| Problem Chosen | 2020 MCM/ICM Summary Sheet | Team Control Number |
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| A | | 2022246 |


The rise of global ocean temperatures is affecting the populations of Atlantic herring and mackerel and Scottish fishing industry that heavily depends on them. To predict the migration of herring and mackerel to the north, first we limited our region of interest to 56˚N - 70˚N latitudes and 15˚W - 3˚E longitudes, based on the geography of Northeastern Atlantic and exclusive economic zones of the United Kingdom, Norway and Faroe Islands. Then, we divided the region into 1˚latitude by 1˚longitude cells, as the data sets on sea surface temperature from NASA, which we used, dictate. The predicted rates of change of temperature that we found ranged from 0.013˚C to 0.02˚C linear increase per year. Additionally, research shows 0.1˚C increase in the rate of change of temperature per year with each latitude closer to the north, which we have accounted for in our implementation. We eliminated other variables that might influence fish migration, such as salinity or pH level, since they linearly depend on the temperature and have negligible effect in the next 50 years.

After building the *linear temperature rates varied by latitude submodel*, we developed our first main model, a *fish habitability index*, which ranges from 0 to 1 and predicts the likelihood of herring and mackerel fisheries to live in each cell, based on the positively skewed Gaussian distribution of temperature, as both species prefer colder waters. 0 value means fish are unlikely to be found in that region, whereas 1 – fish are very likely live in the given region. We built the pdfs for two species separately, accounting for their preferred temperature ranges and unique skewness, established by multiple findings.

Then, to estimate how economically practical is to fish in each cell in any given number of years, we built a submodel of *operational distance index*. It assesses the feasibility of catching fish in each cell from a fixed port of operations, given the inputs of locations, vessel speed, harvest time and market distribution time. The time constraint on fish going bad without refrigeration is fixed to 24 hours. Operating in degrees, we find the great-circle distance between two locations in kilometers, using the haversine formula. The essence of our second model is a *fishing practicality index* for each cell, which is simply scaled fish habitability index times the operational distance index. It ranges from 0 to 1 and estimates whether it is practical to fish in each location given the probability of herring or mackerel in it and distance. 0 corresponds to a very low probability of finding fish in the area along with it being far from the fixed port of operations, and 1 corresponds to a high likelihood of fishery in the location along with short distance to it.

Implementation has shown that for southwestern Scottish ports of operations herring and mackerel will be either too far or in foreign territorial waters to pursue catching them in approximately 35 years. The southwestern region near Aberdeen will be bare in 50 years, whereas the northeastern region will be economically unattractive for fishermen in 30 years, as most of their fisheries will move to the Norwegian and Faroe Islands waters.

Our recommendations in order of preference include relocation to southwestern ports, diversification of fleet, e.g. switching to crustacean sector, or harvesting other species more adaptable to higher temperatures, subsequently, advertising them, or developing climate-informed management tools and cooperation with other fishing companies.

# Table of contents

# 1. Introduction

## 1.1. Background information

As ocean waters absorb more than 90% of excess heat retained by the Earth due to increased greenhouses gases, global ocean temperatures rise significantly, affecting the habitats for

many marine species.[1,2] A Scottish North Atlantic fishery management consortium is looking into the potential migration of Scottish herring and mackerel away from ports of operations of small fishing companies. As fish migrate to the north, it might become impractical for fishing vessels with no on-board refrigeration to pursue the fish further because by the time they catch them, travel back and distribute it on the market, they will not be fresh anymore.

First of all, it is essential to note that the rate of warming in the North Atlantic region has been rapidly increasing since the 1980s and is expected to continue rising at 0.5°C per decade at the least.[3] Secondly, exclusive economic zones of Norway and Faroe Islands lie close to the north of UK waters, which must be accounted for in the case where fish migrate to other sovereign regions, making the fisheries inaccessible to Scottish fishermen.[4] Lastly, many small fishing companies have very limited financial resources, so they have very few economically attractive options, which might be:

- Relocation to a new port of operation further north;
- Investment into tools that keep the catch fresh;
- Re-specialization in other abundant species in the region.

