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Keep Moving North: Where fish live in the next 50 years

Summary

There is no doubt that the trend of global warming is leading to the rise of ocean temperature and affecting the survival of many organisms. Herring and mackerel in Scotland are also carrying out a large-scale migration due to it. For Scottish fisheries, this will be bound to cause a huge impact on them.Hired by Scottish North Atlantic Fishery Management Consortium, we predict the distribution of these two species over the next 50 years, analyze its impact on small fishing companies in Scotland, and give reasonable suggestions for their business strategies.

First, we make a function fit to the ocean temperature change rate and the relationship between herring and mackerel density and temperature. Considering the fact that fish has sensory organs, we establish a **cellular automaton model**, which combines temperature, population, and corner factors to predict the distribution of fish schools in the next 50 years. We use **K-means cluster analysis** method to analyze its aggregation center. Comparing the changes in fish clusters over the next 50 years, we find that fish schools tend to move northward and away from the Scottish land.

Secondly, based on the available data, we set the standard that if the profit of a small fishing company drops below 75% of its initial profit after 50 years, the company will experience an "operating crisis". We select 8 typical companies as samples for analysis. The most likely scenario is a crisis in 2037 and the worst scenario is 2030. The best scenario is to maintain the current trend, which will prevent the crisis until 2070, but the overall profits will still decrease.

Finally, as a consultant, we made **decision-making suggestions** to the fishing companies: 1. upgrade the fishing equipment; 2. move to the port closer to where both two fishes accumulate; 3. upgrade the equipment and move the site at the same time; 4. Improve the surrounding environment to attract fish. For the sample of eight companies, we analyze the expenses and revenue of each solution and select the optimal strategy for each company. **It is worth noting that** considering that fishing vessels cannot enter other countries' territorial waters and exclusive economic zones for fishing, and that the number of fishes that can be caught in British exclusive economic zone has increased after Brexit, we need to appropriately reduce the scope of fishing and increase the amount that can be caught. Then re-decision.

In the sensitivity analysis, in order to analyze the influence of parameters on the results, we focus on the analysis of the temperature change rate, the iteration times of the Fish Cellular Automaton Model, the evaluation index of whether fish populations will be too far away for small companies to harvest, and the parameters that affect the costs and benefits of each strategy. **What's more**, we prepare an article for the magazine to help fishermen understand the seriousness of this problem and how our proposed solutions will improve their future business prospects.

Contents

1 Introduction

1.1 Problem Restatement

In recent years, the trend of global warming has become increasingly apparent. Ocean temperature is also rising, threatening the survival of some marine life. This forces them to leave their original habitats for large-scale population migration. Scottish herring and mackerel are part of it. Herring and mackerel are essential economic sources of Scottish fisheries, and this migration has severely disrupted the vitality of Scottish-based fishing companies. Even worse, this could be a disaster for small fishing companies.

As a consultant to the Scottish North Atlantic Fisheries Management Association, we face the following issues:

1. Analyze changes in sea temperature over time and the effect of sea temperature on fish migration trajectories and make reasonable predictions.

2. Investigate how small fishing companies operate with changes in sea temperature, including the best case, worst case, and most likely elapsed time.

3. Based on future forecasts, analyze whether small fishing companies need to relocate company assets and asset ratios, and study the impact of some fishery moves into another country's territorial sea.

1.2 Our Work

First of all, in order to study the change of sea temperature with time, we draw a fitting curve of the temperature change rate according to the ocean temperature changes from 1961 to 2019 [3, 4] and add the temperature that changes linearly according to the year. The κ value that measures the change rate can be controlled artificially. At the same time, according to the initial sea temperature map and the density distribution map of 0-group herring and mackerel [2], the relationship between the occurrence probability of the two fishes and the sea temperature was obtained, and the images were fitted to a normal distribution.

In analyzing the movement model of fish migration, since the migration of herring and mackerel is spawning migration, which has the characteristics of fixed route, time and direction, we ignore the seasonal migration of fish in this model. The overall movement trajectory in the same time period of each year is selected as the research object. In addition, because fish have sensory organs, they can sense the temperature and direction of water flow.

According to the above conditions, we establish a cellular automaton model and divide the study area into small cells of 300 * 300. According to the calculation of the scale, it is verified that the fish swim within one grid each year. The number and temperature data of fish in each grid are linearly interpolated from the original data. According to the Bayesian formula and the normal distribution density function, the probability that the temperature factor attracts the fish to a specific grid can be obtained. At the same time, the influencing factors of the number of fish on the fish's desire to swim are considered, as well as the edge probability factor of the fish spreading in a circle under the same environmental conditions. Based on the corner factors, population factors, and temperature factors, the probability of the fish reaching a specific grid (including in-situ motion) is known. Based on the fish distribution map and sea temperature map at this moment, the fish distribution at the next moment can be obtained. Iterate this way.

In order to more intuitively observe the trajectory of fish migration, we use K-means clustering analysis to find the main distribution locations of fish, and the results show that the whole migrates north.

Then, after analyzing the operation of small fishing companies in Scotland, we selected eight representative companies as the research sample and verified that the fishing range was basically consistent with the initial fish distribution map.

By studying the tonnage and net profit of British herring and mackerel exports in previous years, combined with the average weight of a single fish and the company's catch range, we calculated the selling price of each fish and the net profit of each company's initial year. Under different temperature growth rates (κ), we predict the change of company earnings in 2019-2070, and draw a curve. According to different evaluation factors, estimate the best case, worst case, and most likely elapsed year of fish swimming.

Based on the company's operating conditions and the prediction of fish distribution, we have made the following decisions for small fishing companies: upgrade fishing equipment, change company address, upgrade equipment and change address at the same time, improve the current living environment of fish and stay in place. Comprehensive analysis of the costs and benefits of each decision, we choose the appropriate parameters to get the company's optimal decision, and we recommend that most companies combine fishing boat upgrades and transfer some assets north to get better returns. When taking into account the movement of some fish to other countries, the catchment scope of domestic fishing companies will be reduced, which will definitely affect our final decision.

2 Assumptions and Justifications

To simplify our model and better analyze the problem, we made these major assumptions:

1. The population of the herring and mackerel will not have significant variations within the next 50 years, which indicates that their optimum seawater temperature remains the same. Besides, the quantity of these two species are abundant and will not change significantly.

2. Ignore the inconsistent increase in seawater temperature caused by human factors, ocean currents, seawater properties in different regions, and other factors. Since the sample is Scotland and its surrounding waters, which is a small region, we assume that the sea temperature change is evenly distributed in different spaces.

3. The inter-species relations that affect the life of herring and mackerel, such as predation and competition, are expressed in the form of temperature. That is, the environment in regions with suitable temperature is also more attractive for herring and mackerel. That's because the distribution of other species is also affected by global warming.

4. Ignore seasonal migration of herring and mackerel. Since herring and mackerel are spawning migratory species, their routes, directions, and times have relatively fixed characteristics, and their randomness is small. Therefore, in analyzing and forecasting, we ignore their seasonal migratory phenomena and study the overall migration of the same period each year.

5. Herring and mackerel tend to look for an environment more conducive to their own survival. This is because they have the ability to sense the temperature and direction of the current, and can observe the number of fish around.

6. The basic situation of the number of fishing vessels, operating methods, and fishing methods of the sample companies will remain unchanged in the next 50 years. Considering that the size of the company cannot be changed significantly, we believe that its basic situation will not change.

3 Notations

symbols	definitions
κ	parameter to measure how rapidly the ocean water temperature change occurs
τ	iteration times per year
λ	percentage to judge whether fishes are too far away for small fishing companies
$\alpha, \beta, \gamma, \delta, \zeta, \epsilon, a, b$	evaluation factors in Company Strategy Model
W	width of each cell (km)
H	height of each cell (km)
p_i	the probability of fish move to grid number i
G_i	the temperature in the grid number i obtained by fitting the gaussian function
ω	the profit
X	the amount of fish

Table 1: Notations

4 Fish Migration Model

Mackerel is a kind of migrating pelagic fish living in the Northeast Atlantic. It has a large population and prefers to live in groups. It feeds on zooplankton and the upper larvae and juveniles of many commercially important fish populations and plays an important role in ecology. In winter, it swims in deep waters to spend winter, and in spring it swims to coastal waters to lay eggs.

Herring is commonly found in the temperate zones in sallow water of the North Pacific, North Atlantic, Baltic Sea, and the west coast of South America.They have cold-water migration habits. They play an important role in European fisheries.

These two species both have the habit of seasonal breeding migration. In order to better predict the distribution of mackerel and herring in the next 50 years, we study their migration behavior in the same period of each year, ignoring the impact of their seasonal migration.

4.1 Rate of Temperature Change

We get the sea temperature data from 1961 to 2019 from NASA Earth Observation Database (NEO)[3, 4]. We find that the variation of seawater temperature is cyclical and the seawater temperature has a trend of increaing in the whole. We use the sum of one linear function and three sine functions to describe the relation between seawater temperature and time. cf. function (1).

$$y = a_1 \sin(b_1 x + c_1) + a_2 \sin(b_2 x + c_2) + a_3 \sin(b_3 x + c_3) + tx + s \tag{1}$$

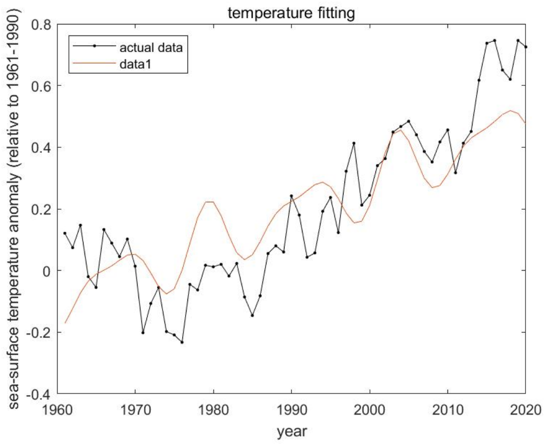


Figure 1: temperature fitting from 1961 to 2020

The curve fitting result is shown in Figure 1. It is required that the variation of seawater temperature should be large enough for Herring and Mackerel to migration. Thus, when we predict seawater temperature from 2020 to 2070, we add an extra linear factor

$$\frac{3\kappa}{51}(x - 2019)$$

Then we can predict the seawater temperature from 2020 to 2070. cf. Figure 2.

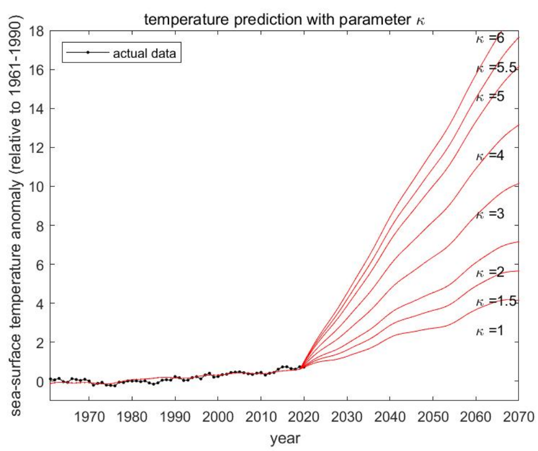


Figure 2: temperature prediction from 2019 to 2070

Finally, we choose the most appropriate one $\kappa = 3$ to study the distribution of herring and mackerel in the next 50 years.

