa and division IVb to division IVa. As temperature increases, fish may also migrate to the north from division VIa. However, for boundary conditions, we assumed no fish would migrate into division VIa and division IVb to avoid unknown complexity (see fig.4).

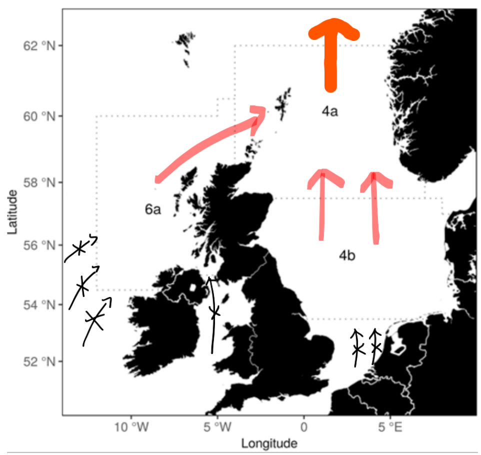


Fig. 4. Migration Pattern

2.2.4. The Model.

Putting all the assumptions above together, the dynamics of fish population can be generally described by the following equation:

$$N(t+\Delta t) - N(t) = r(t) * N(t) - h * N(t) - d * N(t) - m(t) * N(t)$$

Expanding the equation above for herring and mackerel, we have:

$$N_h(t+\Delta t) - N_h(t) = [f_h * p_h * s_h * tf_h(t) - h - d - m(t)] * N_h(t)$$

$$N_m(t+\Delta t) - N_m(t) = [f_m * p_m * s_m * tf_m(t) - h - d - m(t)] * N_m(t)$$

Where

- $N(t)$ is the fish population in a division
- $r(t)$ is the overall survival rate
  - f is the proportion of mature female fish in the population.
  - p is the number of eggs a female can produce in the spawning season.
  - s is the survival factor of fish eggs in the wild.
  - $tf(T(t))$ is the the temperature factor of fish eggs.
- h is the harvest rate.
- d is the natural death rate.
- $m(T(t))$ is the migration rate.
- $T(t)$ is the temperature at year t.
- Δt is the time interval of interest, we set it to be 1.

3. Business Is Yet to End In 50 Years

To solve the most likely elapsed time(s) that the fish populations move far away for small fishing companies to harvest, we approached using the landing tonnage/population dynamics. Using our modeling assumptions, the herring and mackerel population within the ICES division will decrease as temperature increases. Since landing tonnage is proportional to the population size in the division, the small fishing companies will eventually run out of business because some fish "moved to the north." Therefore, we need to solve the time when the small fishing companies' revenues cannot cover their costs. We started by considering the temperature change.

3.1. Predicting Temperature.

In previous discussions, we construct the model to describe the fish population dynamics based on the spawning grounds' sea surface temperatures. In this section, we will explain the methodology we used to model temperature change.

3.1.1. Assumptions.

To predict the future temperature of the spawning grounds, we made two critical assumptions. We assumed the temperature of the spawning grounds is the same as the temperature of the ICES division. We also assumed the temperature change in an ICES division is the same as the average global sea surface temperature change.

3.1.2. Methodology.

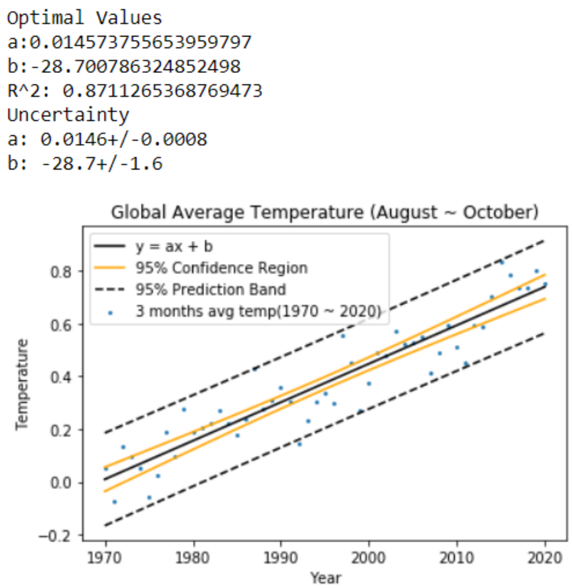
To predict the ocean temperature growth rate in the next 50 years, we used the global average sea surface temperature data collected by NOAA for the past 50 years. We calculate the average temperature growth rate in herring and mackerel's spawning seasons from the past data using linear regression. We assumed it will still be valid for the next 50 years' temperature forecasts.