All solutions to the herring and mackerel migration problem for small fishing companies were evaluated based on two models:

1. *Index of habitability*, which predicts the likelihood of fish living in the given area based on its temperature in the future years up to 5 decades;
2. *Index of practicality*, which estimates how feasible it is to catch the fish in the predicted fishery locations from a fixed port location based on the time elapsed, distance, boat speed, and operational time constraint.

First, this report thoroughly explores the rise of global ocean temperature and the resulting migration of Atlantic herring and mackerel in the Northeastern Atlantic region in the next 50 years to the north. Next, we investigate the consequences of these natural phenomena on the Scottish fishing industry and derive possible solutions that will help small fishing companies to continue their operations.

## 1.2. Assumptions

In the process of our research on global warming effects on the ocean, Atlantic herring and mackerel's biological characteristics, commercial fishing practices, and geography of the

Northeastern Atlantic region, we developed a set of reasonable assumptions, upon which we build our models.

1. The rate of change in temperature across 50 years is linear within the same latitude.
2. The higher the latitude, the higher the rate of change in temperature.[3]
3. Mackerel can survive only within the following temperature range: 3°C - 27.°C.[5]
4. Herring can survive only within the following temperature range: -1.34°C - 24.7°C.[5]
5. Sea Surface Temperature is an accurate measurement of the temperature of the ocean, where mackerel and herring live.
6. Fish populations are uniformly distributed in the regions with the same temperature. In other words, the distribution of fish in the ocean directly corresponds to their temperature preference.
7. Our unit of location is a (1° latitude) ×(1° longitude) field. We aggregate the values of temperature, index of habitability, and index of practicality in the region by the average values in each area, as the common practice of sea surface temperature data collection dictates.[6] From now on "location," or "area," means the (1° latitude) ×(1° longitude) field.
8. Our range of locations is a 14x18 grid of latitudes and longitudes: (56°N - 70°N) × (15°W - 3°E). This is the grid that encompasses Scotland (UK) and neighboring countries' exclusive economic zones. The territory of Scotland starts approximately at 56°N, and 70°N is far enough into the territorial waters of Norway and Faroe Islands, so we assumed it as a reasonable cutoff value, as we are not interested in fish moving even further away to the north.
9. We assume the fish are moving only to the north and not to the east, or to the west, so we bounded the longitudes by the range of the UK exclusive economic zone above 56°N, as we are interested only in the locations where Scottish fishing companies can operate.
10. The likelihood of herring and mackerel fisheries' locations is described by a positively skewed normal distribution of temperature in the given location, reflecting the fish preference to colder waters.[5]
11. We assume that the first fish caught has to stay fresh by the time it is distributed on the market. Thus, the total time of harvest, trip back, and market distribution has to be less than the operational time constraint, in which the quality of the fish significantly reduces.

# 2. The Models

## 2.1. Fish Habitability Index (FHI)

### 2.1.1. Variable selection: Sea Surface Temperature (SST)

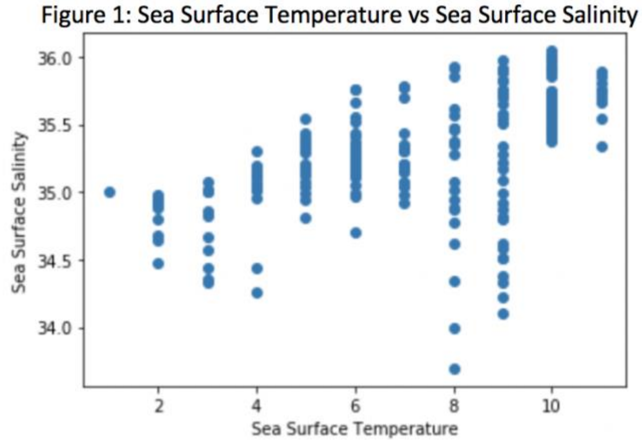
Based on research on fish habitat, we identified ecological variables like sea surface temperature, sea surface salinity etc. which would determine whether herring and mackerel can live in a given location or not. The plan was to understand the relation between mackerel and herring's ability to survive in a particular condition determined by the variables. Then, scale each variable from 0-1, where 1 means they have 100% chance of surviving and 0 means no chance. We then would find a weighted average of the selected variables to form a composite habitability index.

