Moving North

2020 MCM Problem A

Summary

Global ocean temperature affects the species that are sensitive to temperature changes to seek and migrate to the n ew habitat. One example of this is seen in the lobster population of Maine, USA that is slowly migrating north to Canada where the lower ocean temperatures provide a more suitable habitat. This geographic population shift can significantly disrupt the livelihood of companies who depend on the stability of ocean-dwelling species.

We are hired as consultants by a Scottish North Atlantic fishery management consortium. They want to know the potential migration of two kinds of fish, herring and mackerel from their current habitat near Scotland when the gl obal ocean temperature increases. In this report, we are going to make a Marine Fish Distribution Shift Model to predict the future habitat of two kinds of fish, herring and mackerel. Changes in population locations of herring an d mackerel could make a great economical impact on smaller Scotland-based fishing companies.

I. INTRODUCTION

1.Global Assumption

a) Given that these two species of fish have different behaviors, we will treat both mackerel a nd herring fish as a single species. This implies that the concentration of both fish will be l ocated in the same regions, and the migration will occur in the same fashion.

b) The proportion of the species at each location will not only depend on the migration factor, birth rate and death rate also affect the population.

c) We will assume that the fish live at a depth of 2 meters below the surface at the most, this will guarantee that the temperature in the sea is proportional to the temperature at the surfa ce.

d) We will only consider the fish located inside the North Sea, and more specifically, we will have a bounded system where the fish can only move within our 8 determined regions.

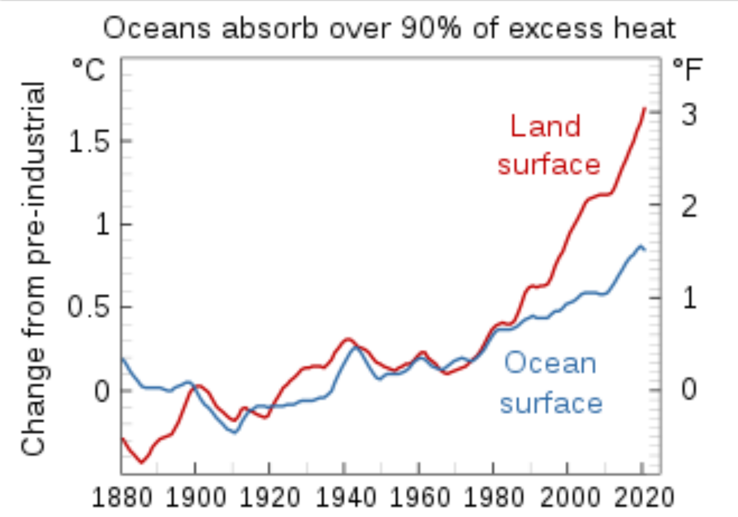
e) The sea surface temperature of each region rises by the same factor yearly, and the increas e in temperature is the only reason that will make the fish migrate.

f) Fish can travel at most 400 km to find a more adequate habitat.

In the question, we only concern two fishes, which is Scottish herring and mackerel. In this model, we do not include other fishes. The sea temperature within the same area might not be too differen t. According to wikipedia, we can refer to the **graph(1)** from wikipedia, oceans absorb over 90% of excess heat. In order to make our model more accurate, we make the assumption that ocean temper ature is proportional to the land temperature.

According to the website "OXFORD ACADEMIC", Scottish herring and mackerel prefer to liv e in sea temperature 1 – 12°C, if the living environment is more than 12C, Scottish herring and ma ckerel will move to another sea region that has cooler temperature. In the model, we assume the st andard living temperature for scottish herring and mackerel is 12C. If the sea temperature is higher than the standard, they will seek another place.

graph(1):



II. ANALYSIS OF THE PROBLEM AND THE MODEL

1.Ocean temperature

In this model, ocean temperature is one of the important factors in this model. We analyze the data of ocean temperature from "Scottish Government Riahaltas na J-Alba". We can see from the **gr aph(1)** below, that the sea surface temperature tends to increase relative to the latitude; the closer t o the poles, the colder it gets.

Additionally, in order to make our model more realistic, one tool that helped us determine the aver age sea surface temperature of each of the regions is the interactive map at "ventusky.com". We picked 15 random points inside each region (a total of 90 random points), recorded the precise tem perature, and then averaged the values to obtain our result.