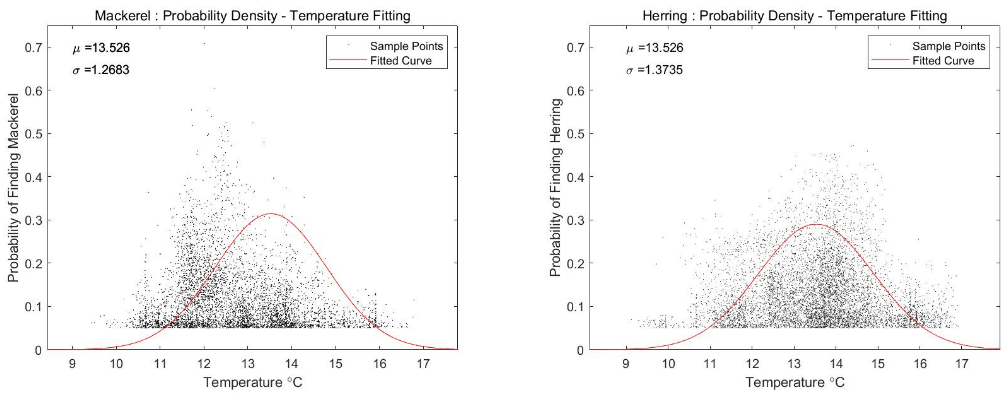
4.2 Effect of Temperature on Fish

We have assumed that seawater temperature is an important factor affecting the distribution of herring and mackerel, and that the sea temperature will change to the same extent in the area near

Scotland. In addition, since mackerel and herring are both pelagic fish, we choose the sea surface temperature for evaluation.

According to the data we get from NASA Earth Observation Database(NEO)[1], we take the seawater temperature as the original temperature. We can find the data of 0-group Herring and 0-group Mackerel distribution in 2017 from the official website of the Scottish Government [2], we can use it to estimate the fish distribution in 2019. Based on this we can get scatter plots of fish and sea temperature in 2019. We can find that their distribution is approximately normal distribution, we use the normal distribution function to fit, and get the relationship between fish density and seawater temperature. cf. Figure 3(a), Figure 3(b).

Note: Points whose value is less than 0.05 are not counted.



(a) fish density - temperature for Mackerel (b) fish density - temperature for Herring

Figure 3: fish density - temperature curve fitting

4.3 Cellular Automation Model of Fish

According to the hypothesis, the fish has a sensing organ and can sense the temperature of the surrounding environment. And fish are more inclined to find suitable environments. In this model, we assume that all fish make decisions at the same time when determining their trajectory.

We take the square area between $(18°W, 63°N)$ and $(12°E, 48°N)$as the research scope, and divide it into small cells of $300 * 300$. According to the scale, take the middle latitude and longitude $(3°W, 55.5°N)$ to calculate W and H (Width and Height). cf. equation 2.

$$\begin{aligned} W &= 6371 * \cos(55°) * 2 * \pi * \frac{30}{360 * 300} \approx 6.3 \\ H &= 63712 * \pi * \frac{15}{360 * 300} \approx 5.5 \end{aligned} \tag{2}$$

The number and temperature data of herring and mackerel per grid can be obtained by linear interpolation of the original data. One grid represents $6km$ in reality approximately. According to the data[9], from 1968 to 2008, mackerel moved $250km$ northward and about $50km$ eastward, and the average annual movement was about $6km$, which is consistent with the length of each side. When there is a fish in a grid, because it moves about $6km$ per year, which is exactly the length of one grid, it will only move around 9 grids (including the original place) each year.

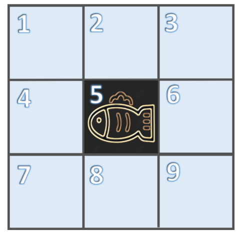
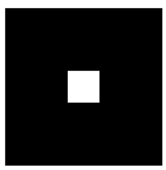
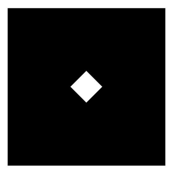


Figure 4: The sketch map of cells

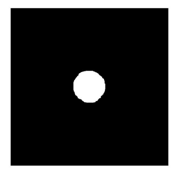
If the surrounding 8 blocks (except the original place) have the same conditions, the probabilities of fish movement to those blocks are the same. It is not difficult to imagine that the final result is a square. If we only consider that the fish moves to the grid number 2,4,6,8, and the probability is the same for each grid under the same conditions, the final result should be a rhombus. According to the actual situation, the result of fish diffusion should be a circle, so the probabilities that the fish swims to the corner number 1,3,7,9 are $\frac{\sqrt{2}-1}{2}$ times the probabilities that of cell number 2,4,6,8 under the same conditions, and the result will be a circle under this circumstances. cf. Figure 5



(a) square



(b) rhombus



(c) circle

Figure 5: Three situations above when fishes spread from the center

Use the value of the fitted normal distribution curve to indicate the probability of a fish entering. From the Bayes formula, the probability that the fish swims to the grid number i can be calculated by equation (3).

Note : G_i is the temperature in the grid numberobtained by fitting the gaussian function.

$$p_i = \frac{G_i}{\sum_{j=1}^{9} G_j} \tag{3}$$

Taking into account the Logistic population growth model, the larger the original number of fish, the lower the desire to swim. Therefore, the probability of each cell is multiplied by $\frac{1}{X_i+1}$. In addition, p_1, p_3, p_7, p_9 must be multiplied by the corner factor $\frac{\sqrt{2}-1}{2}$. After correcting p_i so that $\sum_{i=1}^{9} p_i = 1$ Combining three factors, using random numbers, we can get the fish distribution at the next moment based on the current fish map and sea temperature map. We call such a process an iteration. τ is defined as iteration times per year. Fix τ as 10, we can simulate the fish migration of 2020-2070 fish.

The red points in Figure 6 represent mackerels while fuchsia points represent herrings. The points where the temperature is equal to 0 are mostly land.The same rule applies to the following figures. Using cellular automaton algorithm to iterate 50 times over the fish distribution map of 2019. Compared the fish distribution map of 2019 (Figure 6) to the result (Figure 7), the overall distribution of the fish has not changed much, so the algorithm can be considered reasonable.

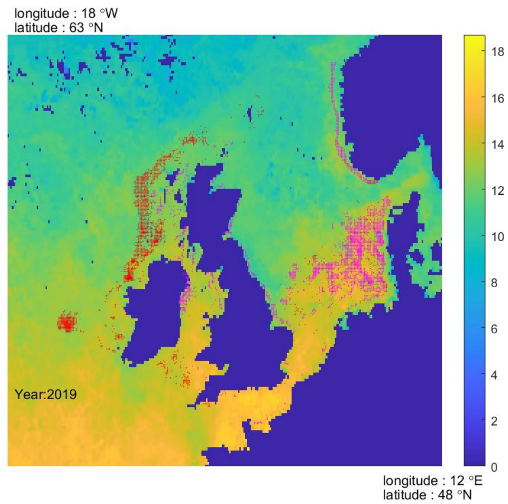


Figure 6: fishes in 2019

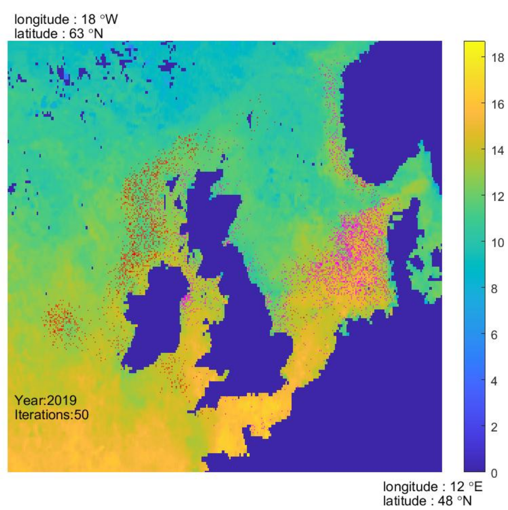


Figure 7: fishes in 2019 (iterate 50 times)

4.4 Clustering Analysis

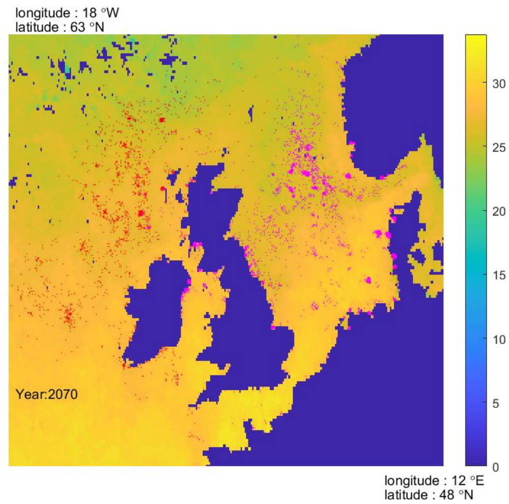


Figure 8: fishes in 2070 (iterate 10 times per year)

After obtaining the estimated distribution of two types of fish in 2070 (Figure 8), we used K-means clustering analysis to find the accumulation points of fish.

The K-means clustering method calculates multiple aggregation centers of a point set by iterating. First, we randomly selected K samples as the initial cluster centers, and then calculated the distance between each remaining sample and each cluster center. And assign each point to the cluster center closest to it. The cluster center and the samples assigned to it represent a cluster. For each point assigned, the clustering center of the cluster is recalculated based on the existing point set in the cluster, and iteratively repeats until a certain termination condition is met. The termination condition may be that no (or minimum number) samples are reassigned to different clusters, at this time no (or minimum number) cluster centers change again, and the squared error and local minimum. We use K-means clustering analysis to find the aggregation centers of the two fish distributions, so that we can more intuitively see the azimuth trend of the migration of the two fish schools.

We found 10 together accumulation points for each of the two fish species. cf. Figure 9. The blue points represent the accumulation points of mackerel while the blue-green points represent those of herring. The same rule applies to the following figures.

Detailed latitude and longitude information can be found in the appendix.cf. Table 5. Negative longitude is west longitude and positive longitude is east longitude.

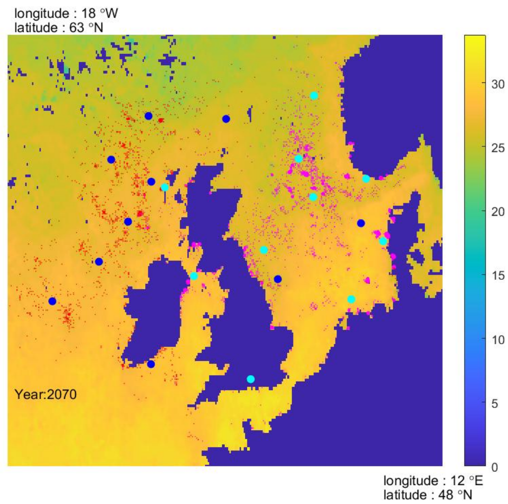


Figure 9: Accumulation point analysis: fishes in 2070 ($\tau = 10$)

5 Impact of Fish Migration on Companies

5.1 Company Revenue Prediction Model

In this model we will predict the company's annual profit and give prediction of best case, worst case, and most likely elapsed time(s) until these populations will be too far away for small fishing companies to harvest if the small fishing companies continue to operate out of their current locations.

