Problem Chosen	2020 MCM/ICM Summary Sheet	Team Control Number
A		2001438

Live Long and Prosper: How Herring and Mackerel Affect Scottish Fisheries

Abstract

Herring and mackerel have always been an integral part of the Scottish fisheries industry, and are more important sources of livelihoods for local fishermen. Therefore, studying herring and mackerel's future trends will be very meaningful and valuable.

First, we collect data of the daily catches of herring in the British waters over the 19 years at different latitudes and longitudes, combined with water temperature, water pressure, and water depth at the same period of time. We set up a linear regression model based on this model and find the optimal temperature for herring. Using it as the benchmark for us to indicate the possible location of these two fish over the next 50 years. **Secondly**, we use **'Profits for Small Fishing Companies Changing Model'** to analysis the best case and worst case for the small fishing companies to profit by calculating the impact of transporting time on the number of fish that can be sold. Protein and fat spoilage rate are taken into account for greater accuracy. **Thirdly**, we add parameter into the 'Profits for Small Fishing Companies Changing Model' and collect the expenditures of a small fishing company, to analyze the best suggestions for the local fishermen. Because our final predicted addresses for the two species of fish are not within the UK region, we have also listed the impact **territorial waters** on fisherman's fishing. And we do the model evaluation to indicate the weakness in our models. In the further discussion, we expect to give the alternative fish for the local.

What's more, we write an article for the small fishing companies to have a better understanding of the current situations and provide them with some suggestions.

Key words: Herring, Mackerel, North Atlantic, Fishery, Temperature, Migration

Contents

1. Introduction & Backgrounds

In order to indicate the most likely locations for these two fish species over the next 50 years, the information of these two fishes are worth mentioning.

1.1. Introduction of Herring

Herring has provided Scotland with plentiful, cheap and nutritious source of food for a long time. It eats such minute organisms as copepods, pteropods, and other planktonic crustaceans, as well as fish larvae. Herring is a cold-water fish. It is suitable for water temperatures ranging from 0-17℃, mostly in 6℃ water foraging, spawning in 16℃ water, and cold upper water migratory fish. It is used to travel in vast schools, providing food for larger predators such as cod, salmon, and tuna.

1.2. Introduction of Mackerel

Mackerel, with an annual value of over 89 million euros, mackerel is a very important species for the Scottish fleet. It is a fish with a water temperature of 0-20℃, mostly in 6℃ water foraging and spawning in 15℃ water and it is also a cold-water upper layer migratory fish. Mackerel is carnivorous fish and feeds on plankton, crustaceans, mollusks, fish eggs, and small fish.

1.3. Problem Restatement

As the global temperature rises, the temperature of the ocean also rises at an alarming rate year by year. When this change is too large, marine life will also be greatly affected. This blow made them have to find a new place to survive. However, these two species are critical to Scotland's fisheries industry and they create great value from them. Their migration will also take a toll on small Scottish fishing companies. In this article, we will better analyze the migration of Scottish herring and mackerel within the next 50 years on the premise of rising global ocean temperatures, in order to bring better suggestions to surrounding small fishing companies. We need to build mathematical models to solve the following problems:

Make a prediction of the most likely addresses for herring and mackerel over the next 50 years, in case of extreme changes in seawater temperature.

To analyze the best case, worst case and most likely elapsed time(s) until these populations are too far to harvest for small fishing companies with the address unchanged.

Propose plans for fishery companies to adjust business strategies such as relocating factories, using small fishing boats, or not changing.

2. Problem Analysis

2.1. Location of two Fish Species over 50 years

Under this problem, we set up a regression model based on the daily catches of herring in the British waters over the 19 years at different latitudes and longitudes, combined with water temperature, water pressure, and water depth at the same period of time. By obtaining the optimal temperature for herring, we use it as a benchmark to infer the position of the fish over the next 50 years.