Other than the sea surface temperature, we explored the following variables, which were ultimately not included in the model for various reasons:

- Sea Surface Salinity (ppt):

  Salinity has been identified as one of the key factors which affect fish growth, and ultimately the survival of the species.[7] Further, we found that salinity is a function of temperature. Thus, to understand the exact relation between the two variables, we decided to look at real data on salinity and temperature within the latitude and longitude range around Scotland.[6,8] The following image is a scatterplot of Temperature vs. Salinity. The Pearson correlation is 0.485 for a linear relation. Thus, we concluded that salinity and temperature have a linear relation.

  Figure 1: Sea Surface Temperature vs Sea Surface Salinity

  We had already decided to include Sea Surface Temperature in our model. Thus, adding Sea Surface Salinity, which is a linear function of the Temperature, would not have added anything new to our model and would have led to multicollinearity problems. Thus, we decided to drop Sea Surface Salinity from our model.

- Acidity (pH):

  It was found that acidity and fish livability are highly correlated, but there was not much data available on acidity to make assumptions and still maintain the integrity of our model. Further, although the acidity is changing, it is not a consequence of temperature changes, but increased pumping of carbons and toxins in the ocean. Thus, to keep the model focused on the effect of change in temperature, we decided not to include this as a variable in our final model.

- Food availability:

Food availability is one of the driving forces to whether fish chose to stay in a location or not. If food is scarce, then fish usually die out or move in search of other food sources. Keeping this in mind, we found out that the primary foods consumed by the herring and the mackerel include planktons and copepods. Both of these food items have a higher range of temperatures they are tolerant to than mackerel or herring.[11] Thus, if mackerel and herring can survive in some locations, their primary sources of food can survive in the same location. Thus, we decided not to include the variable and retain the simplicity of our model, since it would not add anything to our model.

- Presence of Predators:

  If there is a certain region that has an abundance of herring/mackerel predators, then this would be a concern for the habitability of the fish. Mackerel and herring are sought after fish by both humans and other animals/fish. However, despite this both mackerel and herring are in the "Least Concern" stage of the extinction spectrum.[12,13] Further, we reasoned that temperature changes lead to ecological changes, which would not reconfigure the conditions required for species to live, but simply shift the location of where different species live. Thus, we do not anticipate there being an artificial increase of a certain species who are mackerel/herring predators in ecosystems where mackerel/herring would live. Thus, we decided to not include this variable as well.

Thus, we decided to build a *habitability index* for each location, based only on temperature. The habitability index estimates the probability of herring or mackerel living in a given area on a scale from 0 to 1 based on the species' temperature preference. The greater value of a habitability index in a location indicates a higher preference of the fish to live in this location.

Based on the data of herring and mackerel populations distributions at different temperatures we defined the functions of a positively skewed normal distribution to reflect fish lower temperature preference. The details of the function construction process are described in the next section.

### 2.1.2. Construction of FHI: Skewed Gaussian Distribution

Sea Surface Temperature, based on the prompt and background information is our most important variable. Based on theoretical research, we made assumptions about the range of temperature that mackerel and herring could survive in. We wanted to create a function which transformed the temperature of a given location into an index in the range [0,1], where 1 corresponded to the most livable conditions for the fish, while 0 the least. A higher index would correspond to temperature values more central in the range of livable temperatures, while the lower index would correspond to either extremes of the range.