5.1.1 Company Location

According to the fishery company distribution data on the official website of the Scottish Government [10], we selected 8 typical fishery companies.

Assuming that the small fishing company's boats are all less than 16 meters in length and travel at a constant speed. The average speed is 10 knot [8] (about $18.52km/h$). Assume the fishing boat runs for 8 hours to reach the longest distance. The longest fishing distance are calculated in formula (4)

$$\frac{18.52km/h * 8h}{6km/grid} \approx 24.69grids \tag{4}$$

It is reasonable to assume that the fishing range of each company is a circle with a radius of 25 grids.

In Figure 10, yellow points represent companies and the circle represents its fishing range. The same rule applies to the following figures. The company is indeed located in the fish gathering area, and it is widely located in various regions of Scotland. The situation is basically consistent, and the company selected can be considered reasonable.

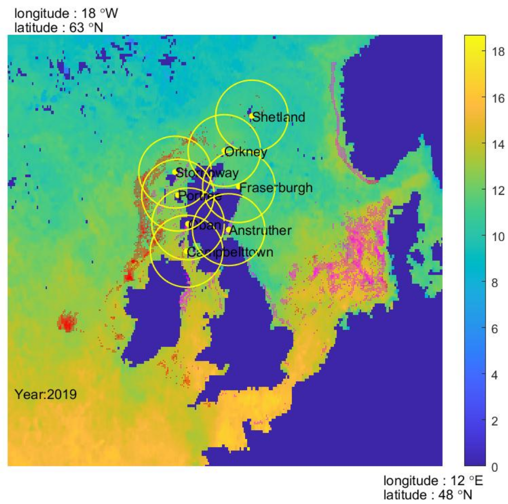


Figure 10: fishes and companies in 2019

5.1.2 Benefit Evaluation over the next 50 years

	Tonnage					Value EUR'000				
	2014	2015	2016	2017	2018	2014	2015	2016	2017	2018
Mackerel	120,539	87,362	96,095	84,808	75,023	98,945	55,507	82,157	78,667	78,295
Herring	31,298	32,076	33,093	34,886	38,138	8,541	11,341	21,664	14,234	13,882

Table 2: Tonnage and value of fishes from 2014 to 2018 [10]

$$\omega_{eachfish} = \frac{Value}{Tonnage} * Weight \tag{5}$$

According to the 2015-2019 tonnage and net income of herring and mackerel exported from the official website of the Scottish Marine Corps shown in Table 2 [10] and the average adult weight of herring and mackerel derived from Wikipedia [6, 7](Mackerel:400g Herring:700g) , we can calculate the profit of each fish by equation (5).

We can estimate the company's profit by the sum of multiplying the number of two fishes in the fishing circle by their respective selling profit, like equation (6)

$$\omega = X_{Herring} * \omega_{eachHerring} + X_{Mackerel} * \omega_{eachMackerel} \tag{6}$$

According to the fish distribution from 2020 to 2070, the profit percentage of each company in each year (relative to 2019) is shown in Figure 11.

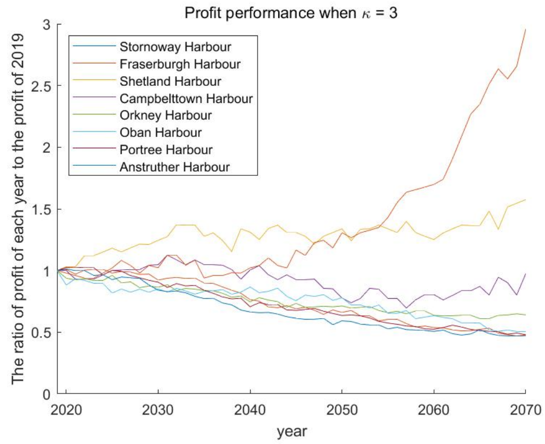


Figure 11: profit performance from 2019 to 2070

Evaluate factor λ is defined to judge if the fishes are too far away for small fishing companies to harvest. We choose the year in which the profit drops to λ times the original profit as the elapsed year. Figure 11 indicates that the profit itself has some fluctuations between 0.8 and 1.2. Let $\lambda = 0.75$ which guarantees that the elapsed years obtained are not caused by fluctuations, but indeed by fish migration caused by global warming. With different values of κ, we get elapsed time of 8 companies. cf. Figure 12.

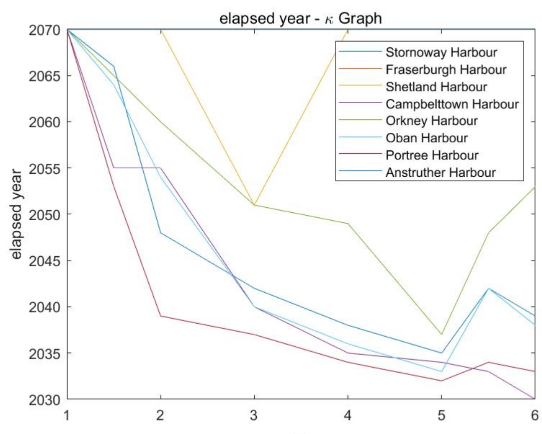


Figure 12: elapsed year - κ Graph ($\lambda = 0.75$)

According to figure 12, the worst case and the most likely elapsed year are about 2030 and 2037 respectively. If the rate of global warming is not so high, like the situation of $\kappa = 1$, fish population may not be too far away for small fishing companies till 2070. However, the population will still shrink for most companies. Although some companies may get more profit in the next fifty years, like Fraserburgh Harbour and Shetland Harbour, that's because fishes that were there in 2019 will move North while the fishes were in the south in 2019 will move to these companies. It is believed that these fishes in 2070 will move North as well.

5.2 Company Strategy Model

5.2.1 Company Strategies

The migration of fish will affect the future benefits of the company. We consider that the company may have the following strategies:

1. Using some proportion of small fishing vessels capable of operating without landbased support for a period of time while still ensuring the freshness and high quality of the catch.
2. Relocating some or all of a fishing company's assets from a current location in a Scottish port to closer to where both fish populations are moving;
3. Execute strategy 1 and strategy 2 simultaneously.
4. Modify the ecological environment nearby to make it suitable for fish to live in order to attract more fish.
5. Stay in their current locations.

We use k-means cluster analysis algorithm to get the nine points that are most suitable for starting a new company in 2070. The moving object in strategy 2 and 3 can be any of these nine points. cf. Figure 13. The black points represent the most suitable place to start a new company. The same rule applies to the following figures.

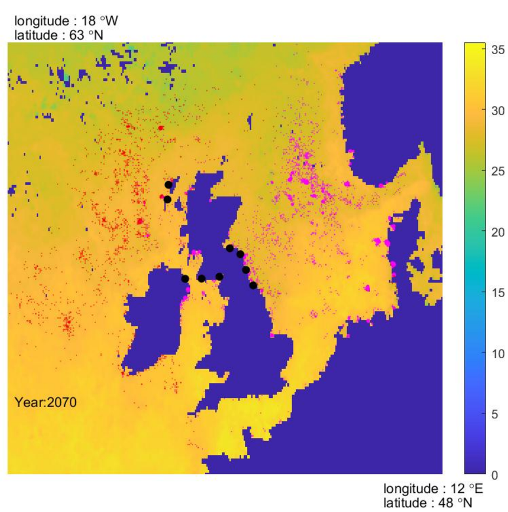


Figure 13: 9 New company location

5.2.2 Company Strategy Evaluation Factors

Consider the costs and benefits of each strategy :

Strategy 1

Since the company is fishing normally in 2019, it is assumed that the number of its fishing vessels is directly proportional to the profit in 2019. And the cost of upgrading fishing vessels is directly proportional to the number of fishing vessels. Therefore, it is assumed that the cost of upgrading the fishing boat is $\alpha\%$ times the profit in 2019.

Strategy 2

The cost of relocation is also directly proportional to the number of fishing vessels, and the cost of relocation is related to the distance moved. Assume that the cost of the relocation is $\gamma\%$ times the profit in 2019 for each grid moved (about $6km$). The relocation income is measured by the profit of the fish in the fishing area after the relocation. At the same time, because other companies may have the same decision to compete, the number of fish that can be caught is $\delta\%$ times the original number. Choose the best location among the nine candidate locations after considering the above costs and benefits as the moving location.

Strategy 3

Consider both the costs and benefits of Strategy 1 and Strategy 2

Strategy 4

Since the cost of rebuilding the ecological environment is linearly related to the number of fish, it is assumed that the cost of rebuilding is $\zeta\%$ times the profit in 2019. Assume that the transformed ecological environment can increase the number of fish by $\epsilon\%$ times.

Strategy 5

If none of the above strategic returns are higher than the original 2070 returns, choose to stay in the original position.

Other Factors

Considering the limited storage space of fishing vessels, it is assumed that the fishing of each fishing vessel will be close to saturation in 2019. If the fishing vessel is not upgraded, the fishing vessel's profit will not exceed the a times the profit in 2019. But if the fishing boat is upgraded, it is assumed that the fishing boat space can be expanded to b times the profit in 2019.

5.2.3 Company Decisions

After repeated tests, the following parameters work well. cf. Table 3. The optimum strategy for each company is shown in Table 4.

α	β	γ	δ	ζ	ϵ	a	b
20	90	0.2	80	1	10	1.2	1.8

Table 3: Test Parameters set 1

Habour	Stornoway	Fraserburgh	Shetland	Campbelttown
Strategy	3	5	1	3
Habour	Orkney	Oban	Portree	Anstruther
Strategy	3	3	3	5

Table 4: Company Decisions with parameters set 1

5.3 Territorial Sea Effects

According to international regulations, fish that swim to the territorial waters of other countries cannot be caught by fishing vessels from Scotland. Therefore, we should adjust our Company Revenue

Prediction Model and Company Strategy Model and redecide the best strategy. To do this, we mark the territorial waters' borders of the countries around Scotland. For fish entering the territorial water of other countries, we will not count them into calculations. This will change the number of catchable fish around each location along the coast of Scotland. It will affect our Company Revenue Prediction Model and Company Strategy Model through this data, and then affect the best strategy calculated by these two models.

6 Sensitivity Analysis

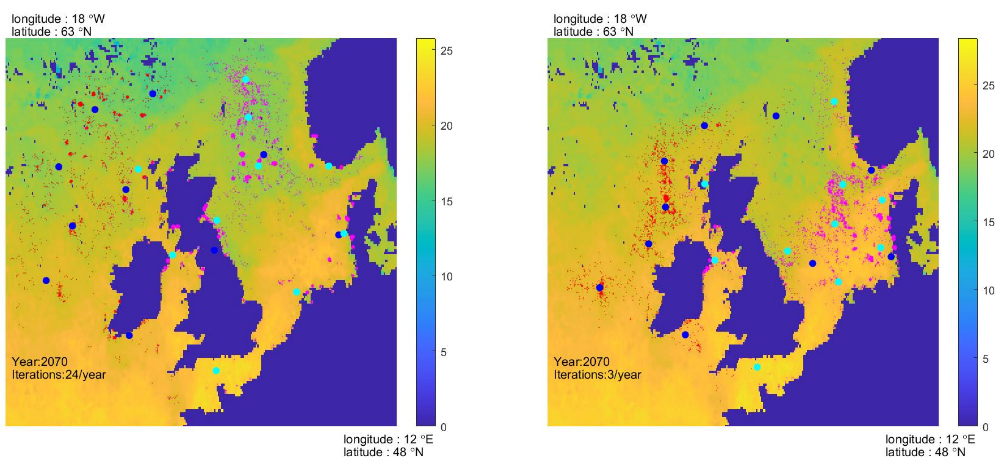
In the Fish Migration Model, we choose $\tau = 10$ and $\kappa = 3$ to measure the rate of temperature change. However, different value of τ and κ may lead to different results.We are going to consider the effects of changes in τ and κ on the Model.