2.2. The Best and Worst Cases for Small Fisheries to Gain the Profits

After removing many external factors, the only data that affects the profit of fishing companies is the number of fish that can be sold which is associated with the rate of deterioration of the fish. Since the freshness of the fish varies with the time it takes to transport to the port after fishing. The longer the transit time, the more fish cannot be sold. Therefore, we built the 'Profits for Small Fishing Companies Changing Model' to fit the impact of transporting time on the number of fish which can be sold. Combining these to the conclusion of Section 2.1, we can conclude the best case and worst case for small fishing companies.

2.3. The Strategy Improvement Suggestions

In terms of this question, we have to provide some solutions for the small fishing companies to make them continue developing in the next 50 years. And we also learned that all these kinds of companies haven't equipped freezer equipment in their boats. Therefore, we decided to build a model to test all the possible circumstances if we suggest them to equip this device. For example, we want to know how many boats that they need to equip with this machine would make them continue gaining profits in next 50 years. In addition, because we will predict the movement of the group of herring and mackerel, we also want to know what would occur, if we recommend them to relocate their companies positions or ports locations. Afterwards, according to the results of the model to provide the best recommendation to the small fishing companies.

3. Assumptions and Justification

By adequate analysis of the problem, to simplify our model, we make the following well-justified assumptions.

The only factor affecting the distribution and behavior of fish is the ocean temperature, and ignore uncertain and uncontrollable factors such as water quality, oxygen content, and climate.

The two fishes we mentioned in the introduction, because they both are cold-water upper migratory fishes and have similar suitable living temperature. Therefore, we assume they have similar habits and migratory routes.

Since herring and mackerel have the similar living conditions, the model have established for herring by default also applies to mackerel.

We abstract the locations of fish into a point, because herring and mackerel are gregarious animals so that we will use the latitude and longitude coordinates to locate the position of them, so as to get their migration route.

In order to eliminate the influence of population density, we assume that all the small fishing companies will not overfishing.

Assuming that in the absence of major economic problems and the global financial crisis in the next 50 years, the small fishing companies' operating costs should be maintained within a certain range.

Assume the average value of sales prices of herring and mackerel are stable.

4. Model Development

4.1. Approximate Location for Herring and Mackerel

4.1.1. Optimal Temperature for Herring and Mackerel

Combining daily water temperature, water pressure, and depth data for different latitudes and longitudes in British over 50 years and the herring catches at relevant latitude and longitude, we use Matlab to set up a regression model to predict the optimal temperature for herring. And the optimal temperature is 6.0489℃. From this we will use 6.0489℃ as a benchmark, and study the position of the fish by studying the different positions of this benchmark in British daily.

4.1.2. Forecast of Heat Capacity of North Atlantic

In order to evaluate the temperature changing in North Atlantic Ocean, we decided not to directly using temperature to do the prediction. We will use the heat capacity to evaluate the caloric content of seawater per cubic centimeter instead of the seawater temperature change assessment.

Then we collected 602 data for the heat capacities changing in North Atlantic per month from 1970 to 2020.

Due to the scatter plot showing above, our team decided to apply the linear regression to predict the heat capacity's changing in future.

After we having made the decision of how to build the temperature prediction model, we start to using python to do the linear regression. Then get the fitting line displaying below:

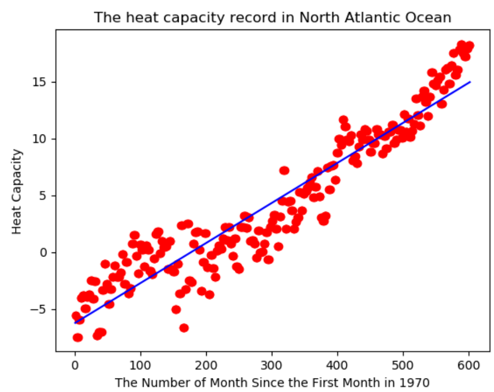


Figure 1 The Heat Capacity Record in North Atlantic Ocean

In this case, we can easily get the knowledge about that the heat capacity's in North Atlantic Ocean is increasing when the time went by.

4.1.3. Forecast of Sea Surface Temperature Data in North Atlantic

Using a linear regression model (least square method), we can get the function curve and function relationship of temperature and time.