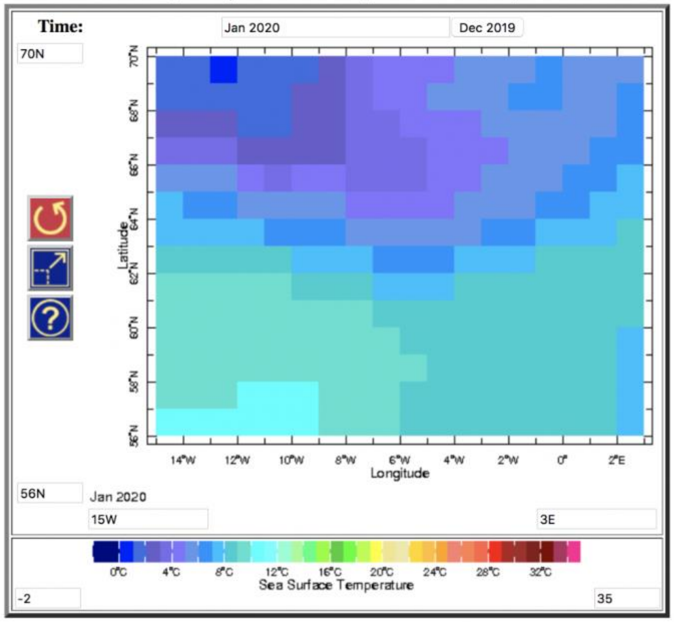



Figure 2: Sea Surface Temperature Heat Map

To this end, we started off by assuming that the distribution of fish present in relation to temperature would follow a gaussian distribution. Next, in order to make the distribution reflect the reality, we looked at the data on the distribution of herring and mackerel population.[5]

*Table 1: Preference quintiles of Mackerel and Herring Population*

| | Minimum | 10th Percentile | Left SD | Optimum Temperature | Right SD | 90th Percentile | Maximum |
|---|---|---|---|---|---|---|---|
| Herring | 3 | 7.5 | 3.2 | 12.94 | 4.5 | 18.38 | 27.15 |
| Mackerel | -1.34 | -0.1 | 1.8 | 4.62 | 5 | 9.34 | 24.7 |

Notice from the table above that the distribution follows a skewed Gaussian function. In order to find the shape parameter for herring and mackerel, we first wanted to calculate a z-score for which we would need the mean and standard deviation if the distribution was normal. Thus, we assumed that the optimum temperature is the mean of the distribution. Next, the standard deviation was calculated by taking an average of the left and right SD. Next, we know the values that correspond to the 90th and 10th percentile of the distribution. Given this, and the fact that 80% of the distribution lies within 1.28 standard deviations from the mean, we use this to calculate the standard deviation under the skewed distribution. Then we calculate:

$$z = \frac{SD_{skewed} - mean_{normal}}{SD_{normal}}$$

The moment generating function of a skewed Gaussian distribution is as follows:

$$M_z(t) \ = e^{\frac{t^2}{2}\Phi(\frac{\lambda t}{\sqrt{1+\lambda^2}})}$$

where $\lambda$is the shape coefficient, $\Phi(.)$is standard normal distribution function. Thus, we equated the variance (square of Standard Deviation) to the second moment and solved for $\lambda$.

From this we got the following function which is the unscaled habitability index:

$$h_{herring}(t) \ = \ 2\frac{1}{\sqrt{2\pi}}exp(\frac{t-\mu}{\sigma})^2.\frac{1}{2}[1+erf(\frac{-0.76355t-\mu}{\sigma\sqrt{2}})]$$

$$h_{mackerel}(t) \ = \ 2\frac{1}{\sqrt{2\pi}}exp(\frac{t-\mu}{\sigma})^2.\frac{1}{2}[1+erf(\frac{-1.10303t-\mu}{\sigma\sqrt{2}})]$$

where:

$$erf(z) \ = \ \frac{2}{\sqrt{\pi}}\int_0^z e^{-t^2}dt;$$

$t$ is the temperature (in °C);

$\mu$ is the mean;

$\sigma$is the standard deviation.

Next, we came up with the scaled habitability index:

$$H_{herring}(t) \ = k \ \cdot 2\frac{1}{\sqrt{2\pi}}exp(\frac{t-\mu}{\sigma})^2.\frac{1}{2}[1+erf(\frac{-0.76355t-\mu}{\sigma\sqrt{2}})],$$

$$H_{mackerel}(t) \ = k \ \cdot 2\frac{1}{\sqrt{2\pi}}exp(\frac{t-\mu}{\sigma})^2.\frac{1}{2}[1+erf(\frac{-1.10303t-\mu}{\sigma\sqrt{2}})],$$

Where $k$ is the scaling factor, so that $H$ would range from 0 to 1.