In the Company Revenue Prediction Model,the parameter λ is the key to evaluate whether fishes are too far away for small fishing companies to harvest.We only consider the effects of changes in λ on Company Revenue Prediction Model.

In the Company Strategy Model, we consider the effects of changes in parameters $\alpha, \beta, \gamma, \delta, \zeta, \epsilon, a, b$ on the model, since each parameter can affect the final optimum decision.

6.1 Impact of τ on Fish Migration Model

In the previous Fish Migration Model ($\kappa = 3$), τ equals 10. Now we fix value of τ as 3 and 24 to simulate the fish distribution in 2070 and use k-means clustering algorithm to compare the pictures.



(a) Accumulation point analysis: fishes in 2070 ($\tau = 24$)

(b) Accumulation point analysis: fishes in 2070 ($\tau = 3$)

Figure 14: Accumulation point analysis: fishes in 2070 with different value of τ

Figure 14(a), Figure 14(b) are the situations of $\tau = 24$ and $\tau = 3$,respectively.

The fish distribution of $\tau = 3$ is generally southward compared to $\tau = 10$ (Figure 9), which is close to the density distribution (Figure 6). We consider that small value of τ can not describe the results well.

When the value of τ increases, which means the fish have more chance to do choice during a year, the move distance will increase correspondingly. The fish distribution of $\tau = 24$ moves northward overall compared to Figure 9, but the trend remains unchanged. The result of $\tau = 24$ illustrates the rationality of our model to some extent. The result of $\tau = 24$ has the same move trend as $\tau = 10$. It also illustrates that the result of $\tau = 10$ is reasonable.

6.2 Impact of κ on Fish Migration Model

We fix value of κ as 2,4 and 5 to get results.

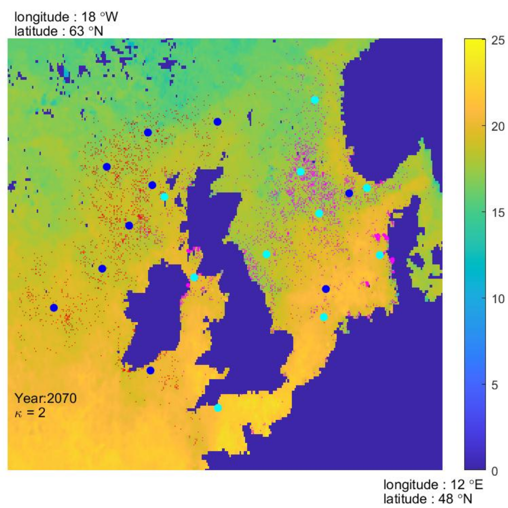


Figure 15: Accumulation point analysis: fishes in 2070 ($\kappa = 2$)

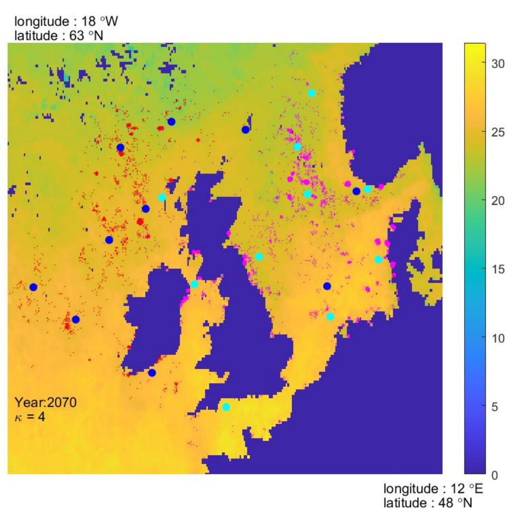


Figure 16: Accumulation point analysis: fishes in 2070 ($\kappa = 4$)

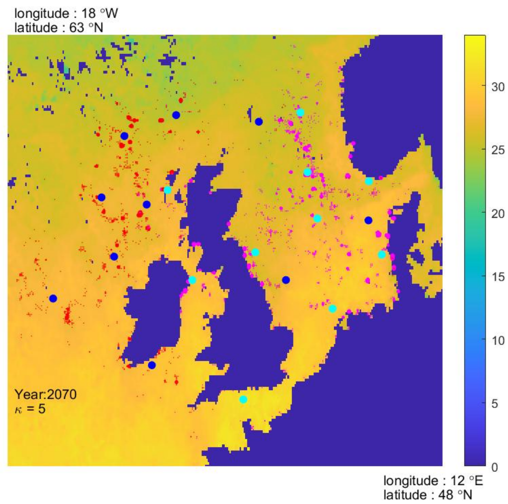


Figure 17: Accumulation point analysis: fishes in 2070 (κ = 5)

Figure 15, Figure 16 and Figure 17 are the situations of $\kappa = 2, 4, 5$ respectively. Compare these figures to Figure 9,we can draw a conclution that the change of κ dose not have much impact on the results,which also shows Fish Migration Model is non-sensitive to κ.

6.3 Impact of λ on Company Revenue Prediction Model

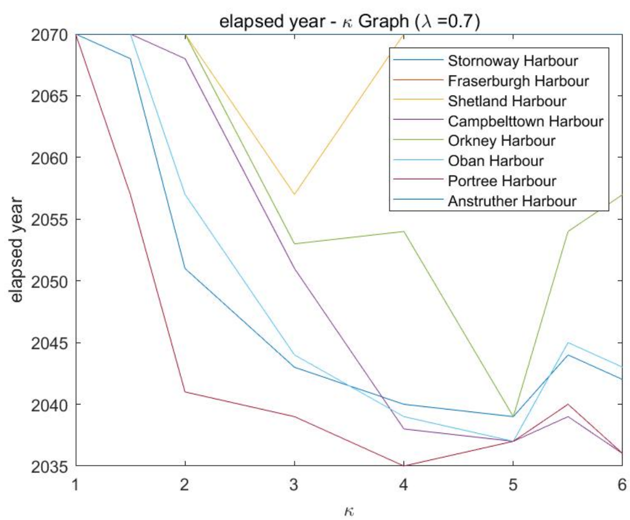


Figure 18: elapsed year - κ Graph (λ = 0.7)

Figure 18, Figure 19 and Figure 12 are the results of $\lambda = 0.7, 0.8, 0.9$ respectively. When λ fluctuates from 0.7 to 0.8, the image trend does not change. But when $\lambda = 0.9$, the image has become disordered. That's because normal fluctuations have affected the results. In summary, we consider that Company Revenue Prediction Model is non-sensitive to λ.

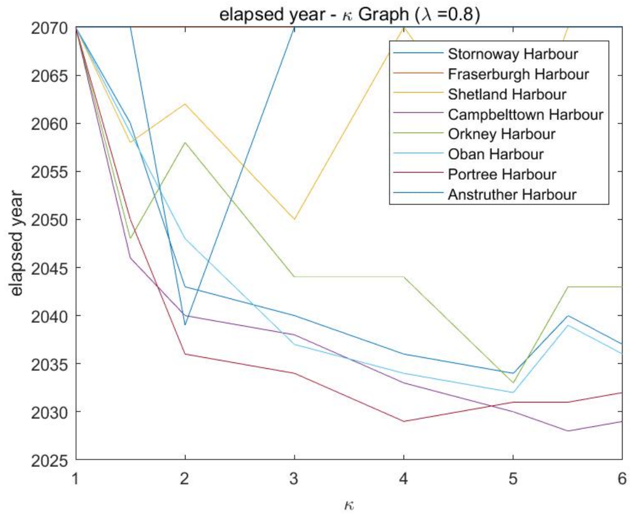


Figure 19: elapsed year - κ Graph (λ = 0.8)

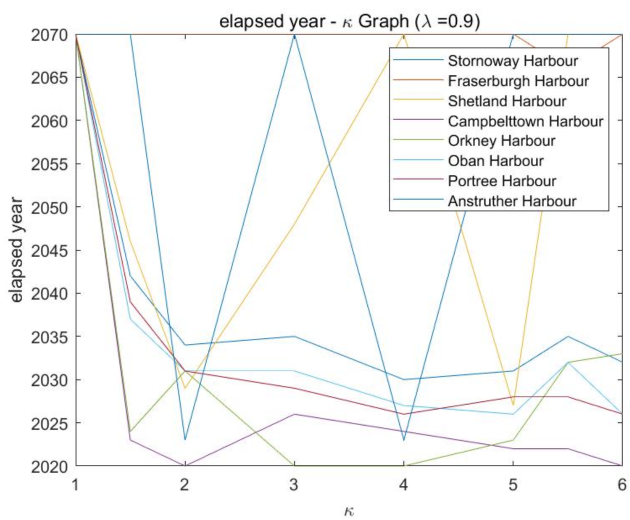


Figure 20: elapsed year - κ Graph (λ = 0.9)

6.4 Impact of Test Parameters $\alpha, \beta, \gamma, \delta, \zeta, \epsilon, a, b$ on Company Strategy Model

Fixing α as 0.5, only the optimum strategy of Shetland Harbour changes from 1 to 3. Fixing α as 0.1, only the optimum strategy of Oban Harbour changes from 3 to 1. Fixing β as 1 and 0.8, the optimum strategies remain unchanged. Fixing γ as 0.5 and 0.11, the optimum strategies remain unchanged. Fixing γ as 0.10, only the optimum strategy of Shetland Harbour changes from 1 to 3. Fixing δ as 0.9, only the optimum strategy of Shetland Harbour changes from 1 to 3. Fixing δ as 0.7, the optimum strategies remain unchanged. When ζ changes from 0 to 0.5, the optimum strategies remain unchanged. When ϵ changes from 0 to 0.1, the optimum strategies remain unchanged. When a changes from 1 to 1.4, the optimum strategies remain unchanged. When b changes from 1.4 to 2, the optimum strategies remain unchanged.

In summary, Company Strategy Model is considered non-sensitive to those parameters.

7 Model Evaluation and Future Discussion

7.1 Evaluation of Models

As we all know, global warming is closely related to the lives of all people. Many phenomena and data support the impact of global warming. Therefore, in order to build an illustrative model, we conducted the data analysis on ocean temperature, studied the living habits of herring and mackerel, and inquired about the fishery in Scotland. Finally, we established the following models: ocean temperature prediction model, fish cellular automaton model, company revenue prediction model, and company strategy model. According to the model, we successfully predicted the migration direction of fish in the next 50 years, the impact of small fishing companies, and made recommendations for their corporate decisions.

At the same time, in order to better analyze the problem, we made reasonable assumptions, and subsequently verified the correctness and sensitivity of the model, which made an interpretation for the reasonableness of the prediction results.

In the process of establishing the cellular automaton model, we considered the randomness of fish when making movement decisions. By analyzing temperature, population factors, and corner factors, we gave the probability of moving to the surrounding nine cells, and iterating continuously. The prediction result is finally obtained.