3.1.3. Results.

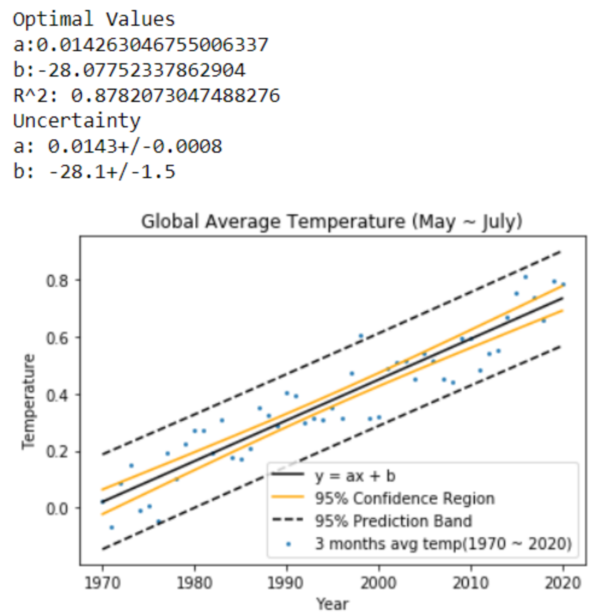
Rate Of Change From fig.5, we can see the global average temperature changes in herring and mackerel's spawning seasons are quite close, which are 0.0146°C and 0.0143°C, respectively. For the sake of simplicity, we used the rounded average value of 0.0145 to be the yearly global average temperature change. We also used the uncertainties to derive the best and worst cases. The worst case has the highest increasing rate, which is $0.0145 + 0.0008 = 0.0153°C$. The best case has the lowest increasing rate, which is $0.0145 - 0.0008 = 0.0137°C$.

R Squared The R^2 values of those two linear regressions in the above figure are 87.82% and 87.11%, which means that the model explained 87.82% and 87.11% of the real-world data, respectively. We consider this is a fairly good approximation which we can achieve for this project.

Confidence Interval Since all the data we collected were officially published, and the time interval is long enough, the lines we generated should be quite accurate. The two orange lines define the 95% confidence region, where we expect the true regression line to be. The dashed lines define the prediction band. If we took another observation, we would expect the data point to lie within that prediction band.



(a) August to October



(b) May to July

Fig. 5. Global Temperature Trend

3.2. Simulation.

3.2.1. Dynamics For All ICES Divisions.

Recall the relationship between the landing tonnage $L(t)$ and fish population $N(t)$ discussed in 2.1.2, we used it to derive the equation that describes the dynamics of fishing activities in landing tonnage for herring and mackerel. They are:

$$L_h(t+\Delta t) - L_h(t) = [f_h * p_h * s_h * tf_h(T_h(t)) - h - d - m(T_h(t))] * L_h(t)$$

$$L_m(t+\Delta t) - L_m(t) = [f_m * p_m * s_m * tf_m(T_m(t)) - h - d - m(T_m(t))] * L_m(t)$$

This allows us to understand the population dynamics without the prior knowledge of the actual number of herring or mackerel in the ocean.