### 2.1.3. Linear Model of Increasing Temperature Rates Varied by Latitude

The International Union for Conservation of Nature determined that the temperature of the upper few meters of the ocean has increased by approximately 0.13°C per decade over the past 100 years.[14] Thus, we set our lowest (best case scenario) rate of change of temperature to $\alpha_{global}$ =0.013°C/year. The Food and Agriculture Organization of the UN published their findings on ocean warming in May 2018, which stated that with each degree of increase in latitude, the rate of change in temperature increases by 0.1°C/year.[3] Taking these results into account we construct the following model of the rates of change of temperature in different latitudes of our region of interest in Northeastern Atlantic.

To compute the future temperature of a given location $x$, we came up with the following model:

$$t_{future} = t_{current} + \alpha_x \cdot (t_{future} - t_{current})$$

where

$t_{current}$: = the current temperature at $x$ (in °C),
$t_{future}$: =the future temperature at $x$ (in °C), and
$\alpha_x$: =the rate of change in temperature at $x$ (in °C/year), modeled by

$$\alpha_x = \alpha_{global} \cdot (1 + 0.1 \cdot (latitude_x - 56)).$$

## 2.2. Fishing Practicality Index (FPI)

### 2.2.1. Operational Distance Index (ODI)

We want to accurately estimate the best case, worst case and the most likely elapsed time(s) until herring and mackerel populations will be too far away for fishing companies to keep harvesting them and delivering them fresh to the market. We will define "*too far away for small fishing companies to harvest*" in terms of operational distance index.

As we stated in introductory assumptions, we want all fish to stay fresh, including the very first one caught. Thus, the time it takes to catch all fish, travel back to the port and distribute the fish on the market must not exceed the time constraint for the fish staying fresh without being frozen or artificially kept alive in some body of water. Remember, we assume that the fishing vessels do not have any on-board refrigerators, as small fishing companies have limited financial resources. Therefore, "too far away" is when the total time of operations exceeds the time constraint of fish staying fresh. This logic leads us to the following variables:

- $F$ = time the fish keeps fresh without being refrigerated (in hours);
- $c$ = total harvest ("catch") time for all fish (in hours);
- $m$ = time of market distribution of the caught fish (in hours);
- $d$ = distance from port of operations to the fishery location (in km);

- $v$ = boat speed (in km/h);
- $t_t = d/v$ = time it takes to travel back to the port (in hours).

Thus, the smaller the difference $F - (c + m + t_t)$ the less total time fishermen have for all operations and the lower the quality (freshness) of fish caught.

The great-circle distance from the port of operation to the fisher location was calculated using the haversine formula that computes the distance of two points on a sphere given their latitude and longitude coordinates[9]:

$$d(x, y) = 2r \cdot arcsin(\sqrt{hav(\varphi_y - \varphi_x) + cos(\varphi_x)cos(\varphi_y)hav(\lambda_y - \lambda_x)},$$

where

$hav(x) = sin^2(\frac{x}{2})$;

$r$ is the radius of the earth at 6371km [10];

$(\varphi_x, \lambda_x)$ is the (latitude, longitude) for location $x$;

$(\varphi_y, \lambda_y)$ is the (latitude, longitude) for location $y$.

Finally, the operational distance index was calibrated as:

$$O(x, y) = scaling\_constant \cdot (F - (c + m + t_t)$$

where the *scaling_constant* rescaled the operational distance index where the minimum value corresponds to 0 and maximum value corresponds to 1. Thus, the higher the ODI, lower the cost of fishing in that location and vice versa.

### 2.2.2. Construction of FPI based on ODI

Fishing Practicality Index represents whether fishermen should fish at a location or not, with 1 being the highest practicality and 0 being the lowest.