Limited by conditions and resources, our model has some shortcomings:

1. Our ocean temperature prediction simulation is based on the existing data to make a fit and artificially control the linear growth. There is no suitable existing model or algorithm to fit the prediction, so actuality may fluctuate.

2. In studying the distribution of fish with temperature, we used a normal distribution fitted curve. When the temperature change rate is too large, as the year increases, the temperature rapidly deviates from the mathematical expectation of the normal distribution, and the proportion of the impact of ocean temperature on fish movement decisions rapidly decreases, which may lead to poor prediction results.

3. In the cellular automaton model, we used random numbers, which caused the program to run slower.

4. In our company decision-making model, in order to simplify the calculation, we reasonably specified the cost of the company's relocation and upgrading of fishing vessels, and the impact of upgrading fishing vessels on the radius, based on the available data. If these parameters change, the model results may change correspondingly.

7.2 Further Discussion

Under the circumstance, we made several assumptions to build the model, but in fact, fish migration and company decisions are affected by many factors and may produce more results. Such as, changes in the number of fish caught by humans and national fishery policies, the impact of other species on the migration of herring and mackerel species, and the number of fishing vessels that fishing companies can consider when making decisions.

We only discuss the migration of herring and mackerel in this topic. According to the available information, 60% of marine life is affected by ocean temperature, which may be positive feedback or negative feedback. If we can know the sensitivity of the remaining marine life to temperature, we may be able to simulate the migration and distribution of the remaining species in the future through the established fish migration prediction model. At the same time, by studying the migration tendency of more organisms in more areas, our company decision model can provide more reasonable suggestions for more fishermen and companies.

8 An Article to the Magazine

Our future is in our hands

For many people in the world, the ocean acts an indispensable role in sustaining the living of human. However, the ocean, which makes up 71% of the Earth, is changing with an imaginable speed.

According to the research data, sea temperature is increasing under the impact of the global warming. In the past 50 years, The ocean has absorbed most heat and carbon dioxide from the atmosphere, the land and melted ice, which resulted the great rise of sea temperature. Correspondingly, up to 60% sea creatures have made responds to this.

As a result, the herring and mackerel living around Scotland are now forced to a big scale migration. Herring and mackerel, as temperature sensitive species, prefer lower seawater temperatures. According to existing research, they moved nearly 40 kilometers northward in ten years. If global warming is not mitigated, it will seriously affect fishermen and businesses that depend on the stability of the oceans for their livelihoods. Unfortunately, these two fishes are precisely the backbone of Scottish fisheries.

For some Scottish fishermen, this is no less than a disaster. These two fish will disappear into their fishing nets as soon as ten years. Of course, fishermen could choose to move along with the fish northward correspondingly. However, the moving requires tremendous courage and financial support. Stay or move? This will be an ambivalent problem for fishermen

The following suggestions may greatly help fishermen set the future strategy:

1. As for fishermen living on the south coast of Scotland, it is better to move north as soon as possible because they will be affected the earliest as the ocean temperature rises gradually. Although some fish that prefer higher temperatures will move southward, from the perspective of the overall trend, however, global primary marine production has fallen by 6% in the past half century. This means that the primary production of food web dependence has shown a downward trend, which is bound to affect the fisheries production

2. As for fishermen living on the north coast of Scotland, they are not facing a significant reduction in catches in a rather short period of time. However, in the long run, the northward movement of Herring and Mackerel will cause some of them to exceed their territorial seas and exclusive economic region. It will undoubtedly affect the fishermen's own catch. Thus, we recommend that fishermen upgrade their fishing equipment, such as power units or refrigeration units, which provides a guarantee for expanding the fishing range and extending the preservation time. Purchase of PPE(Property, plant, equipment) affects the cash flow thus affects the liquidity for companies to face short-term financial pressure. However, in the long-term perspective, the increase of corporate's assets will generate more revenue (exclude the impact of depreciation)thus create high ROI(Return on investment). Therefore, the recommendation is for companies which has abundant cash to increase the expenditure on assets under the current risk management policies.

With deeper research, it is obvious to find that human activities have an impact of the ocean all the time, as the ocean also affects humans in a more profound way. Whether it is the upgrading of fishing boats or the change in fishing scope, it is ultimately due to us human activities. And in order to meet our existing global warming challenges and build a sustainable future, we need to make our own efforts to reduce carbon dioxide emissions, protect green plants, and respect the laws of nature. Our future is in our hands.

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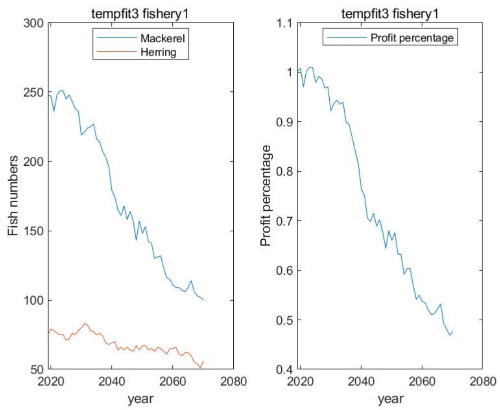
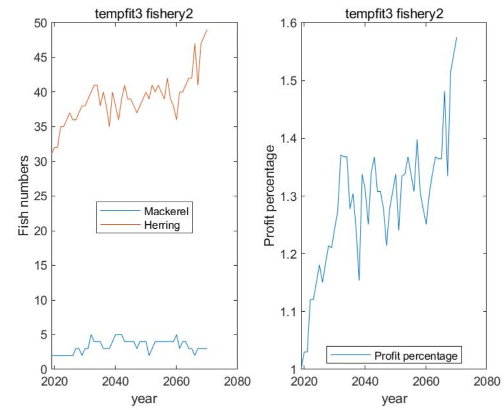
Appendix

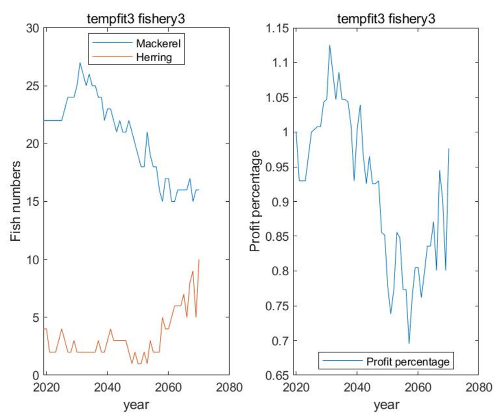
A Figures



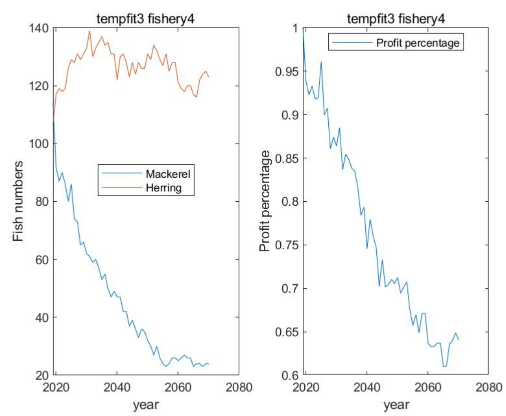
(a) Stornoway



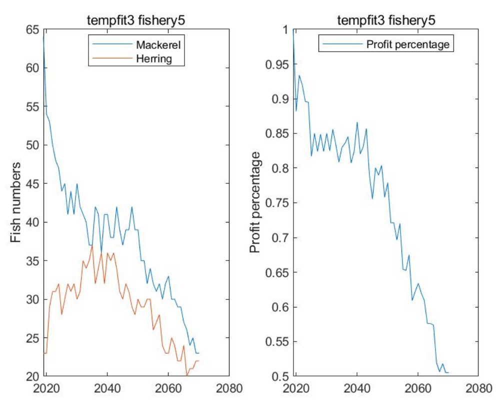
(b) Fraserburgh



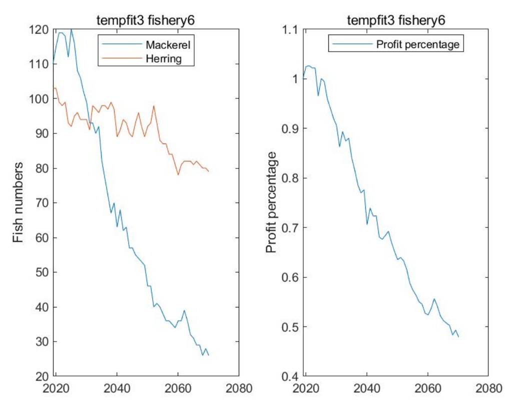
(c) Shetland



(d) Campbelttown

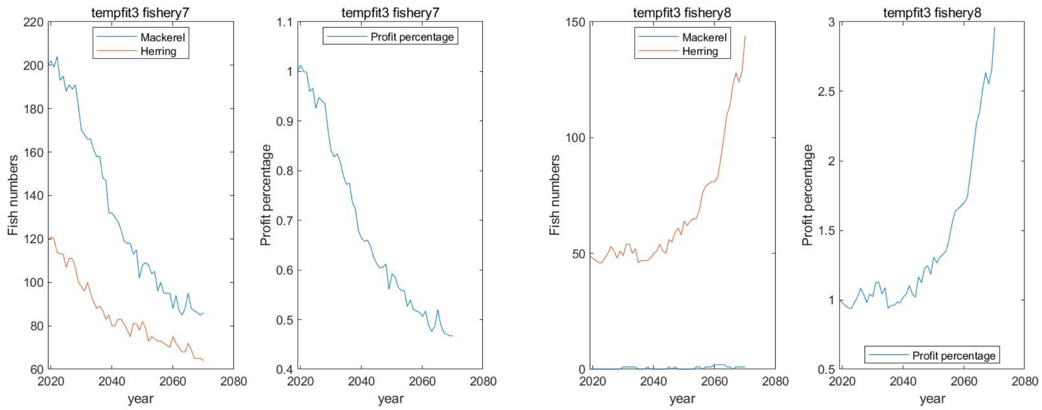


(e) Orkney



(f) Oban

Figure 21: Fish number and profit change from 2019 to 2070 of different Habour($\tau = 10, \kappa = 3$) Graph 1



(a) Portree (b) Anstruther

Figure 22: Fish number and profit change from 2019 to 2070 of different Habour($\tau = 10, \kappa = 3$) Graph 2

B Tables

Mackerel		Herring	
latitude	**longitude**	**latitude**	**longitude**
57.33	−11.43	55.54	−0.31
59.40	−9.98	50.32	−3.00
51.53	−8.13	57.71	−7.21
54.50	0.65	60.86	3.12
53.75	−14.90	53.41	4.32
55.36	−10.97	57.94	6.95
60.24	−1.28	54.69	−5.09
56.45	6.41	55.51	7.80
60.16	−6.66	57.34	3.36
57.20	−8.35	58.61	2.00

Table 5: The latitude and longitude of 10 Accumulation points of Mackerel and Herring

latitude	54.78	54.56	58.06	55.09	54.86	54.79	55.85	57.55	55.64
longitude	−5.76	−1.05	−6.91	−1.55	−3.39	−4.62	−2.67	−6.95	−1.94