2. Limits of migrations

Using the fact that fish can travel at most 400 kilometers, this will imply that the probabilities of fi sh moving between two distinct regions will be equal to 0 if the distance from the center of each re gion is less than 400 km. To measure this distance, we used the "measure distance" tool availab le in google maps. With a reference of 160 km, we then calculated the distances by manually meas uring the distance between the center of each region with a ruler.

3. Birth rate and Death rate

According to wikipedia, each Scottish herring and mackerel can lay around 20,000 - 40,000 eggs per year, but not every egg can survive. Also, the population of scottish herring and mackerel is de clining every year. We make an assumption that the birth rate is 0.3 and the death rate is 0.31.

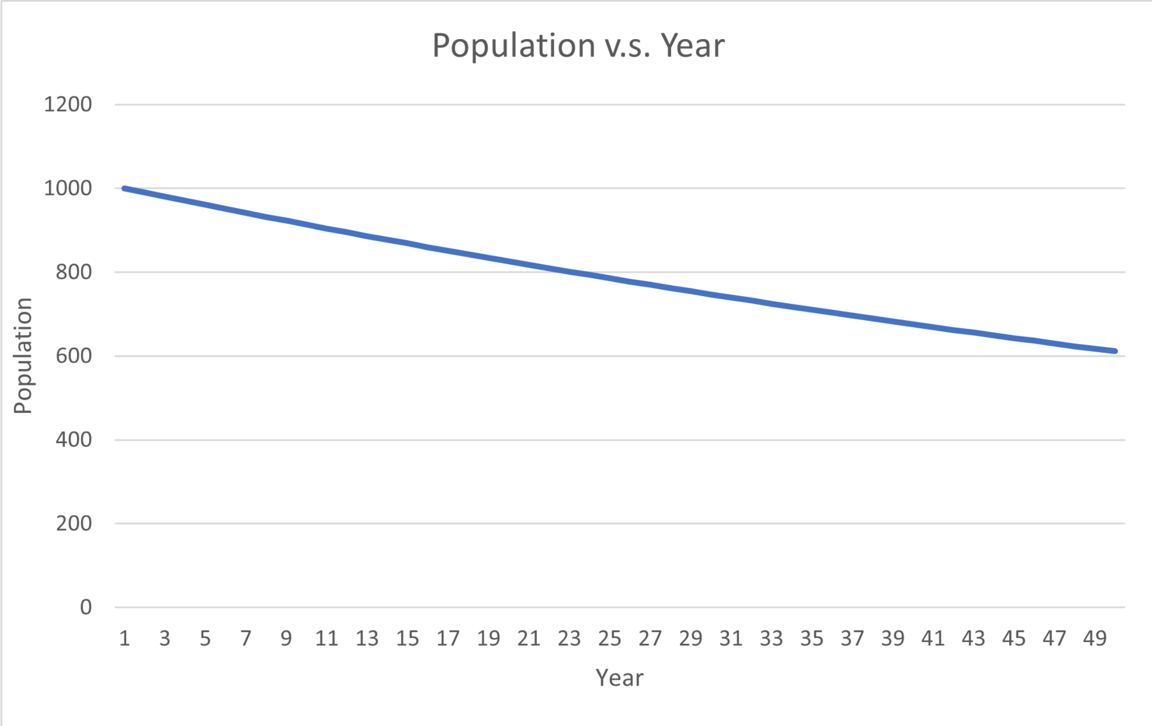
Birth rate	Death rate
0.3	0.31

which give us the formula:

$$x(t) - x(t-1) = 0.3 * x(t-1) - 0.31 * x(t-1)$$

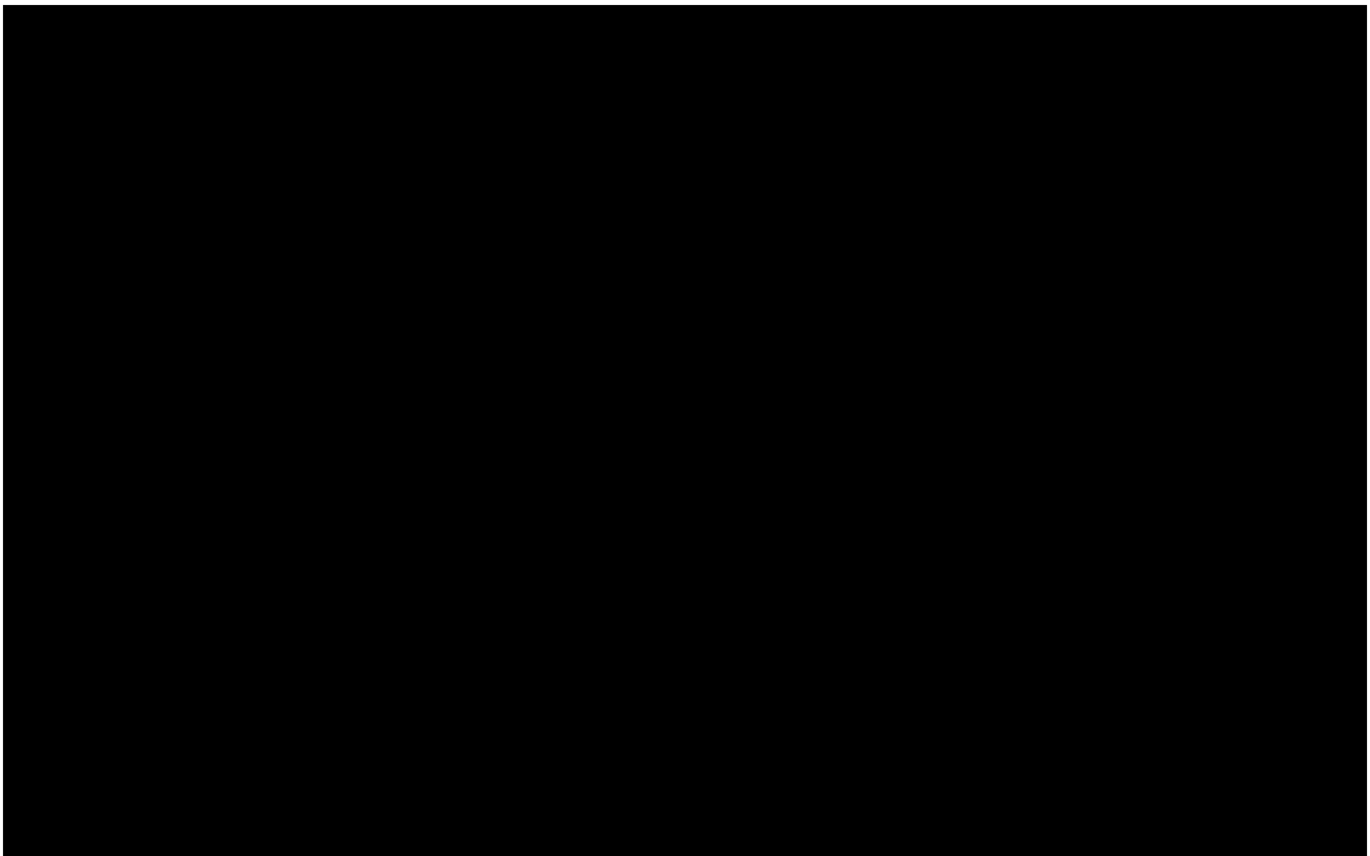
where "t" is a time step for each year.

If we assume the initial population is 1000, after 50 year the population will becomes:



From the graph, we can tell that the population is declining every year, at the year 49, the population will be around 600, which is a reasonable number. This graph has proved that our assumption is correct.