If we only use the existing 50-year data to predict the water temperature change in the next 50 years, it will produce very predictive errors, so we choose to use the gray prediction that is we use the data from the first 50 years to predict the data for the 51st year, and then bring the data from the 51st year into the 50th year, so as to predict the 52nd year. Then we can get more accurate prediction functions and results. Through prediction, we can predict the model of time and temperature in the Figure 2.

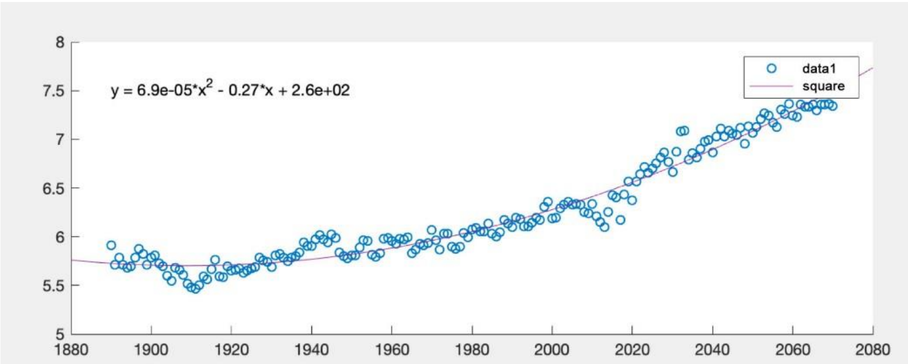


Figure 2 The Sea Surface Temperature Changing Prediction

4.1.4. Relationship between Temperature and Time at Different Latitudes and Longitudes

Since the data in this paper does not follow sudden changes in data, it advances at a relatively small pace; past and current phenomena can indicate current and future trend of changes (the gray prediction), so we use a Time-Series model, with Scotland as the origin, and latitude and longitude as the coordinate axis to establish a coordinate system. By studying the temperature changes in the surrounding area, find the area closest to the reference temperature (6.0498°C).

We select the annual data from ‘50-month global sea surface temperature data from 1970 to 2019’ as a sample for Time-Series Analysis modeling and prediction, with a sample capacity of 50 (blue line in Figure 3). Due to the limitations of direct predictions, we use smoothing method to smooth the data. The average value of two adjacent data is inserted as a data between these two data to obtain 49 average values. The obtained average data is added to the original data to obtain new data and this new data (red line in Figure 3) is used to make a timing chart (Figure 3) using statisticala software.

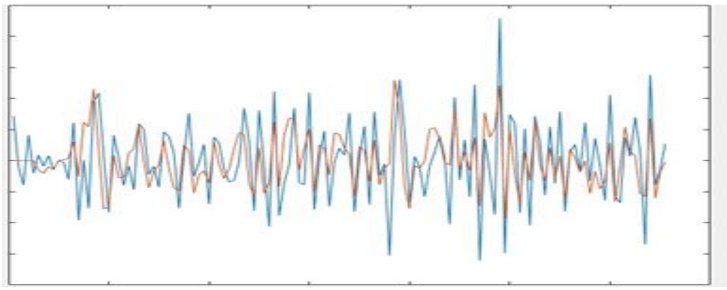


Figure 3 The Timing Chart

Next, we perform a white noise test on the data on the timing chart to indicate whether it is usable or not. Since the data is not a stationary series and is not white noise, we perform a first difference method on the data and use the auto-correlation function ACF to detect it. We get Figure 4.