Putting everything together, the system of equations that describes the herring population dynamics within three ICES divisions would be:

$$\begin{aligned} L_{h,6a}(t+\Delta t) - L_{h,6a}(t) &= [f_h * p_h * s_h * tf_h(T_{h,6a}(t)) - h - d - m(T_{h,6a}(t))] * L_{h,6a}(t) \\ L_{h,4b}(t+\Delta t) - L_{h,4b}(t) &= [f_h * p_h * s_h * tf_h(T_{h,4b}(t)) - h - d - m(T_{h,4b}(t))] * L_{h,4b}(t) \\ L_{h,4a}(t+\Delta t) - L_{h,4a}(t) &= [f_h * p_h * s_h * tf_h(T_{h,6a}(t)) - h - d - m(T_{h,4a}(t))] * L_{h,6a}(t) \\ &\quad + m(T_{h,6a}(t)) * L_{h,6a}(t) + m(T_{h,4b}(t)) * L_{h,4b}(t) \end{aligned} \quad [1]$$

Similarly, the system of equations that describes the mackerel population dynamics within three ICES divisions would be:

$$\begin{aligned} L_{m,6a}(t+\Delta t) - L_{m,6a}(t) &= [f_m * p_m * s_m * tf_m(T_{m,6a}(t)) - h - d - m(T_{m,6a}(t))] * L_{m,6a}(t) \\ L_{m,4b}(t+\Delta t) - L_{m,4b}(t) &= [f_m * p_m * s_m * tf_m(T_{m,4b}(t)) - h - d - m(T_{m,4b}(t))] * L_{m,4b}(t) \\ L_{m,4a}(t+\Delta t) - L_{m,4a}(t) &= [f_m * p_m * s_m * tf_m(T_{m,6a}(t)) - h - d - m(T_{m,4a}(t))] * L_{m,6a}(t) \\ &\quad + m(T_{m,6a}(t)) * L_{m,6a}(t) + m(T_{m,4b}(t)) * L_{m,4b}(t) \end{aligned} \quad [2]$$

3.2.2. *Different Models For Migration Rate* $m(T(t))$.

To determine the function of migration $m(T(t))$, we have tried three types of models: linear, power and exponential. The expressions are: $m(T(t)) = \frac{[T(t) - critical\ temperature]}{100}$, $m(T(t)) = \frac{[T(t) - critical\ temperature]^2}{100}$, and $m(T(t)) = e^[T(t) - critical\ temperature]$. Interestingly, we found that the impact of different models of $m(T(t))$ is negligible. Using the landing prediction of mackerel in ICES division 4a as an example (see fig.6), we can see there is barely any difference. Therefore, for the sake of simplicity, we used the linear model in our simulation.

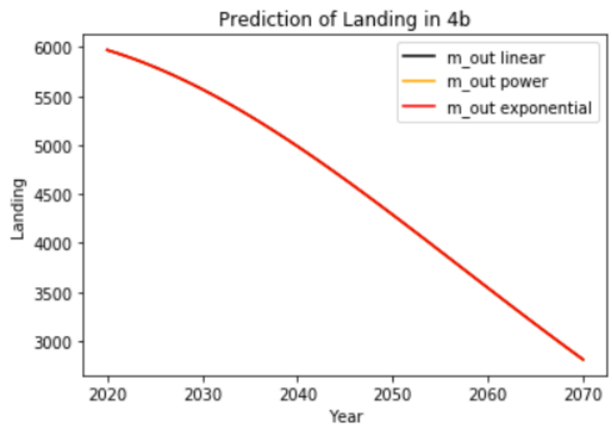
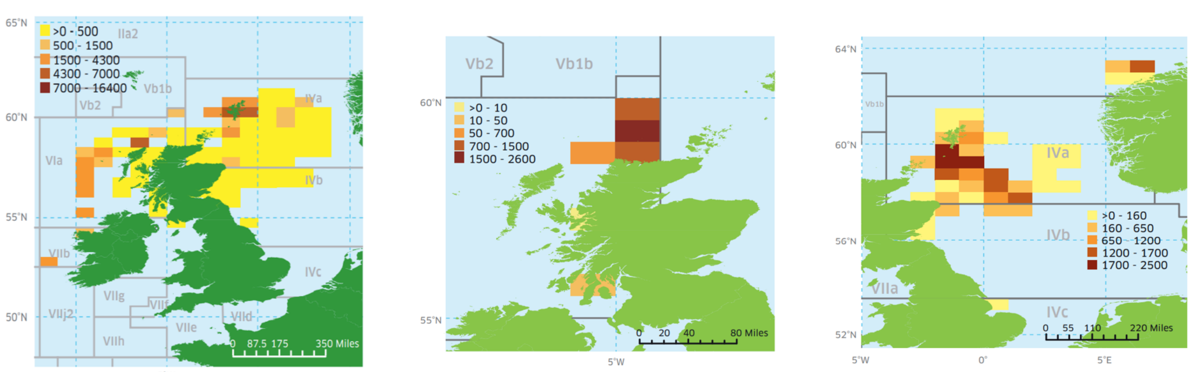