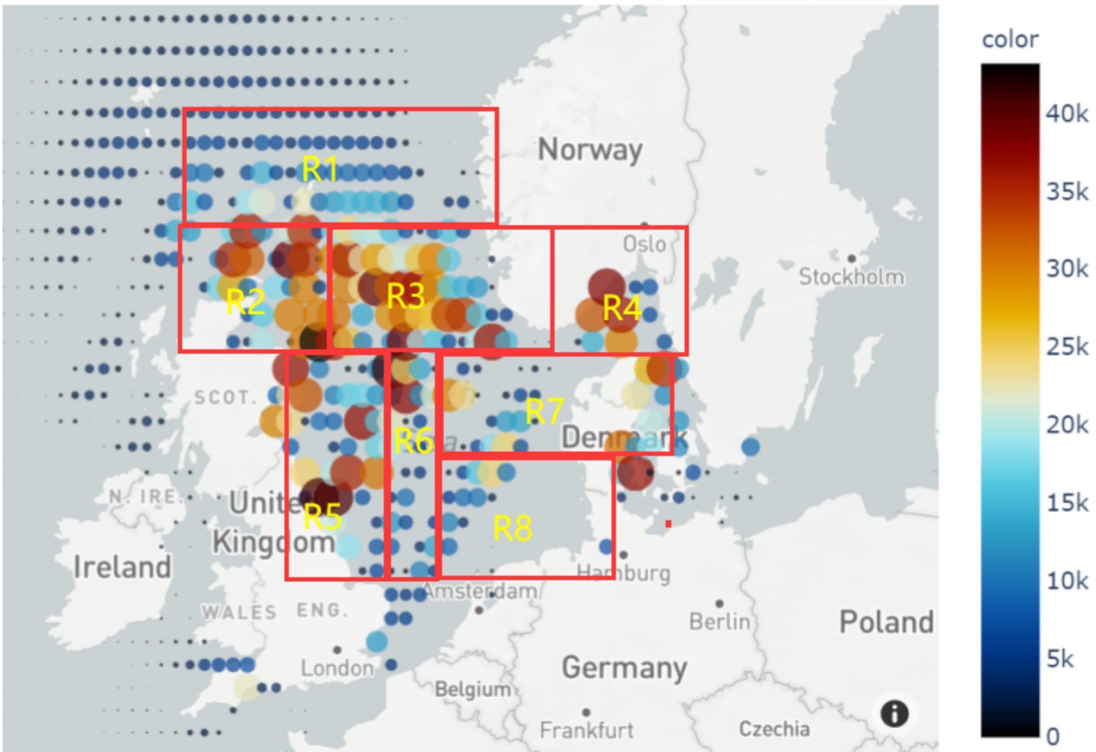
4. Calculating Distances



CENTIMETERS									
	FROM								
		1	2	3	4	5	6	7	8
TO	1	0	3	2.75	6.45	5.9	5.6	5.5	7.5
	2	3	0	4.15	8.25	3.7	4.5	5	7.4
	3	2.75	4.15	0	4.2	5	4	2.7	5
	4	6.45	8.25	4.2	0	8.3	6.15	3	5.1
	5	5.9	3.7	5	8.3	0	2	5	4.95
	6	5.6	4.5	4	6.15	2	0	3.7	3.3
	7	5.5	5	2.7	3	5	3.7	0	2.2
	8	7.5	7.4	5	5.1	4.95	3.3	2.2	0

KILOMETERS									
	FROM								
		1	2	3	4	5	6	7	8
TO	1	***0***	***240***	***220***	516	472	448	440	600
	2	***240***	***0***	***332***	660	***296***	***360***	***400***	592
	3	***220***	***332***	***0***	***336***	***400***	***320***	***216***	***400***
	4	516	660	***336***	***0***	664	492	***240***	408
	5	472	***296***	***400***	664	***0***	***160***	***400***	***396***
	6	448	***360***	***320***	492	***160***	***0***	***296***	***264***
	7	440	***400***	***216***	***240***	***400***	***296***	***0***	***176***
	8	600	592	***400***	408	***396***	***264***	***176***	***0***

5. Simulation of Fish Population Shift



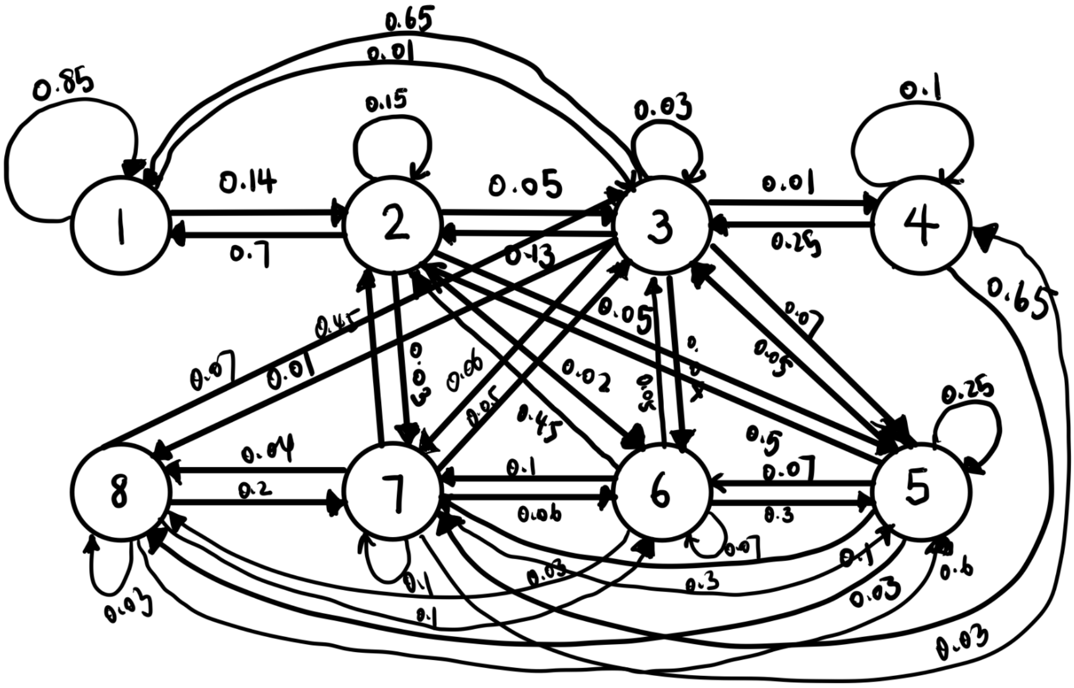
Region	Average Sea Surface Temperature (°C)
1	8.7
2	9.6
3	12.2
4	13.5
5	10.5
6	11.2
7	11.1
8	13.2