We wanted the FPI to encapsulate both the time-cost of getting to the fish harvesting location from the port and the quantity of fish available at the port. The rationale behind doing so was to make sure that each fish harvesting location had enough fish given the time-price of getting to said location. For example, if fish habitability (which would measure the quantity of fish in the location) was very high, but the cost of getting the fish is very high as well, then the location might not be ‘practical’ to fish because the fishermen need low cost, but a high quantity of product.

To this end we decided to create the FPI for each fish by multiplying the Fish Habitability Index and the ODI. The Fish Habitability Index represents the quantity of fish living in a given location and the ODI accounts for the time-cost of getting to the location.

Thus, we get the following function:

$$F_{herring}(t, x, y) = scalingfactor \cdot H_{herring}(t) \cdot O(x, y),$$

$$F_{mackerel}(t, x, y) = scalingfactor \cdot H_{mackerel}(t) \cdot O(x, y),$$

where

*x* is the location of the fishery;

*y* is perspective location of fish harvestation;

*t* is the temperature at *y* (in °C);

*scalingfactor* transforms min(F)=0 and max(F)=1.

Thus, higher the FPI, higher the practicality of fishermen fishing there in terms of time-cost, distance and quantity and vice versa.

# 3. Operational Solutions

## 3.1. Relocation to a New Port

Based on the model we have developed, we assessed possible locations that the small fishing companies could move their assets to. The following table summarizes our results; our assessment process and explanations are provided afterward.

*Table 2. Assessment of possible port locations*

| Name | Latitude | Longitude | T (herring) | T (mackerel) | T:= Time Elapsed Until “Unfeasible” (years) | Number of non-Scottish areas | |
|---|---|---|---|---|---|---|---|
| | | | | | | Herring | Mackerel |
| Applecross | 57.5°N | 6°W | 35.6 | NA | 35.6 | 3 | NA |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Stornoway | 58.2°N | 6.3°W | 35.6 | NA | 35.6 | 3 | NA |
| John O'Groats | 58.6°N | 3°W | 35.6 | 50 | 42.8 | 2 | 1 |
| Skaw | 60.8°N | 0.8°W | 30.8 | 40.4 | 35.6 | 5 | 3 |
| Duntulm | 57.7°N | 6.3°W | 35.6 | NA | 35.6 | 3 | NA |
| Aberdeen | 57.1°N | 2.1°W | 50 | 50 | 50 | 1 | 1 |
| Inverness | 57.7°N | 4.5°W | 50 | 50 | 50 | 0 | 0 |

### 3.1.1. Assumptions

In our assessment of possible port locations, we made the following assumptions:

1. *Herring and mackerel are equally important species for all the fisheries* (i.e. when computing T, herring and mackerel are given equal weights)
2. *We round the coordinates of port locations to the nearest integer*. In order to have a macro-level assessment, we decided to group the locations as "same" if there are within 1° from one another. Therefore, Applecross, Stornaway, and Duntulm are considered the "same port."
3. *We assume that each port locations, even when they are islands, have the same time required for market distribution.*

### 3.1.2 Computing the Number of Years Until the Location is Unfeasible

We came up with a list of seven possible port locations for small fisheries based on the population of the main islands and mainland. For each location, we identified 10 locations in the ocean with the highest FPI after 50 years. We then examined the time it takes for the FPI in those locations to decrease below threshold (=0.8) for each species ($T_{herring}, T_{mackerel}$). We averaged the two values to provide the small fisheries with a single number $T$, which represents the number of years elapsed until a given port location will be unfeasible for herring/mackerel fishery.

### 3.1.3 Conclusions and Suggestions Regarding Relocation

Based on our analysis, we have the following conclusions:

- At Aberdeen and Inverness, fishermen will find enough of both herring and mackerel for the next 50 years. However, More unlike Inverness, Aberdeen has a couple of locations that are not within the Scottish territory.
- The remaining other locations do not guarantee as long of a time frame than those of Aberdeen and Inverness; however, they are still sustainable for the next 35-40 years.
- The difference in T among the bottom five locations (Applecross, John O'Groats, Stornoway, Skaw, Duntulm) is not large enough to recommend one port location over another. However, Skaw has a significantly higher number of locations that are outside the Scottish territory.