Fig. 6. Mackerel Landing Prediction Using Different $m(T(t))$

3.2.3. *Initial Conditions.*

Initial Landings $L(0)$ Since the landing tonnage data for mackerel and herring in our targeted ICES divisions are not available, we estimated the real data using graphs provided in 2013 statistics. We carefully counted the box in fig.7 and calculated the approximate proportions of total landing tonnage for each ICES division. Assuming these proportions are still valid, we multiply it by the 2019 total landing tonnage and obtain our initial landing tonnage values. The estimations are presented in the table 1.



(a) Distribution of mackerel landing.

(b) Distribution of mackerel landing.

(c) Distribution of mackerel landing.

Fig. 7. 2013 distribution of mackerel landing by Scottish vessels (Tonnes).

Fish	Region	Symbol	Landing Tonnage
Mackerel	6a	$L_{m,6a}(0)$	55500
Mackerel	4b	$L_{m,4b}(0)$	6000
Mackerel	4a	$L_{m,4a}(0)$	66400
Herring	6a	$L_{h,6a}(0)$	6700
Herring	4b	$L_{h,4b}(0)$	2800
Herring	4a	$L_{h,6a}(0)$	39700

Table 1. Initial landing tonnage.

Initial Temperatures $T(0)$ For each ICES division's starting temperature, we took the current year's average sea surface temperature of ICES division 6a, 4a, and 4b as the initial value $T(t=0)$. Due to a large number of monitoring sites, we randomly selected ten sites for each targeted region. We collected the temperature data of herring and mackerel spawning seasons and averaged their values to obtain those three regions' initial temperature in 2020. $T(0)$ for each ICES division/spawning grounds and species is presented in table 2 below.

Fish	Region	Symbol	Initial Temperature
Mackerel	6a	$T_{m,6a}(0)$	11.75°C
Mackerel	4b	$T_{m,4b}(0)$	11.62°C
Mackerel	4a	$T_{m,4a}(0)$	11.11°C
Herring	6a	$T_{h,6a}(0)$	13.85°C
Herring	4b	$T_{h,4b}(0)$	13.45°C
Herring	4a	$T_{h,6a}(0)$	12.79°C

Table 2. Initial landing tonnage.

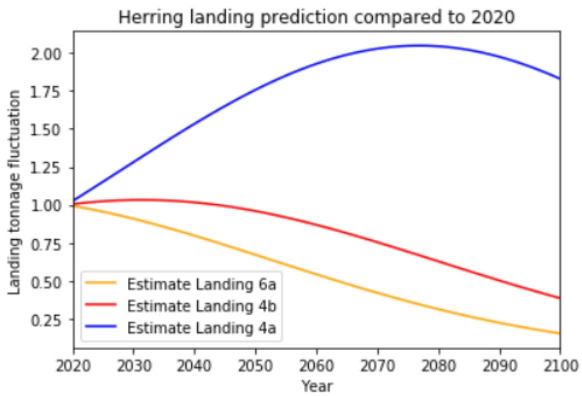
3.2.4. Parameters.