Table 6: The latitude and longitude of 9 New companies location

C Codes

```
function fishmap=GenerateFishmap(filename,celllat0,celllon0,celllat1,celllon1,
    cellsizex,cellsizey)
%celllon,celllat are the longitude and latitude of the area
%cellsizex cellsizey are the number of cells
%fishmap is the cellsizex*cellsizey fishmap
```

```
fishmap=zeros(cellsizex,cellsizey);
%%
%filename='Herring_Full_UK';%Herring density map
%filename='Mackerel_Full_UK';%Mackerel density map

[A,refmat,bbox] = geotiffread(filename);
info=geotiffinfo(filename);
%refmat=info.RefMatrix;
Height=info.Height;
Width=info.Width;

%[x,y] = pix2map(info.RefMatrix,1 ,1);
%[fishlat0,fishlon0] = projinv(info,x,y);
%from position to latitude and longitude

THR=0.1;%threshold value to generate fishmap
for i=1:1:cellsizex-1
    for j=1:1:cellsizey-1
        lon=celllon0+(celllon1-celllon0)*(j-1)/(cellsizey-1);
        lat=celllat0-(celllat0-celllat1)*(i-1)/(cellsizex-1);
        [x1,y1] =projfwd(info,lat,lon);
        [row,col] =map2pix(refmat,x1,y1);
        row=floor(row);
        col=floor(col);
        if(row>0 && col >0 && row<Height && col < Width)
            if(A(row,col)>THR)
                fishmap(i,j)=floor(A(row,col)/THR);
            end
        end
    end
end
end
```

Listing 1: function to generate fishdensity map

```
function temperature=GetTemperaturemap(filename,celllat0,celllon0,celllat1,
    celllon1,cellsizex,cellsizey)
%temperature is cellsizex*cellsizey matrix, storing temperature data
%filename='MYD28M_2019-10-01_rgb_3600x1800.csv';%temperature table
[num]=csvread(filename) ;
[row, col]=size(num);
for i=1:row
    for j=1:col
    if(num(i,j)==99999)
        num(i,j)=0;
    end
    end
end
temperature=zeros(cellsizex,cellsizey);
for i=1:cellsizex
    for j=1:cellsizey
        lon=celllon0+(celllon1-celllon0)*(j-1)/(cellsizey-1);
        lat=celllat0-(celllat0-celllat1)*(i-1)/(cellsizex-1);
        [x,frac1]=temlat2x(lat);
```

```
        [y,frac2]=temlon2y(lon);
        if (num(x,y)~=0 && num(x+1,y)~=0 && num(x,y+1)~=0 && num(x+1,y+1)~=0 )
            temperature(i,j)=num(x,y)*(1-frac1)*(1-frac2)+num(x+1,y)*frac1*(1-
    frac2)+num(x,y+1)*(1-frac1)*frac2+num(x+1,y+1)*frac1*frac2;
        elseif (num(x,y)~=0 && num(x+1,y)~=0)
            temperature(i,j)=num(x,y)*(1-frac1)+num(x+1,y)*frac1;
        elseif (num(x,y)~=0 && num(x,y+1)~=0 )
            temperature(i,j)=num(x,y)*(1-frac2)+num(x,y+1)*frac2;
        else
            temperature(i,j)=num(x,y);
        end
        %%linear interpolation to get temperature map
    end
end

end
function [x,frac]=temlat2x(lat)
t=(90.15-lat)*10;
x=floor(t);
frac=t-x;
end
function [y,frac]=temlon2y(lon)
t=(180.15+lon)*10;
y=floor(t);
frac=t-y;
end
```

Listing 2: function to get temperature map

```
function fisherymap=GetFisherymap(filename,celllat0,celllon0,celllat1,celllon1,
    cellsizex,cellsizey)
%fisherymap is 8*3 cell storing 8 Habour's name and coordinates
%filename='fisherymap_8';
%filename='fisherymap_full';
[num,name]=xlsread(filename);
[t,~]=size(name);
fisherymap=cell(t,3);
fisherymap(:,1)=name;
lat=num(:,2);lon=num(:,3);
x=(celllat0-lat)/(celllat0-celllat1)*(cellsizex-1)+1;
y=(lon-celllon0)/(celllon1-celllon0)*(cellsizey-1)+1;
x=floor(x);
y=floor(y);
for i=1:t
    fisherymap{i,2}=x(i);
    fisherymap{i,3}=y(i);
end
end
```

Listing 3: function to get fishery data

```
function Desire=MoveDesire_Herring(i,j,temperaturemap,fishmap)
%i,j is the coordinate of fish
x=[temperaturemap(i-1,j-1),temperaturemap(i-1,j),temperaturemap(i-1,j+1),...
    temperaturemap(i,j-1),temperaturemap(i,j),temperaturemap(i,j+1),...
```

```
    temperaturemap(i+1,j-1),temperaturemap(i+1,j),temperaturemap(i+1,j+1)];
mu=13.526;
sigma=1.3735;
expect=1/sqrt(2*pi)/sigma*exp(-(x-mu).^2/(2*sigma*sigma));
Corner=(sqrt(2)-1)/2;
Population=[fishmap(i-1,j-1),fishmap(i-1,j),fishmap(i-1,j+1),...
    fishmap(i,j-1),fishmap(i,j),fishmap(i,j+1),...
    fishmap(i+1,j-1),fishmap(i+1,j),fishmap(i+1,j+1)]+1;
for i=1:9
    if(x(i)==0)
        expect(i)=0;
    end
end
Desire=expect.*[Corner,1,Corner,1,1,1,Corner,1,Corner]./Population;
Desire=Desire/sum(Desire);
end

function Desire=MoveDesire_Mackerel(i,j,temperaturemap,fishmap)
x=[temperaturemap(i-1,j-1),temperaturemap(i-1,j),temperaturemap(i-1,j+1),...
    temperaturemap(i,j-1),temperaturemap(i,j),temperaturemap(i,j+1),...
    temperaturemap(i+1,j-1),temperaturemap(i+1,j),temperaturemap(i+1,j+1)];
mu=13.526;
sigma=1.2683;
expect=1/sqrt(2*pi)/sigma*exp(-(x-mu).^2/(2*sigma*sigma));
Corner=(sqrt(2)-1)/2;
Population=[fishmap(i-1,j-1),fishmap(i-1,j),fishmap(i-1,j+1),...
    fishmap(i,j-1),fishmap(i,j),fishmap(i,j+1),...
    fishmap(i+1,j-1),fishmap(i+1,j),fishmap(i+1,j+1)]+1;
for i=1:9
    if(x(i)==0)
        expect(i)=0;
    end
end
Desire=expect.*[Corner,1,Corner,1,1,1,Corner,1,Corner]./Population;
Desire=Desire/sum(Desire);
end
```

Listing 4: function to calculate fish's move posibility

```
function nextfishmap=Move_Herring(fishmap,cellsizex,cellsizey,temperaturemap)
nextfishmap=zeros(cellsizex,cellsizey);
for i=2:cellsizex-1
        for j=2:cellsizey-2
            while(fishmap(i,j)>=1)
                desire=MoveDesire_Herring(i,j,temperaturemap,fishmap);
                %desire is 1*9 matrix, storing move posibility from 1 to 9
                r=rand();
                k=1;
                while(r>desire(k))
                    r=r-desire(k);
                    k=k+1;
                end
                switch k
                    case 1 ,nextfishmap(i-1,j-1)=nextfishmap(i-1,j-1)+1;
```

```
                    case 2 ,nextfishmap(i-1,j)=nextfishmap(i-1,j)+1;
                    case 3 ,nextfishmap(i-1,j+1)=nextfishmap(i-1,j+1)+1;
                    case 4 ,nextfishmap(i,j-1)=nextfishmap(i,j-1)+1;
                    case 5 ,nextfishmap(i,j)=nextfishmap(i,j)+1;
                    case 6 ,nextfishmap(i,j+1)=nextfishmap(i,j+1)+1;
                    case 7 ,nextfishmap(i+1,j-1)=nextfishmap(i+1,j-1)+1;
                    case 8 ,nextfishmap(i+1,j)=nextfishmap(i+1,j)+1;
                    case 9 ,nextfishmap(i+1,j+1)=nextfishmap(i+1,j+1)+1;
                end
                fishmap(i,j)=fishmap(i,j)-1;
                end
    end
end
end

function nextfishmap=Move_Markerel(fishmap,cellsizex,cellsizey,temperaturemap)
nextfishmap=zeros(cellsizex,cellsizey);
for i=2:cellsizex-1
        for j=2:cellsizey-2
            while(fishmap(i,j)>=1)
                desire=MoveDesire_Mackerel(i,j,temperaturemap,fishmap);
                %desire is 1*9 matrix, storing move posibility from 1 to 9
                r=rand();
                k=1;
                while(r>desire(k))
                    r=r-desire(k);
                    k=k+1;
                end
                switch k
                    case 1 ,nextfishmap(i-1,j-1)=nextfishmap(i-1,j-1)+1;
                    case 2 ,nextfishmap(i-1,j)=nextfishmap(i-1,j)+1;
                    case 3 ,nextfishmap(i-1,j+1)=nextfishmap(i-1,j+1)+1;
                    case 4 ,nextfishmap(i,j-1)=nextfishmap(i,j-1)+1;
                    case 5 ,nextfishmap(i,j)=nextfishmap(i,j)+1;
                    case 6 ,nextfishmap(i,j+1)=nextfishmap(i,j+1)+1;
                    case 7 ,nextfishmap(i+1,j-1)=nextfishmap(i+1,j-1)+1;
                    case 8 ,nextfishmap(i+1,j)=nextfishmap(i+1,j)+1;
                    case 9 ,nextfishmap(i+1,j+1)=nextfishmap(i+1,j+1)+1;
                end
                fishmap(i,j)=fishmap(i,j)-1;
              end
   end
end
end
```

Listing 5: function to calculate fish's movement

```
function Ctrs = MyKmeans(cellsizex,cellsizey,M,K)
%M: fishmap  K: number of accumulation points
%Ctrs K*2 matrix storing the coordinate of the points
fishnumber=floor(sum(M(:)));
X=zeros(fishnumber,2);
m=1;
for i=2:cellsizex-1
```

```
        for j=2:cellsizey-1
            if(M(i,j)>=1)
                while(M(i,j)>=1)
                    X(m,1)=i;X(m,2)=j;
                    m=m+1;
                    M(i,j)=M(i,j)-1;
                end
            end
        end
end
opts=statset('Display','final');
[Idx,Ctrs,SumD,D] = kmeans(X,K,'Replicates',K,'Options',opts);
end
```

Listing 6: k-means clustering algorithm

```
function result=TemperatureChange(i)
%i : \kappa
C=load('HadSST_annual_nh.mat').M;%temperature data
[right,~]=size(C(:,1));
left=find(C(:,1)==1961);
year=C(left:right,1)';
temp=C(left:right,2)';
ft = fittype('fitfunction(x,a1,b1,c1,a2,b2,c3,a3,b3,c3,k,s)');
model2 = fit(year',temp',ft);
x=1961:2070;
y=feval(model2,x);
k=i/4/51*12;
s=[zeros(1,2019-1961),k*(0:2070-2019)];
y1=y'+s;
result=y1(2019-1961+1:2070-1961+1);
result=result-result(1);
%     plot(x,y1','r.-','MarkerSize',1);
end

function y=fitfunction(x,a1,b1,c1,a2,b2,c2,a3,b3,c3,k,s)
y=a1*sin(b1*x+c1)+a2*sin(b2*x+c2)+a3*sin(b3*x+c3)+k*x+s;
end
```