Our recommendations are as follows:

- If the fishing companies need to operate within the Scottish territory, they should not consider Skaw.
- If the fishing companies are looking to operate long-term (>50 years), then they should consider moving some or all of their assets to Inverness. If they are not constrained by which territorial waters they operate in, Aberdeen is an equally sustainable option.
- If a fishing company makes a profit solely on mackerel, they can also consider John O'Groats for long-term sustainability.
- If the fishing companies are not looking to operate long-term (<40 years), then we suggest that they move their assets to whichever one of the bottom five locations (Applecross, John O'Groats, Stornoway, Skaw, Duntulm) that incurs them the least amount of moving cost.

## 3.2 Other Suggestions

Other than relocating to a new port, we suggest that the fishing companies take one or more of the options below to maximize their profit and the number of operating years.

### 3.2.1. Enhancing Vessel Capacity

Given that the small fishing companies still continue harvesting mackerel and herring, one of the biggest problems is that we are constrained by the short shelf-life of the fish. If the shelf-life were higher, then the fishermen could fish from farther distances, harvest fish and take a longer time to get back to the port. Two ways to increase the shelf-life of the fish by investing in enhancing vessel capacity include:

- **Refrigeration on Board:** Refrigerators would keep the fish fresh for longer.

- **Tubs to keep fish alive:** If vessel capacity increases, having tubs of water with the caught herring and mackerel with enough nutrients to keep them alive for the desired amount of time would increase their shelf life.

### 3.2.2. Diversification

Climate change is changing the structure of the ecosystems around Scotland. This means where there once was an abundance of mackerel and herring, there is now an availability of fish that were not there before. To this end, small fishing companies should harvest fish other than mackerel and herring. These fish, since they were not in the waters near Scotland before, will not be protected with a quota by the EU. Even if they are protected, it will take time for the legislation to pass. Taking advantage of this climate change, the companies should harvest species that are more easily available in the region surrounding the ports like crustaceans.

There are two channels by which a market for the diversified fish can be created:

- **Change Consumer Demands in Scotland:** Advertisements and campaigns are a tool to signal to consumers what their preferences should look like. Over time, this leads to changing consumer demand towards what is being advertised to them. Hence, the companies should invest in advertising different kinds of fish, thereby structurally changing Scottish preferences away from the otherwise-classic mackerel and herring. This allows them to create a market for more kinds of fish, making them flexible to future shocks in climate as well.
- **Develop New Supply Routes outside Scotland:** There is a demand for different kinds of fish in non-Scottish EU countries and non-EU countries. Tapping into this, the consortium should build relations to try to find markets that already have a demand for the fish they have harvested. Perhaps markets that were further south, where the fish that are new near Scotland used to live.

### 3.2.3. Management-Level Sustainability Changes

- **Climate-related R&D:** Developing climate-informed management tools that predict the effect of continuously changing environment on fish availability. This would allow for flexibility in responses to sudden changes, and the response time to adapt to these shocks would be decreased. Thus, the consortium should work to promote climate-smart fishing and processing technologies.
- **Develop Sophisticated Fishing Skills:** Reducing the amount of fish product losses and waste will increase the value of each fish, thereby counterbalance the gains from the reduced quantity of fish now available. The Scottish North Atlantic fishery management consortium should provide programs for workers in the fishing industry to develop skills to increase per fish gain.

### 3.2.4. National-Level Changes

The Scottish North Atlantic fishery management consortium should work to enhance their relations with the Scottish government, to enable flexible adaptive measures to climate change socks. These measures should include encouraging the government to lax quota on fish, improve relations with other countries to allow for fishing in non-Scottish territories, and create alternate employment opportunities for fishermen suffering the impact of climate change. This would include providing them with opportunities to learn more skills, or improving their fishing skills.