We've assumed some parameters to be constants in previous discussions, for example, the natural death rate $d = 0.1$ and harvest rate $h = 0.3$. We further assumed that the proportion of mature female fish in the herring and mackerel population are $f_h = 0.4$ and $f_m = 0.4$, respectively. We also assumed the number of eggs a female herring and mackerel can produce in the spawning season are $p_h = 115,000$ and $p_m = 1,143,000$, respectively.

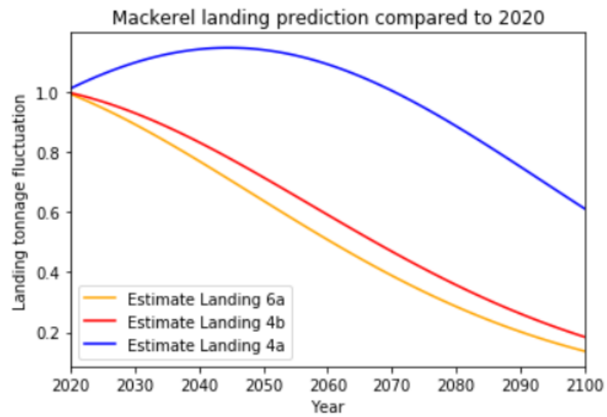
The survival factor of fish eggs in the wild s is calculated by assuming the herring and mackerel population are at equilibrium positions in 2019. The survival factors calculated for herring and mackerel are $s_m = 2.61 * 10^{-5}$ and $s_m = 1.94 * 10^{-6}$, respectively. We assumed these rate would hold constant.

3.2.5. Numerical Simulation.

The simulations for herring and mackerel population dynamics are presented in fig.8. In the graph of herring landing prediction, we can see that as time goes on, the estimated landing in both 6a and 4b regions are dropping, representing a decrease in population. We also observed an increase in herring population in ICES division 4a. For the mackerel graph, we can also see the same situation happening on mackerel, but faster. The population decrease in division 6a and 4b is due to the temperature rise, making the sea surface not suitable for spawning. Thus the fish eggs' hatch rate drops, and some may move toward the north (division 4a) for a better environment. Also, comparing



(a) Herring



(b) Mackerel

Fig. 8. Landing tonnage change with respect to initial values.

both graphs shows the landing amounts of mackerel drops faster than herring does. This is because the difference between the current sea surface temperature and mackerel's critical temperature is smaller than herring's. This means as temperature increases, the sea surface temperature would sooner be difficult for mackerel to bear than herring, resulting in a faster mackerel population change.

3.3. Impact On Small Fisheries.

How small is small? Defining what is a small fishing company specifically would be complicated. Rather than doing this, we used a slightly more radical approach. Understanding that having fishing vessels running on the ocean is essential for any fishing company's business. Therefore, the bottom line is, if the average revenue per boat cannot cover the average cost per boat, any fishing company will be in trouble. One critical assumption we made for small fisheries is that they should only own small fishing vessels with a length smaller than 12m. Also, these small boats should not have any on-board refrigeration. Lastly, we assume these small fishing companies' only income sources are herring and mackerel.

3.3.1. Revenue.

To estimate the revenue per boat, we first need to understand these small fishing companies' market share in the Scottish fishing industry.

According to the 2015 Scottish Fisheries Statistics, the mean gross earning of vessels in length group under 12m is £5000. Using the landing tonnage and values for herring and mackerel in 2015, and assuming the harvest season for herring and mackerel only last two months, we calculated that these small fishing companies own a market share of 24% in the herring and mackerel business.

The next step is to calculate the unit value of herring and mackerel. We calculated the average unit value of herring and mackerel using data provided by 2019 Scottish Fisheries Statistics. We got u_h = £460/tone for herring and u_m = £940/tone for mackerel. We assumed the market would balance the supply and demand. Thus the prices will not change in the next 50 years.