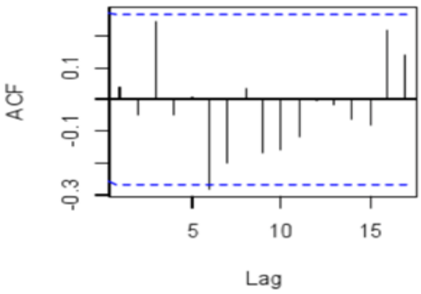
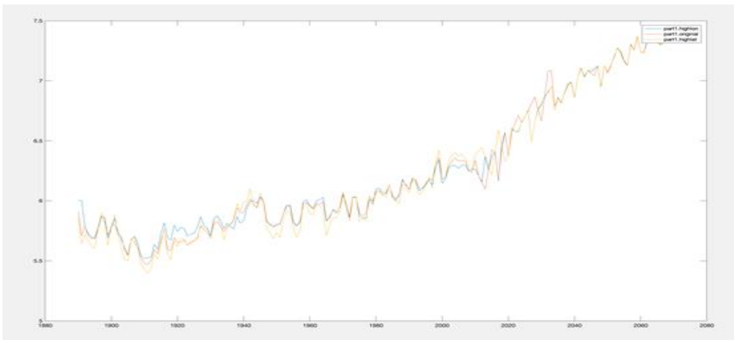


Figure 4 The ACF Image after First Difference Method

From the Figure 4, we can see that the data after first difference method meets the needs of the prediction model, so we perform parameter estimation and prediction on the data after the first difference method which create the Figure 5.



(In Figure 5 the blue line (high lon)) refers to the region that has bigger longitude than Scotland; the red line (original) refers to Scotland; the yellow line(high lat) refers to the region that has bigger latitude than Scotland.)

We can see that the temperature in high latitudes is lower than that in low latitudes, and the global warming rate is relatively slow. However, the temperature difference between high latitudes and Scotland is not large, so we infer that the trend of temperature changes more slowly toward the north, and the sea surface temperature at the same time is lower.

4.1.5. The Predicted Location

Since we already know the trend of sea surface temperature changes, we bring the predicted data into the weather processing software, and we can get a map of sea surface temperature changes (the darker the blue, the higher the temperature) in the next 50 years Figure. 6-11. (one every ten years)