# 4. Conclusion

## 4.1. Strengths and Weaknesses

Some of the strengths of our model include:

- **Simplicity:** The model is easy to understand and simple to understand. We try not to overcomplicate things, while still maintaining the precision.
- **Focused:** Our model hones in on the effect of climate change (as shown by temperature) on mackerel and herring. There are several other changes that affect fish populations, but to keep our model focused, we decided to only look at one channel.
- **Variables Robustly supported by Research:** At every stage we have made decisions based on research including the change of temperature, the fish populations, the food availability and so on.
- **No Collinearity:** We eliminated collinearity between the variables to ensure that every variable that was added, was adding substantial amounts of information to the model.
- **Use of Index:** Several indices we created composited to form the model. Each index holds a lot of meaning, thus Small Fishing Companies can use each index to learn more about the fishing conditions in different ways.
- **Scope for improvement:** The simplicity and the use of indices, both make the model highly editable, which can allow us to easily revise and improve our re

Some of the limitations of our model are as follows:

- **Model weaknesses**
    - **Unit:** Our unit of measurement for location was 1 latitude and longitude. This leads to us discrediting the differences between different locations within the grid of 1 latitude and longitude. Due to this our recommendations were not as concise as possible.
    - **Lack of sensitivity:** Our model was not sensitive to different rates of temperature change, which means that it was giving similar recommendations for the sea heating it a faster rate vs. a slower rate.

- **Assumption weaknesses**
  - **Temperature** is the only thing that affects habitability was a simplifying assumption since after research we found that temperature was the strongest channel. There are, however other channels which we discounted.
  - **Time** it takes to harvest x number of fish is the same as the time it takes to harvest 2x. We made a questionable assumption about our fish harvestability to keep the model simple and concise, but accurate.

## 4.2. "*Not Finding Nemo: The Climate Change Effect on Migration of Northeast Atlantic herring and mackerel and new fishing guidelines*," an article for *Hook Line and Sinker* magazine

Whenever I heard about all the annual Food and Agriculture Organization of the United Nations and National Oceanic Atmospheric Administration of the US government reports regarding global warming, or ocean acidification, the numbers never made sense to me. How significant 0.13°C per decade increase in temperature could be?[14] Or 0.11pH in the past 200 years?[15] After all, who wouldn't mind a slightly warmer winter on the cold windy Scottish shores?

That was before a quite well-known UK consortium - the Scottish North Atlantic fishery management consortium - hired my team to investigate the migration of Atlantic herring and mackerel in the next few decades. Here's what we found: if you are a part of a small fishing company that goes after pelagic fish in that region, which prefer more temperate waters, chances are, you will go out of business in your lifetime, if you don't act *now*.

- If you are fishing on the west coast (Isle of Skye, Isle of Lewis, or not far from Applecross or Ullapool on the mainland), consider moving to the northwest. In approximately 35 years, all herring and mackerel will be gone too far north to Faroe Islands waters.
- Inverness and Aberdeen are safe for now, but in 50 years all the good pelagic fisheries will relocate to the territorial waters of Norway, making them inaccessible to all Scottish fishermen. If you plan to pass on your small fishing business to your children, or expand, then you should consider saving for on-board coolers to go after the herring by the Northern Isles and beyond, which are still in Scottish waters.
- John o' Groats and Wick fishermen are doing better than the western ones, but they are too far from the richer waters of Aberdeen. You have about 40 more years of fishing herring and mackerel.

*Recommendations:*

The decision to relocate might not come easy to you if you don't want to leave your hometown. Buying on-board refrigerators and technologically advancing your vessel can ensure your business lasting for several decades more.

For northeastern fishermen, it might be economically attractive to switch from pelagic to nephrops fleet.[17] Although it is hard to switch from one sector to another, the crustaceans are a good alternative opportunity. They can adapt to higher temperatures and might survive in the region for a few decades more than herring or mackerel.[16]

Finally, my advice to all fishermen, whether your fleet is based on the beautiful Scottish cliffs and green scenic sheep pastures, or anywhere else in the world, - climate change is real, and it is affecting all marine species to a great extent. So it is crucial to stay informed and develop new climate-aware tools to not only to sustain your business, but also not to endanger any ocean-dwelling species. They depend on us as much as we depend on them.

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