Now, we can calculate the average revenue per boat using the following expression:

$$revenue\ per\ vessel = \frac{\sum_{herring\&mackerel}^{(species\ total\ landing\ tonnage)(small\ fisheries'\ share)(unit\ value)}}{\#\ of\ small\ fishing\ vessels}$$

Expanding it, we have:

$$revenue\ per\ vessel = \frac{L_h(t) * 24\% * u_h + L_m(t) * 24\% * u_m}{\#\ of\ small\ fishing\ vessels\ in\ the\ division}$$

For the number of small vessels in each ICES division, we assume the distribution is the weighted average of herring and mackerel's divisional market share. The calculated distribution is [6a: 38%, 4a: 57%, 4b: 5%], thus the corresponding number of small fishing vessels in each division is [6a: 646, 4a: 969, 4b: 85].

3.3.2. "What Did It Cost?".

"Everything" Essential For simplicity, we assumed that the fisheries own the dock. Thus, the annual depreciation costs of land and equipment are negligible. We assumed that the essential costs to operate a fishing vessel are the fixed vessel costs such as insurance, administration fees, vessel loans, etc. and crews' labor cost. The variable expenses are not in our consideration. Using data provided by 2015 Scottish Fisheries Statistics, the monthly essential cost to have a vessel to operate is about £4,000. Thus the cost of running a small fishing vessel during the 3-month harvest seasons of herring and mackerel will be £12,000. We assume the cost stays constant until 2070.

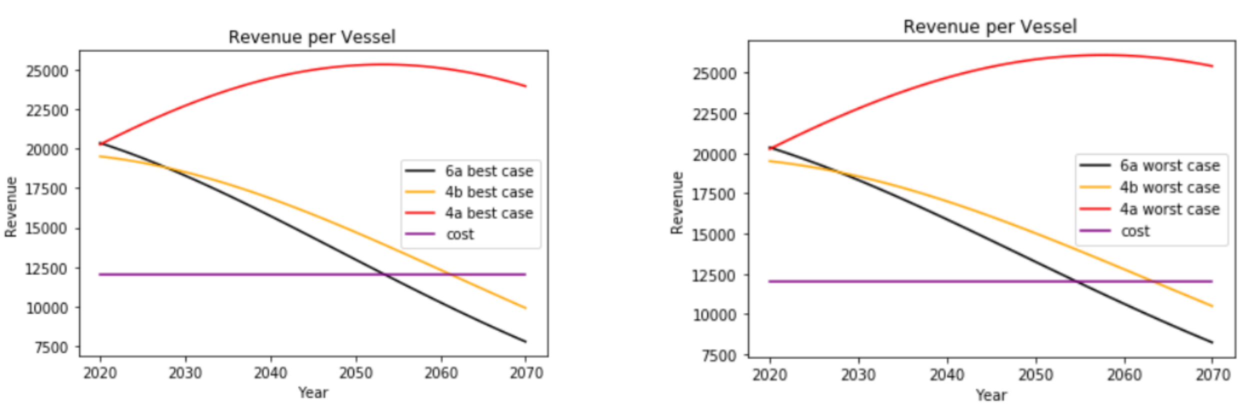
3.4. Long way to go.

The final step is to solve the following inequality for time t:

$$revenue\ per\ vessel = \frac{L_h(t) * 24\% * u_h + L_m(t) * 24\% * u_m}{\#\ of\ small\ fishing\ vessels\ in\ the\ division}$$

Substitute the values in, we have:

$$\frac{L_h(t) * 24\% * \pounds 460 + L_m(t) * 24\% * \pounds 940}{\#\ of\ small\ fishing\ vessels\ in\ the\ division} \leq \pounds 12,000$$



(a) Best case.

(b) Worst Case

Fig. 9. The change of revenue per vessel over time.

3.4.1. Best Case vs. Worst Case.

The impact of temperature change on the small fishing industry is present in fig.9 in terms of annual revenue per fishing vessel with respect to time. As we can see, the difference between the best case and the worst case is hardly discernible. This is due to the operations we used in our formula above. The 24% shrinks the difference, and being divided by the number of small vessels made the difference even smaller. Although we can not tell a big difference between the two cases, we can still gain useful insights from both plots.