Transition Matrix for Markov chain

	1	2	3	4	5	6	7	8
1	0.85	0.7	0.65	0	0	0	0	0
2	0.14	0.15	0.13	0	0.5	0.45	0.45	0
3	0.01	0.05	0.03	0.25	0.05	0.05	0.05	0.07
4	0	0	0.01	0.1	0	0	0.03	0
5	0	0.05	0.07	0	0.25	0.3	0.3	0.6
6	0	0.02	0.04	0	0.07	0.07	0.06	0.1
7	0	0.03	0.06	0.65	0.1	0.1	0.07	0.2
8	0	0	0.01	0	0.03	0.03	0.04	0.03

Table representing the transition matrix, columns should add up to 1.

$$T = \begin{bmatrix} 0.85 & 0.7 & 0.65 & 0 & 0 & 0 & 0 & 0 \\ 0.14 & 0.15 & 0.13 & 0 & 0.5 & 0.45 & 0.45 & 0 \\ 0.01 & 0.05 & 0.03 & 0.25 & 0.05 & 0.05 & 0.05 & 0.07 \\ 0 & 0 & 0.01 & 0.1 & 0 & 0 & 0.03 & 0 \\ 0 & 0.05 & 0.07 & 0 & 0.25 & 0.3 & 0.3 & 0.6 \\ 0 & 0.02 & 0.04 & 0 & 0.07 & 0.07 & 0.06 & 0.1 \\ 0 & 0.03 & 0.06 & 0.65 & 0.1 & 0.1 & 0.07 & 0.2 \\ 0 & 0 & 0.01 & 0 & 0.03 & 0.03 & 0.04 & 0.03 \end{bmatrix}$$



State Diagram

Eigenvalue	Eigenvector
1	0.981, 0.189, 0.022, 0.001, 0.024, 0.008, 0.012, 0.002
0.57702870	0.894, -0.289, -0.064, -0.009 -0.300, -0.078, -0.123,-0.031
0.16965111	-0.564, 0.596,-0.052,-0.163, 0.379, 0.156,-0.360,0.008
-0.12761257	-0.363, 0.766, -0.279, 0.068, 0.113, 0.016, -0.421, 0.100,
-0.07171023	-0.403, 0.778, -0.266, -0.017, -0.352, 0.026, 0.184, 0.050,
0.00019861+0.03657912i	0.587, -0.478-0.290i, -0.253+0.345i 0.025-0.008i, -0.051-0.240i, 0.117+0.281i, 0.012-0.057i, 0.040-0.032i

0.00019861-0.03657912i	0.587, -0.478+0.290i, -0.253-0.345i 0.025+0.008i,-0.051+0.240i,0.117-0.281i, 0.012+0.057i, 0.040+0.032i
0.00224578	0.139, 0.000, -0.182, -0.003, 0.615, -0.744, 0.070,0.104

We get the eigenvalues and eigenvectors by using Python, and one of its numpy function called `numpy.linalg.eig` We could see that there are complex and real eigenvalues and we are going to look the real number ones then we can see that there are {1, 0.577, 0.170,-0.128,..}. We choose the dominant eigenvalue so that it can represent the long term population growth or decline rate. We know that in order to let the eigenvalue be dominant, we need to compute all eigenvalue's absolute value and choose the largest one. So in this case we choose the first one, 1 to be our dominant eigenvalue and its corresponding eigenvectors would be the dominant eigenvectors.