Listing 7: function to get temperature prediction data

```
%Normal distribution simulation
%filename='Herring_Full_UK';% herring density
%filename='Mackerel_Full_UK';% mackerel density
[A,refmat,bbox] = geotiffread(filename);
info=geotiffinfo(filename);
Height=info.Height;
Width=info.Width;
k=1;
temp=zeros(2,cellsizex*cellsizey);
for i=1:cellsizex
    for j=1:cellsizey
        lon=celllon0+(celllon1-celllon0)*(j-1)/(cellsizey-1);
        lat=celllat0-(celllat0-celllat1)*(i-1)/(cellsizex-1);
        [x1,y1] =projfwd(info,lat,lon);
```

```
        [row,col] =map2pix(refmat,x1,y1);
        row=floor(row);
        col=floor(col);
        if(row>0 && col >0 && row < Height && col <Width)
            if(A(row,col)>0.05)
            temp(1,k)=temperaturemap(i,j);
            temp(2,k)=A(row,col);
            k=k+1;
            end
        end
    end
end
B=temp(1:2,1:k-1);
G=sortrows(B')';
save('fishdensity-temperature_Mackerel.mat','G');
%%
%draw Normal distribution Graph
G=load('fishdensity-temperature_Mackerel.mat').G;
z=find(G(1,:)==0);
[~,left]=size(z);
[~, right]=size(G);
B=G(1:2,left+1:right);
plot(B(1,:),B(2,:),'k.','MarkerSize',1);
hold on;
x0=B(1,:);y0=B(2,:);
[miu,sigma]=normfit(x0,y0);
x=linspace(min(B(1,:))-1,max(B(1,:))+1);
expect=1/sqrt(2*pi)/sigma*exp(-(x-mu).^2/(2*sigma*sigma));
plot(x,expect,'r.-','MarkerSize',1);
axis([min(x),max(x),0,0.75])
text(9,0.7,strcat('\mu = ',num2str(mu)));
text(9,0.65,strcat('\sigma = ',num2str(sigma)));
xlabel('Temperature \circC');
ylabel('Probability of Finding Mackerel')
title('Mackerel : Probability Density - Temperature Fitting')
legend('Sample Points','Fitted Curve')
```

Listing 8: Normal distribution curve fitting

```
%clustering Analysis and draw points
K=10;
%  fishes1=Getfishes(temperaturemap,M1,25);
%  fishes2=Getfishes(temperaturemap,M2,25);
% Ctrs1 = LocationFocus(cellsizex,cellsizey,fishes1*profit(1)+fishes2*profit(2)
    ,60,10) %new fishery location
Ctrs1 = MyKmeans(cellsizex,cellsizey,M1,K)
Ctrs2 = MyKmeans(cellsizex,cellsizey,M2,K)%fish gathering points location
hold on
for i=1:10
        plot(Ctrs1(i,2),Ctrs1(i,1),'MarkerEdgeColor', 'b', 'Marker', '.', '
    MarkerSize',20);
        plot(Ctrs2(i,2),Ctrs2(i,1),'MarkerEdgeColor', 'c', 'Marker', '.', '
    MarkerSize',20);
```

```
end
```

Listing 9: draw k-means clustering Analysis Graph

```
%fisherfishamount and draw graph
FisheryFishamount_temp=load('
    FisheryFishamount_both_20192070_10_20_tempfit3_fisheryall_52_UK.mat').
    FisheryFishamount;
FisheryFishamount=FisheryFishamount_temp(:,1:1:52);
year=2019:2070;
for k=1:8
    pp=FisheryFishamount(2*k-1,1)*profit(1)+FisheryFishamount(2*k,1)*profit(2);
    p=(FisheryFishamount(2*k-1,1:52)*profit(1)+FisheryFishamount(2*k,1:52)*profit
    (2))/pp;
    hold on
    plot(year,p)
end
axis([2019,2070,0,3])
title('Profit performance when \kappa = 3')
legend(fisherymap{1:8,1},'location','northwest')
xlabel('year')
ylabel('The ratio of profit of each year to the profit of 2019')
```

Listing 10: draw profit performance graph

```
%draw elapsedyear_kappa graph
far=0.9;%\lambda
faryear_tempfit=zeros(8,8);%1 1.5 2 3 4 5 5.5 6
fisheryfishamount_tempfit1=load('
    FisheryFishamount_both_20192070_5_10_tempfit1_fisheryall_260_UK.mat').
    FisheryFishamount;
for k=1:8
    initial=fisheryfishamount_tempfit1(2*k-1,1)*profit(1)+
    fisheryfishamount_tempfit1(2*k,1)*profit(2);
    for i=1:5:260
        if ((fisheryfishamount_tempfit1(2*k-1,i)*profit(1)+
    fisheryfishamount_tempfit1(2*k,i)*profit(2))<initial*far)
            break
        end
    end
    faryear_tempfit(k,1)=2019+floor(i/5);
end
fisheryfishamount_tempfit15=load('
    FisheryFishamount_both_20192070_5_10_tempfit1_5_fisheryall_260_UK.mat').
    FisheryFishamount;
for k=1:8
    initial=fisheryfishamount_tempfit15(2*k-1,1)*profit(1)+
    fisheryfishamount_tempfit15(2*k,1)*profit(2);
    for i=1:5:260
        if ((fisheryfishamount_tempfit15(2*k-1,i)*profit(1)+
    fisheryfishamount_tempfit15(2*k,i)*profit(2))<initial*far)
            break
        end
    end
    faryear_tempfit(k,2)=2019+floor(i/5);
```

```
end
fisheryfishamount_tempfit2=load('FisheryFishamount_both_20192070_10_20_tempfit2_fisheryall_520_UK.mat').FisheryFishamount;
for k=1:8

    initial=fisheryfishamount_tempfit2(2*k-1,1)*profit(1)+fisheryfishamount_tempfit2(2*k,1)*profit(2);
    for i=1:10:520
        if ((fisheryfishamount_tempfit2(2*k-1,i)*profit(1)+fisheryfishamount_tempfit2(2*k,i)*profit(2))<initial*far)
            break
        end
    end
    faryear_tempfit(k,3)=2019+floor(i/10);
end
fisheryfishamount_tempfit3=load('FisheryFishamount_both_20192070_10_20_tempfit3_fisheryall_52_UK.mat').FisheryFishamount;
for k=1:8
    initial=fisheryfishamount_tempfit3(2*k-1,1)*profit(1)+fisheryfishamount_tempfit3(2*k,1)*profit(2);
    for i=1:1:52
        if ((fisheryfishamount_tempfit3(2*k-1,i)*profit(1)+fisheryfishamount_tempfit3(2*k,i)*profit(2))<initial*far)
            break
        end
    end
    faryear_tempfit(k,4)=2018+i;
end
fisheryfishamount_tempfit4=load('FisheryFishamount_both_20192070_10_20_tempfit4_fisheryall_52_UK.mat').FisheryFishamount;
for k=1:8
    initial=fisheryfishamount_tempfit4(2*k-1,1)*profit(1)+fisheryfishamount_tempfit4(2*k,1)*profit(2);
    for i=1:1:52
        if ((fisheryfishamount_tempfit4(2*k-1,i)*profit(1)+fisheryfishamount_tempfit4(2*k,i)*profit(2))<initial*far)
            break
        end
    end
    faryear_tempfit(k,5)=2018+i;
end
fisheryfishamount_tempfit5=load('FisheryFishamount_both_20192070_10_20_tempfit5_fisheryall_520_UK.mat').FisheryFishamount;
for k=1:8
    initial=fisheryfishamount_tempfit5(2*k-1,1)*profit(1)+fisheryfishamount_tempfit5(2*k,1)*profit(2);
    for i=1:10:520
        if ((fisheryfishamount_tempfit5(2*k-1,i)*profit(1)+fisheryfishamount_tempfit5(2*k,i)*profit(2))<initial*far)
            break
```

```
        end
    end
    faryear_tempfit(k,6)=2019+floor(i/10);
end
fisheryfishamount_tempfit55=load('FisheryFishamount_both_20192070_5_10_tempfit55_fisheryall_260_UK.mat').FisheryFishamount;
for k=1:8
    initial=fisheryfishamount_tempfit55(2*k-1,1)*profit(1)+fisheryfishamount_tempfit55(2*k,1)*profit(2);
    for i=1:5:260
        if ((fisheryfishamount_tempfit55(2*k-1,i)*profit(1)+fisheryfishamount_tempfit55(2*k,i)*profit(2))<initial*far)
            break
        end
    end
    faryear_tempfit(k,7)=2019+floor(i/5);
end
fisheryfishamount_tempfit6=load('FisheryFishamount_both_20192070_5_10_tempfit6_fisheryall_260_UK.mat').FisheryFishamount;
for k=1:8
    initial=fisheryfishamount_tempfit6(2*k-1,1)*profit(1)+fisheryfishamount_tempfit6(2*k,1)*profit(2);
    for i=1:5:260
        if ((fisheryfishamount_tempfit6(2*k-1,i)*profit(1)+fisheryfishamount_tempfit6(2*k,i)*profit(2))<initial*far)
            break
        end
    end
    faryear_tempfit(k,8)=2019+floor(i/5);
end
x=[1,1.5,2,3,4,5,5.5,6];
plot(x,faryear_tempfit','MarkerSize',10);
legend(fisherymap{1:8,1})
xlabel('\kappa')
ylabel('elapsed year')
title(strcat('elapsed year - \kappa Graph (\lambda = ',num2str(far),')'))
```