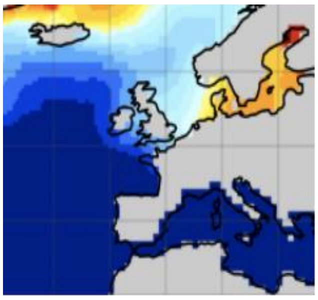


Figure 6 2020-2030

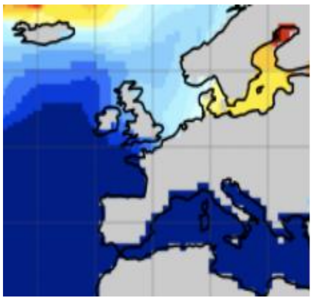


Figure 7 2030-2040

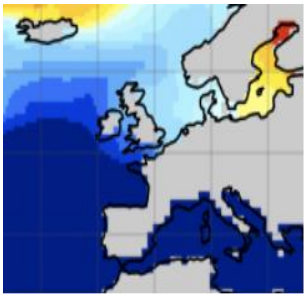


Figure 8 2040-2050

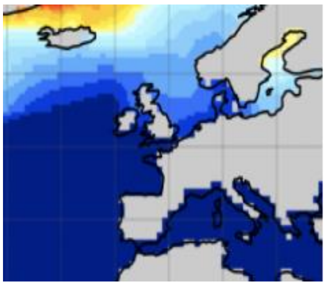


Figure 9 2050-2060

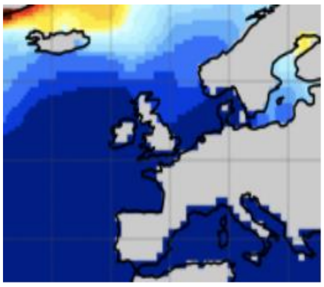


Figure 10 2060-2070

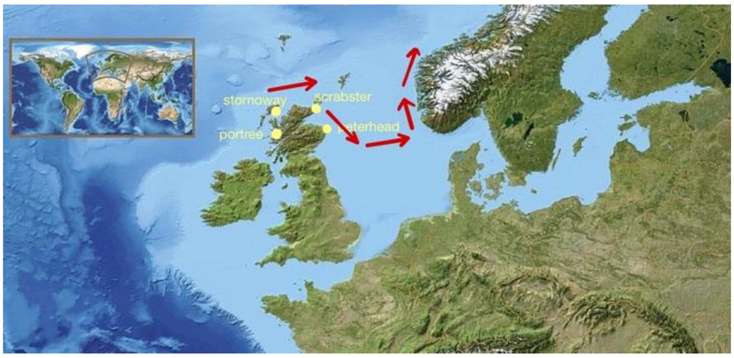


Figure 11 The Migration Route of Herring

From figure 6-11 we can conclude that due to the constant temperature change, the gradual increase in temperature in the United Kingdom is no longer suitable for herring, and it gradually migrates to Norway. We map out its migration route (Figure. 11) and the locations indicated above are all the famous ports.

Since this article predicts the fish migration direction in the next 50 years, the prediction time is too long, and it is easy to cause large errors. Therefore, we combine the known data and the living habits of herring to make the following guesses: at the same sea level, the North Sea is colder than the Atlantic, so the school of fish will migrate to the colder North Sea first. However, as the temperature rises, the school of fish will not continue to migrate to the North Sea but will continue to move northward, into the territorial waters of Norway. Based on this forecast chart and data, we can speculate that it will be difficult to catch herring and mackerel in Scotland by about 2050.

4.2. Profits for Small Fishing Companies' Changing Model

4.2.1. Modeling Notation

The Notation	The Meaning
c	Cost of small fishing company
s	Mean price of each ton of herring and mackerel
n	The number of tons of catching herring and mackerel
n_hat	The number of tons of herring and mackerel which can be sold
proteinSpeed	Rate of protein deterioration
fatSpeed	Rate of fat deterioration
meanSpeed	Mean rate of protein and fat deterioration
p	Output of profits
t	Transporting time from fishing catch point to port.
g(x)	Function to get the probabilities between $-\infty$ and input x in standard normal distribution

4.2.2. Relationship between Profits and Transport Time

In order to fit the deterioration rate of herring and mackerel, we decided to use the standard normal distribution. We use $mean\mathrm{Speed} * \mathrm{t}$ to be the input of the standard normal distribution. And then we assume that the area between $\mu + mean\mathrm{Speed} * \mathrm{t}$ and $\mu - mean\mathrm{Speed} * \mathrm{t}$ to be the probabilities of how many caught fish will be deteriorated among the transporting. Then we can easily get the amount of fish available for sale as a function of shipping time. Then we can get the equation (1):

$$n_{hat} = (1 - 2 * g(meanSpeed * t) - 0.5) * n$$

Now we can also get the equation (2) about profits and transport time t:

$$p = s * n_{hat} - c$$

4.2.3. Determination of the Mean Speed

The $mean\mathrm{Speed}$ is used to point out the average deteriorative rate of the herring and mackerel. With our teams searching, we noticed that the most significant part of herring and mackerel are protein and fat. Therefore, we concentrated to figure out the $mean\mathrm{Speed}$ by pointing out the mean protein deteriorative rate and mean fat deteriorative rate of herring and mackerel.

The we got the data about the mean protein content of these two fish is 18.7g per 100g and the mean fat content is 16.7g per 100g. And the mean weight for each fish is 800g.

We then investigated that the average complete deterioration time of the fish was about 24 hours

Therefore, through all of this data, we got the $\mathrm{proteinSpeed}$ is 6.23333. And the $\mathrm{fatSpeed}$ is 5.56666. Then, because the standard deviation of the standard normal distribution is only 1, we reduce the two rates by 100 times in equal proportions and calculate the $mean\mathrm{Speed}$ is 0.05899995.

4.2.4. The Prediction of two Case

We directly picked up some small fishing companies which using the port named Scrabster to do their businesses and using their data about the mean number of catching fish, which is about 20000 ton per year, and their mean cost, which is about 2780000 pounds per year, then training this model. We also searched about the price of herring and mackerel and computed their mean price which is 1100 pounds per ton.