Dominant Eigenvalue	Dominant Eigenvectors
1	0.981, 0.894, -0.564, -0.363 , -0.403, 0.587, 0.587, 0.139

We then normalize the eigenvectors (Divided by the sum of the entries so that the sum of the resulting vector is one), we get that the sum of the dominant eigenvectors is 1 and the vectors after normalizing are :

Dominant Eigenvalue	Normalized dominant Eig

	envectors
1	0.792, 0.152, 0.018, 0.000 51, 0.0192 0.00628, 0.009 5, 0.00136

This can conclude that eventually 79.2% of the fish will be in the R1 region, 15.3% of them will b e in the R2 region and so on… We could see that the fishes have the trend of moving toward the n orth, where the sea has lower temperature.

From the previous assumption, we assume that Scottish herring and mackerel prefer somewhere wi th a lower temperature. As we can know that when you go to region more close to the north side, t he temperature will be cooler, so the temperature in the R1 region is cooler. Based on the result fro m the model assumption, most of the fishes will move to the R1 region, which verifies our model i s correct.

Because those two kinds of fishes all live and migrate in schools (fish groups), it’ s really hard for the scientists to give the actual number of their population, so we could only have an estimated nu mber of those fishes. According to the graph on page 6, we have divided the graph into 8 regions t hat we are going to run simulation on, this shows the population distribution of herring in 2019. A nd so we could say that from the initial state, here is all the distribution of the fishes.

Initial population of fishes:

R1	400k
R2	450k

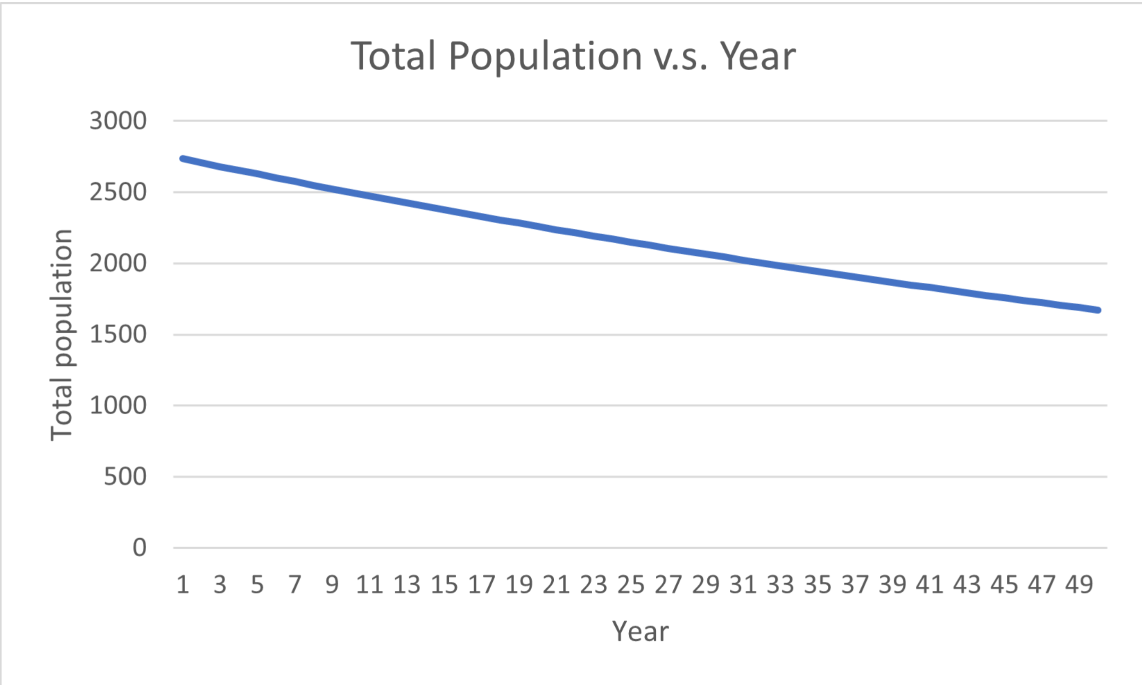
R3	750k
R4	150k
R5	400k
R6	200k
R7	275k
R8	110k

We do the stimulation for 50 years:

Population after 50 years:

Region	Total population
R1	2166

R2	418
R3	49
R4	1
R5	52
R6	17
R7	25
R8	3



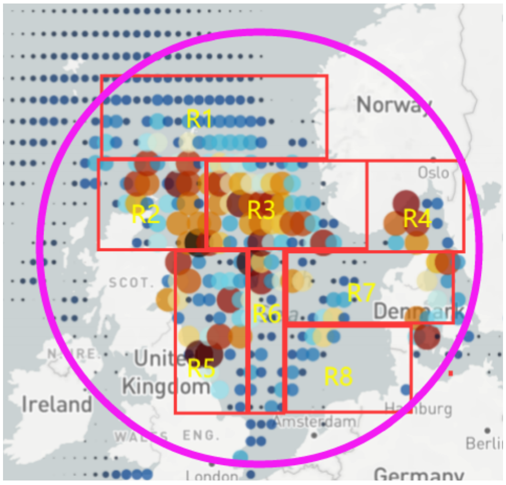
When Will fishes be too Far Away?

The second task for us is to predict the best case, worst case and most likely elapsed time until the fish populations will be too far for small fishing companies to harvest. According to our simulation, there will always be some fish in Scottish water even if the majority have already exited.

Here we are going to define what and where the "harvest" and "small fishing companies" are.

<u>Harvest</u>: Companies can harvest at the region where large amounts of the fishes are located. So I would say in the region 3,4,5,6. These areas are able to let small companies to cover.

<u>Small Companies</u>: Small companies mean that they do not have big boats, so they are not able to travel far. They are only able to travel within the range of region 1 - 8, so outside of those places, they will no longer be able to travel. We could imagine region 1 - 8 as a circle.

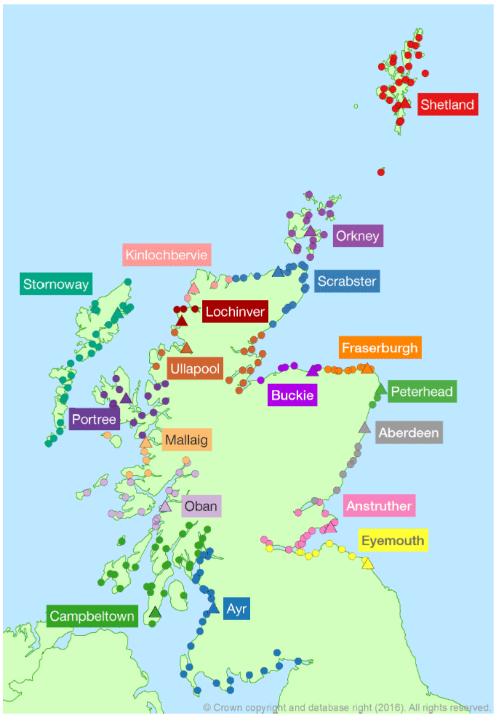


We would say that the best case is the time it takes for region 1 fish to migrate even further(because fishes are moving and not just staying in one region so even for region 1 the fish will move too) , further than the largest distance that the small companies' boats could travel. Because we know the largest distance is from region 1 to 8, so the best case is going to be the time fish travel from 1 to 8 and plus a few days, and the worse case would be the time it takes for the regions other than 1 to have no fish in it. So by looking at our previous simulations, we could make this table:

Best Case	Worst Case	Normal Case
50 years	< 1 year	25 years

We could look at the simulation line plot of the fish, which we could see that for regions other than 1 and 2, the fish population would decline super rapidly, just in the first several years, so the worse case of the fish being too far is travel out of the regions which is less than 1 year and the best case would be the time it takes for fish travel from region 8 to 1 which is around 50 years, and the nor mal cases are just if one of the fish in the middle of region 1 - 8 are going to travel outside of the c ircle, the distance is just the radius of the circle, so we use 50/2 = 25 years.

<u>III Operation suggestions for the small fishing companies</u>



According to Scotish government website, Scotland's inshore waters extend from the coast out to 12 nautical miles (22.2 km),which is mainly in the R2, R5 region based on our previous graphic analysis. (except for the shetland fishing port which is mainly in R1 region) As shown in the simulation above, we conclude that the small fishing companies operating on the East Coast of Scotland should make changes to their operation strategies.

Move the company' s asset to fish migration location

We assume that the small fishing companies relocate their ports to R1 region, around the Shetland Island region. Based on the conclusion, in the normal case scenario, it will take 25 years for the two fish species to migrate to region 1, and this trend will stabilize around 10 years from now on. Hence we will calculate the profit earned by the fishing firms from year 10 to year 25, estimating the profit earned between 2031 and 2046 if the company completed relocate their ports in year 2031.