Listing 11: draw elapsedyear-kappa Graph

```
NewFishery=load('NewFishery_tempfit3_UK.mat').Ctrs1;
M1_2070=load('Fishmap_Mackerel_20192070_10_20_tempfit3_fisheryall_UK').M1;
M2_2070=load('Fishmap_Herring_20192070_10_20_tempfit3_fisheryall_UK').M2;
fishmap=load('Fishmap_Mackerel_300300.mat').fishmap;
M1=fishmap;
fishmap=load('Fishmap_Herring_300300.mat').fishmap;
M2=fishmap;
result=zeros(8,7);
%column1:strategy
%column2:target accumulation point number
%column 3456 :profit of 1 2 3 4 respectively
cost1=0.2;%\alpha
cost2=0.2/100;%\beta
```

```
for k=1:8
    x=fisherymap{k,2};
    y=fisherymap{k,3};
    [result(k,1), result(k,2),result(k,3:6), result(k,7)]= DecideStrategy(M1,M2,
   M1_2070,M2_2070,NewFishery,10,x,y,cost1,cost2,profit);
end
function [beststrategy, bestfocus,profit_s,profit2070]= DecideStrategy(
    fishmap_origin1,fishmap_origin2,M1,M2,location_k,k,location_x,location_y,
    cost1,cost2,profit)
%fishmap_origin1/2,M1/2,fishmap in 2019/2070
%location_k, k accumulation  points matrix, k*2 points  number
%D1,D2 radius before and after upgrading ship
%location_x,location_y,coordinate of habour
%profit profit(1):Mackerel,Profit(2):Herring
profit_s=zeros(1,4);
D1=25;D2=floor(sqrt(2)*25);
upbound=1.2;%$a$
ratelower=0.9;%\bata
updateship=1.7;%$b/a$
gatherlower=0.8;%\delta
baitup=1.1;%\zeta+1
baitcost=0.1;%\epsilon
%strategy 1
fishes1_origin = Getfishes_point(fishmap_origin1, D1, location_x, location_y);
fishes2_origin = Getfishes_point(fishmap_origin2, D1, location_x, location_y);
fishes1_later = Getfishes_point(M1, D2, location_x, location_y);
fishes2_later = Getfishes_point(M2, D2, location_x, location_y);
profit_origin = (profit(1) * fishes1_origin + profit(2) * fishes2_origin);
profit_later = (profit(1) * fishes1_later + profit(2) * fishes2_later);
fishes1_2070 = Getfishes_point(M1, D1, location_x, location_y);
fishes2_2070 = Getfishes_point(M2, D1, location_x, location_y);
profit2070 =(profit(1) * fishes1_2070 + profit(2) * fishes2_2070)/profit_origin
    -1;
if(profit_later > profit_origin * upbound * updateship)
    profit_later = profit_origin * upbound * updateship;
end
profit_s(1) = (profit_later * ratelower- cost1*profit_origin) / profit_origin -
    1;
%strategy 4
profit_s(4)= (profit2070 * baitup - baitcost * profit_origin) / profit_origin -
    1;
%strategy 2
cost_k=zeros(k,1);
profit_k = zeros(k,1);
for i=1:k
    fishes1_focus = Getfishes_point(M1, D1, location_k(i,1), location_k(i,2));
    fishes2_focus = Getfishes_point(M2, D1, location_k(i,1), location_k(i,2));
    cost_k(i)= cost2 * (sqrt((location_x - location_k(i,1))^2 + (location_y -
   location_k(i,2))^2));
    profit_focus=(profit(1) * fishes1_focus + profit(2) * fishes2_focus);
    if(profit_focus > profit_origin * upbound)
        profit_focus = profit_origin * upbound;
    end
    profit_k(i) = ( profit_focus- cost_k(i) * profit_origin) / profit_origin - 1;
```

```
end
[profit_s(2),bestfocus2] = max(profit_k(:));
%strategy 3
profit_k3=zeros(k,1);
for i = 1:k
    fishes1_focus = Getfishes_point(M1, D2, location_k(i,1), location_k(i,2));
    fishes2_focus = Getfishes_point(M2, D2, location_k(i,1), location_k(i,2));
    profit_focus=profit(1) * fishes1_focus + profit(2) * fishes2_focus;
    if(profit_focus > profit_origin * upbound * updateship)
        profit_focus = profit_origin * upbound * updateship;
    end
    profit_k3(i) = ( profit_focus * ratelower * gatherlower- (cost_k(i) - cost1)
   * profit_origin) / profit_origin - 1;
end
[profit_s(3),bestfocus3] = max(profit_k3(:));
[maxprofit,beststrategy] = max(profit_s);
if(beststrategy==3)
    bestfocus=bestfocus3;
elseif(beststrategy==2)
    bestfocus=bestfocus2;
else
    bestfocus=0;
end
if( max(profit_s) < profit2070 )
    beststrategy=5;
end
if( max(profit_s) < 0 )
    beststrategy=6;
end
end
```

Listing 12: Strategy Model

```
function fishes=Getfishes(temperature,fishmap,D)
%D radius of circle; temperature map fishmap
%fishes cellsizex*cellsizey matrix storing fish number in the circle
[cellsizex,cellsizey]=size(temperature);
doubleD=D^2;
fishes=zeros(cellsizex,cellsizey);
for i=2:cellsizex-1
    for j=2:cellsizey-1
        if( (temperature(i,j)==0) && ( (temperature(i-1,j)~=0)||(temperature(i+1,
   j)~=0) ) &&...
                i>80 && i<260 && j>90 && j <193)
            %make sure is in UK
            for x=i-D : i+D
                if(x>0 && x<cellsizex-1)
                for y=j-D : j+D
                    if(y>0 && y<cellsizey-1)
                    if((x-i)^2+(y-j)^2 < doubleD)
                        fishes(i,j)=fishes(i,j)+fishmap(x,y);
                    end
                    end
                end
```

```
                end
            end
        end
    end
end

function locations=LocationFocus(cellsizex,cellsizey,fishes,lowerbounder,K)
%fishes = Getfishes(temperature,fishmap,D)
for i=2:cellsizex
    for j=2:cellsizey
        if(fishes(i,j)<lowerbounder)
            fishes(i,j)=0;
        end
    end
end
locations=MyKmeans(cellsizex,cellsizey,fishes,K);
```

Listing 13: function to calculate fishnumber and new habour locations

```
function fishes=Getfishes_point(fishmap,D,i,j)
%D radius of circle  temperature map  fishmap;i,j coordinate
%fishes : total fish number
[cellsizex,cellsizey]=size(fishmap);
doubleD=D^2;
fishes=0;
i=floor(i);
j=floor(j);
for x=i-D : i+D
    if(x>0 && x<cellsizex-1)
    for y=j-D : j+D
        if(y>0 && y<cellsizey-1)
        if((x-i)^2+(y-j)^2 < doubleD)
            fishes=fishes+fishmap(x,y);
        end
        end
    end
    end
end
end
```

Listing 14: function to calculate fish number in a circle of a certain point

```
cellsizex=300;
cellsizey=300;
%%cell size
celllat0=63;
celllon0=-18;
celllat1=48;
celllon1=12;
%%cell longitude and latitude northwest and southeast

%parameters
r=25;%radius of circle
endyear=2070;
enditeration=24;%\tau
```

```
fisherynumber=8;
tonnage=[61366,58726,65543,56423,64622;
    239470,199887,188487,179956,153000];
value=[18470,21307,43559,23776,24377;
    194798,130513,168602,161892,163399];
weight=[700,400]*10^-3;
profit=zeros(2,1);
profit(2)=value(1,:)/tonnage(1,:)*weight(1);
profit(1)=value(2,:)/tonnage(2,:)*weight(2);

%%
%filename='Herring_Full_UK';%Herring density
%filename='Mackerel_Full_UK';%Mackerel density
%fishmap=GenerateFishmap(filename,celllat0,celllon0,celllat1,celllon1,cellsizex,cellsizey);
fishmap=load('Fishmap_Mackerel_300300.mat').fishmap;
M1=fishmap;
fishmap=load('Fishmap_Herring_300300.mat').fishmap;
M2=fishmap;
temperaturemap=load('Temperaturemap_300300.mat').temperature;
tempchange=TemperatureChange(3);
land=load('landmap.mat').land;%landmap
filename='fisherymap_8'
fisherymap=GetFisherymap(filename,celllat0,celllon0,celllat1,celllon1,cellsizex,cellsizey);
FisheryFishamount=zeros(2*fisherynumber,enditeration*(endyear-2018));
%%
writerObj=VideoWriter('Fisherysim_Both_20192070_24_24_tempfit3_fisherynone_stay_UK.avi');  %// define a video file
%writerObj=VideoWriter('test');  %// define a video file
%name rule  'script_fishtype_years_\tau_framerate_\kappa_others_area'
writerObj.FrameRate=24;%frame rate
open(writerObj);
for simyear=2019:endyear
    simtempchange=tempchange(simyear-2018);
    temperaturemapchange=temperaturemap+simtempchange*(1-land);
    for iterationtime=1:enditeration
        imagesc(temperaturemapchange)
        hold on;
        for i=2:cellsizex-1
            for j=2:cellsizey-1
                if(mod(iterationtime,2)==1)
                    if(M1(i,j)>=1)
                        plot(j,i,'MarkerEdgeColor', 'r', 'Marker', '.', 'MarkerSize',min(M1(i,j),15)+1);
                    end
                    if(M2(i,j)>=1)
                        plot(j,i,'MarkerEdgeColor', 'm', 'Marker', '.', 'MarkerSize',min(M2(i,j),15)+1);
                    end
                else
                    if(M2(i,j)>=1)
                        plot(j,i,'MarkerEdgeColor', 'm', 'Marker', '.', '
```

```
MarkerSize',min(M2(i,j),15)+1);
                    end
                    if(M1(i,j)>=1)
                        plot(j,i,'MarkerEdgeColor', 'r', 'Marker', '.', '
MarkerSize',min(M1(i,j),15)+1);
                    end
                end
            end
        end
        %draw the habours
%         for k=1:fisherynumber
%             jj=fisherymap{k,3};
%             ii=fisherymap{k,2};
%             fisheryname=fisherymap{k,1}(1:length(fisherymap{k,1})-7);
% %             FisheryFishamount(2*k-1,(simyear-2019)*enditeration+iterationtime
)=Getfishes_point(M1,r,ii,jj);
% %             FisheryFishamount(2*k,(simyear-2019)*enditeration+iterationtime)=
Getfishes_point(M2,r,ii,jj);
% %             %store Fishery fish amount
%             theta=0:0.1:2*pi;
%             x=r*cos(theta);y=r*sin(theta);
%             plot(jj,ii,'MarkerEdgeColor', 'y', 'Marker', '.', 'MarkerSize',15);
%             text(jj,ii,fisheryname);
%             plot(x+jj,y+ii,'y.-','LineWidth',1, 'MarkerSize',1);
%         end

%         fishamount_mackerel=Getfishes_point(temperaturemap,M1,r,ii,jj);
%         fishamount_herring=Getfishes_point(temperaturemap,M2,r,ii,jj);
%         profit_new=fishamount_mackerel*profit(1)+fishamount_herring*profit(2);
%         text(jj,ii+10,['Mackerel:',num2str(fishamount_mackerel),' Herring:',
num2str(fishamount_herring)]);

        M1_next=Move_Mackerel(M1,cellsizex,cellsizey,temperaturemapchange);
        M1=M1_next;
        M2_next=Move_Herring(M2,cellsizex,cellsizey,temperaturemapchange);
        M2=M2_next;

        text(5,250,['Year:',num2str(simyear)]);
        text(5,260,['Iterations:',num2str(iterationtime)]);
%         text(5,270,['Temperature Rise:',num2str(simtempchange)]);
%         text(5,280,['Mackerel numbers:',num2str(sum(M1(:)))]);
%         text(5,290,['Herring numbers:',num2str(sum(M2(:)))]);
        set(gcf,'unit','pixels','Position',[300 100 620 520]);
        colorbar;
        axis off
        text(5,-15,['longitude : ',num2str(abs(celllon0)),' \circW']);
        text(5,-5,['latitude : ',num2str(celllat0),' \circN']);

        text(260,310,['longitude : ',num2str(celllon1),' \circE']);
        text(260,320,['latitude : ',num2str(celllat1),' \circN']);
        writeVideo(writerObj,getframe(gcf)); %// write frame into video
        hold off
    end
end
```

```
close(writerObj); %// close video file
save('Fishmap_Mackerel_20192070_24_24_tempfit3_fisheryall_stay_UK','M1')
save('Fishmap_Herring_20192070_24_24_tempfit3_fisheryall_stay_UK','M2')
save('FisheryFishamount_both_20192070_5_10_tempfit55_fisheryall_UK','
    FisheryFishamount')
```

Listing 15: Fish Migration Model