Then we use this model to do the training, beginning with the initial t = 24h. We get the result that as long as the transporting time larger than 25 hours the company will start to deficit.

Because the premise of our model is that we do not consider the abnormal changes in fish density, which means we assume that the fishing company's fishing strategy is a sustainable development strategy, and the annual fishing volume will not exceed half of the fish population. (The number of biological populations is sustainable. Assuming the number of populations is k, the number of catches is not more than k / 2, then the population can be maintained at a certain level.)Under this premise, we assume the density of fish populations in the next 50 years will be no abnormal changes, so the theoretical catch should be kept in the same distribution as the previous data. Then we use the average of previous fishing data as the average catch in the next 50 years.

Since we know that if the transporting time is larger than 25 hours the companies will start to deficit.

Because the average speed of fishing boats is 20 kilometers per hour, as long as the location of the group of fish is 500 kilometers away from the port, small fishing companies will start to lose money.

Thus, for the worst case, based on the results of our research, we believe that the critical point when a fish group moves to the circle boundary which use a port as the center of the circle and 500 kilometers as radius is the worst case (Figure.12).

Figure 11 Worst Case (One Green Arrow Equals 10 Years Migration)

From the figure above, the green line indicates the movement path of the group of fish in the next 50 years, and the red circle is a critical circle centered on the port of Scrabster. Then we can see that it is the worst-case critical position when the group of fish is close to the Aras River in Norway. And because for each arrow, it represents a decade, then we can know that the critical year for the worst case is the around 2060.

At the same time, according to the image, we can see that the orange arrow is showing the shortest path between the fish catching point and the port. Therefore, we can define that the best case is approximate between 2030 and 2040, around 2034. At the same time, the position of the school of fish at any time in the red circle can allow small fisheries companies who use Scrabster to be their ports to continue to get profit.

4.3. The Improvement Suggestions

By analyzing our forecast data, we already know that by 2060, small fisheries companies using Scrabster as a port will begin to lose money. Therefore, we propose two amendments here to maintain the sustainable development of small-scale fisheries.

Since the fishing boats of the small Scottish fishing companies are not equipped with refrigerating and freezing facilities, the herring and mackerel caught are liable to deteriorate quickly in a short time. Therefore, our first recommendation is to let small fisheries companies equip their own fishing vessels with refrigerated freezers.

Therefore, we reanalyzed the same data after equipped with a refrigeration unit. Through our data search, we learned that the price of one kind of cold room is about 132,141.87 pounds, and the effect of cold storage can be kept fresh for about 60 hours.

Based on this data, we modify the 'Profits for Small Fishing Companies' Changing Model', and retraining it.

The change is that we add the new parameter b to obtain the number of boats which will be equipped refrigerated freezes. Then use b to modify the parameter c which is represent the cost, by adding c with 132,141.87 times b. And also change the $proteinSpeed$ and $fatSpeed$ divided by 60 hours rather than the original 24 hours.

After that, we first calculate that how many ships equipped with refrigeration units, the company would also start to lose money in 2060. By adjusting parameter b, we find that when 70 ships are equipped with refrigeration equipment, small fisheries companies will also start to lose money in 2060.

We then use Google Earth to roughly estimate the distance of the school of fish from Scrabster port in 2070, which is about 800 kilometers. Then, adjust parameter b to find that after equipping 35 fishing vessels with refrigeration equipment, small fishery companies will start to lose money when the transmission distance consumes more than 40 hours. (Approximately 800 kilometers, because we assume an average fishing boat speed of 20 kilometers per hour). This means that as long as the number of small fisheries-owned vessels equipped with this type of refrigeration device does not exceed 35, within 50 years, it will not cause losses due to herring and mackerel catching point is too far away from the port (Figure. 12).