3.5. Impact On Future Business.

We observed that the small fisheries in division 6a and 4a would start to struggle in the 2050s' due to the constant decrease in revenue, impacted by the rising temperature. Before 2060, these small fisheries will eventually fail to cover the essential cost of sustaining their vessels. However, the revenue of fisheries in the north, or division 4a, will increase due to fishes' migration. Unfortunately, this will only be a brief prosperous prospect because the revenue started to drop after 2060, and soon, it will be the northern fisheries' turn to struggle.

4. Possible Solutions To Continue The Business

For small fishing companies planning to cope with the rising temperature by changing their operation strategy, we have thought of two plans. The first plan is to relocate the company, moving to the ICES division 4a. This would be the only choice regarding our assumptions—the second plan to purchase and upgrade the on-board refrigeration for their vessels. Small vessels without a refrigeration system can not go far from the harbor because the fish will spoil quickly.

4.1. Moving North With Fishes.

If any company in ICES division 6a and 4b plans to move with the fish population, we assume it will move to the ICES division 4a when the revenue no longer covers the essential annual costs. Since we assumed in the previous discussion that all fishing companies owns the land and equipment, then the cost of purchasing new land and equipment can be covered by selling the previous properties. The uncovered moving cost would be the cost of fuels needed to drive the vessels to the new location and some labor fee. If we depreciate this fixed cost over a long period of time, it will become negligible. Since the benefit of moving will restore the annual income or even increase, and the cost is low enough to ignore, we say the strategy of moving north has a high cost-benefit ratio.

However, we need to take competition into account. Since there are already many fisheries the ICES division 4a, the southern fisheries moving north will need to compete with local companies and themselves. Even if all the fish are all moving to the north, the actual annual revenue might not increase as significantly as expected.

4.2. Upgrade On-board Refrigeration.

So, if moving with the fish might not work, how about upgrading equipment? Notice that the absence of on-board refrigeration systems limited the range and operation time of small fisheries, and purchasing refrigeration system may increase their revenue. However, we should be aware of the significant increase in annual depreciation costs for these cooling units and the fact that the fish population decreases. This strategy may just buy the dying industry a temporary respite.

5. Chaos In The Near Future

5.1. Possible Issues.

As we discussed in 3.4, in the best case, small fishing companies will not be able to cover its cost in xxx years and thus are forced to move. Notice that this is an average estimation so that companies in the far south would probably move earlier than the estimated time. Some fisheries can also move into the territorial waters (sea) of another country. A convenient location to move to is the Faroe Islands locate in the north, which is a self-governing archipelago, part of the Kingdom of Denmark. Another option is to move the company to Norway. However, Scotland, Norway and Faroe Islands fisheries will have to compete against each other in ICES division 4a in the future. Although the northern migration of herring and mackerel population might help relief the survival pressure of these companies, we should expect conflicts between nations.

Although the northern migration of herring and mackerel population might help relieve these companies' survival pressure, we should expect conflicts between nations. Another issue that needs to be taken into consideration is the possibility of overfishing. Since our model is not robust against variations in foreign policies, we would imagine that over-harvesting will significantly impact the fish population than the rising temperature. This may cause most small fisheries to drop out of the race.

5.2. Possible Solutions.

One possible solution would be to close the fishery company. From the above analysis and our models, a small fishery company's revenue eventually will fail to cover the essential annual cost. This is because the landing amount/fish population of herring and mackerel will decrease as temperature increases. Since the eventual result would be a close-down, closing the fishery earlier than later to avoid potential loss may be a wise choice.

Another possible solution would be changing the business type. The fisheries can develop new trades based on their origin business. One suggestion would be the aquaculture fishery, the way that aquaculture fishery company running is pretty similar to the fishery company. It won't be affected by global warming. The aquaculture fishery company can choose the most appropriate kind of seafood, which is more flexible than the fisheries limited by the herring and mackerel.

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