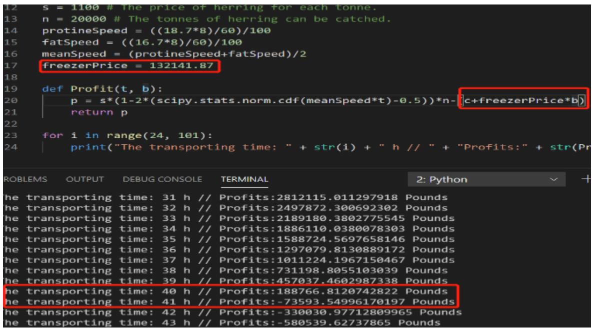


Figure 12 The Model Modified and New Result

4.4. The Territorial Waters Problem

From the result we get, herring and mackerel will both migrate at Norway in 2070. Before brexit, the UK needs to follow the EU's common fisheries policy. In 1973, the European Union put forward the principle of "free access to fishing": all Member States open their waters beyond their coastlines to each other. In 1992, the newly revised

Fisheries Act came into effect, and the EU's principle of free access to fish was extended to EU waters beyond 12 nautical miles, but the operation of waters beyond 12 nautical miles was still strictly restricted.

On January 30, 2020, EU officially approved brexit, but whether the UK continues to share fishing areas with EU Member States has not yet been enacted. Within the framework of international law, after brexit, Britain became an independent coastal state with an exclusive economic zone of 200 nautical miles. But "control" is not absolute. According to the United Nations Convention on the law of the sea, Britain is obliged to manage parts of the North Sea and the Atlantic Ocean shared with Norway and the European Union. From the above conclusion, we can know that the fish will migrate to the north and go to Norway, so we mainly consider the impact and solutions when some fisheries move to another Norwegian territorial sea (sea area).

In terms of international fishing quotas, they are reached through bilateral or multilateral fisheries negotiations. Norway is a participating country of ices, which regularly evaluates the fish resources of the countries concerned and proposes quotas for the next year. National fisheries authorities rotate in the autumn of each year to conduct international negotiations among members, discussing and negotiating the allocation of fishery resources among Member States. After the quota has been initially determined, the members of the Committee submit it to the Council for approval and implementation. For example, the COD resources at 62 degrees north latitude belong to the shared resources of Norway and Russia. Therefore, the two countries take the disputed sea area as the sea area jointly managed by two countries, jointly investigate the important fishery resources, and set quotas based on this to submit to the ACFM Resources Group under ices. The team proposes 3-5 options for Russia and Norway to choose based on the data submitted and the suggestions of fishermen and professionals in the relevant areas. At last, two countries negotiate to determine the quota.

Therefore, the UK can learn from this way to establish a common fishing area with Norway. And in accordance with the "Fishing law of foreign fishing vessels in Norway's exclusive economic zone" promulgated by the Norwegian government on May 13, 1977, they only operate in the waters of 12-200 nautical miles. Ensure that there is only one fishing license for a fishing vessel and that it is not transferred. The fishery license shall indicate fishing gear, fishing ground, quota, validity period of the license and permitted fish species. Mark the fishing vessel and fly the national flag of the country where the vessel is registered.

5. Model Evaluation and Further Discussion

5.1. Model Evaluation

The sea is vast and mysterious. It has energy, resources, and creatures that human cannot imagine. The present of a creature represents the renewal of thousands of ecosystems and changes many elements. Our team used the seawater temperature near Scotland for nearly 50 years and the fixed fishing points and catches of herring and mackerel for Scottish ports for nearly 50 years as the main parameters to predict the relocation site after 50 years. Through forecast locations and economic considerations, we have also made recommendations to small fishing companies in Scotland. However, our models still have many weaknesses:

We use the temperature of seawater as the main parameter, and ignore other potential factors, such as the temperature suitable for mackerel and herring cubs, and the suitable temperature of phytoplankton that these two fish eat in large quantities.

We did not include the fish density data in the parameters, but replaced it with the average of previous fishing. This makes it difficult for us to accurately calculate which point in time is good or bad for fishermen.

5.2. Further Discussion

In addition to the impact of sea surface temperature on fish, there are other factors, such as climate and salt. Due to the different adaptability of different species of fish to the climate and the ability to regulate and infiltrate salt, the distribution and migration direction of fish are also different. In order to make the model more perfect and accurate, we can consider the living environment preference of different fish and the influence of natural enemies in dependent variables.

Taking fish density changes into consideration and combining their migration routes can give fishermen more accurate information and better suggestions.

6. An article for the local fish company

As we all known, Britain is an island country, surrounded by the sea, with a long coastline and rich fishery resources. It is one of the most important fishing countries in Europe. Scotland's fisheries account for 80% of the UK's total production. As one of the three major industries in the UK, fishery has made great contributions to the UK economy and provided a large number of jobs for fishermen.

From 1652 to 1674, three wars broke out between the Netherlands and Scotland. The direct cause of the conflict was that the Netherlands tried to seize the fishing grounds in Scotland. In the 17th century, the Netherlands became the economic center of the world because herring and mackerel swam to the northern sea area of the Netherlands every summer, with an annual fish volume of about 10 million tons. Most of these fish passed through Scotland Field. At the same time, mackerel has become the most valuable fish in the whole Scottish fishery due to its sustainable development, with a total annual export value of more than 100 million pounds. Therefore, the migration of mackerel and herring is very important for Scotland's economic development.

But in recent years, with the global warming, the sea surface temperature in the sea area near Scotland is increasing, and it is no longer suitable for herring and mackerel. According to our prediction, from 2020, the fish will migrate from the North Atlantic to the North Sea where the temperature is lower; around 2040, because the temperature in the North Sea is gradually increasing, it is no longer suitable for the survival of fish, and then the fish will migrate northward to Norway; around 2050, it will be difficult for the fishermen to catch mackerel and herring in the original fishing area. This will have a major impact on local small-scale fisheries.

We have investigated and studied the best and worst cases scenarios for small fishery companies with constant address. Here we will set the port of Scrabster as the center of the circle. If the fish move to the critical point of the circle boundary with a radius of 500km, this will be the worst case, which we predict will happen around 2060.

The best is between 2030 and 2040, when the small fishing company in Scrabster will continue to make profits as usual.

However, after 2060, it will be difficult for small-scale fishery companies in Scotland to maintain their original status. Therefore, we have integrated the economic and other conveniences, and we have come up with a plan for you, that is, to equip small fishing vessels. We have calculated the cost of equipment, as well as the approximate rate of fish deterioration and the value after configuration. We found that as long as the number of fishing boats is within 15, even if they are equipped with refrigeration equipment, they can meet the requirement of 50 years without loss. So, we recommend that you can buy small fishing vessels to ensure the quantity and quality of fishing. Since 20 years later, the fish will migrate northward to Norway, so the fishermen in Scotland will enter the territorial waters of Norway and other countries if they want to continue fishing. Since the UK left the EU on January 30, 2020, although the relevant laws on whether the UK continues to share fishing areas with EU member states have not yet been enacted, within the framework of international law, the UK after the brexit has become an independent coastal state under the jurisdiction of the United Nations Convention on the law of the sea (UNCLOS). Therefore, as an independent country not a member of the European Union, it is necessary to follow the fishing law of foreign fishing vessels in Norway's exclusive economic zone when entering Norwegian territorial waters, i.e. only operating in 12 to 200 nautical miles. Ensure that there is only one fishing license for a fishing vessel and that it is not transferred. The fishery license shall indicate fishing gear, fishing ground, quota, validity period of the license and permitted fish species. Mark the fishing vessel and fly the national flag of the country where the vessel is registered.

So here we call on the government to act. To establish a co fishing area with Norway, through bilateral negotiations or multilateral negotiations relying on ices, the countries of both sides shall regularly assess the fish resources in the fishing area every year, put forward the quota proposal for the next year and submit it to the ACFM Resources Group under ices. Based on the data submitted and the suggestions of fishermen and professionals in relevant areas, the group puts forward 3-5 plans for the countries of both sides to choose, and finally negotiates and decides the quota for the next year. The establishment of common fishing areas and the improvement of relevant laws will be a strong pillar of the development of British fisheries.

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