Profit earned: $\pi(t) = R(t) - C_0$

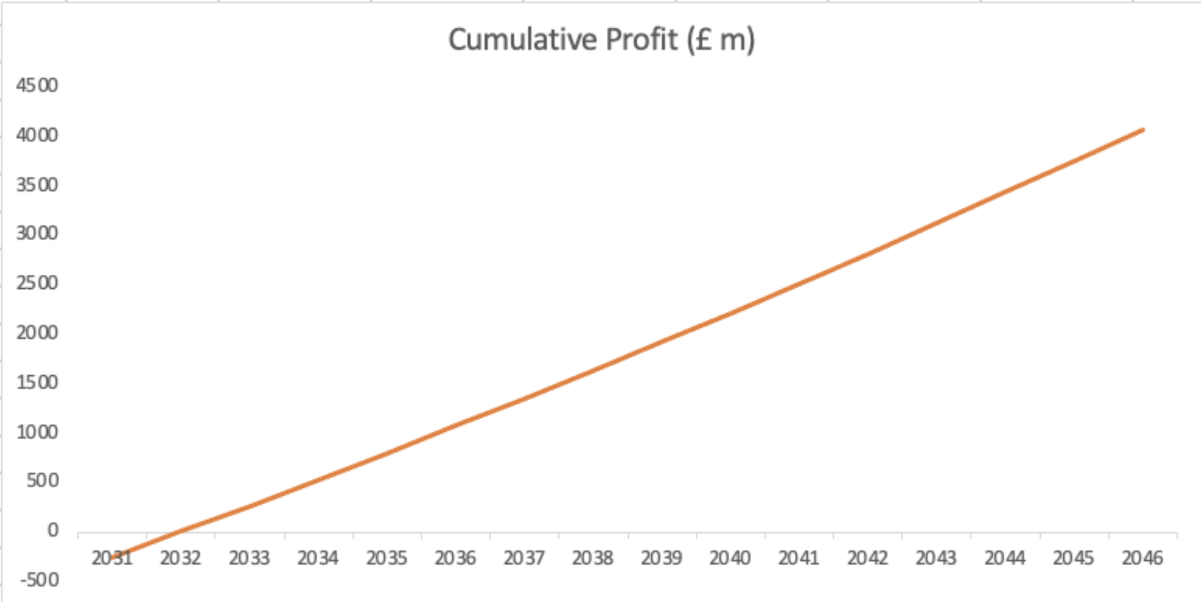
Cumulative profit: $\pi(t_1, t_n) = \sum_1^n R(t) - C_0,\ 1 \le n \le 13$

$R(t) - total\ value\ of\ herring\ and\ mackerel\ at\ year\ t\ in\ millions$

$C_0 -\ cost\ of\ relocating\ the\ fishing\ ports\ in\ millions$

Based on data of fishing port reconstruction cost from the World Bank, the average cost of relocating a fishing port is £ 45 million. To relocate all 11 major fishing ports on the East Coast (within the R2, R5 region) the total cost will be £ 495 million. Therefore, C0 equals to 495.We also assume that, after moving to the new location, the fishing firms generate revenue following patterns from previous years.

Based on Scottish Sea Fisheries Statistics 2019 and 2020, we can graph the estimated cumulative profit earned from 2031 to 2046.



As we can see from the graph, if the small fishing firms relocate ports in 2031 after the migration trends of herring and mackerel stabilized, they will incur one year of losses for £244 million, but th e loss will be quickly recovered by high profits in consecutive years. Therefore, relocating the fishi ng ports to a new location can generate long-term economic benefits for the small fishing compani es.

IV CONCULSION

1) From the line plot, we can see that after 50 years, most of the fishes migrate to region 1. The population in region 1 will exceed 2000k but not increasing and all the fishes in the other reg ons will decrease respectively. If we look at the total population graph, we can tell that the tc al population is actually declining .
2) We set the Population moving rate to be a relatively severe case. In a case where the temper ature did not go that high, the moving rate will not be that high. The population will not mov e so fast, but they all eventually go to R1 in both best and worst cases.
3) Based on the model we create and the simulation of when the fish would be too far away fro m where the companies are able to fish, we would suggest small fishing move the business l ocation to anywhere near region1, region 2 and region3. The graph on page10 indicates that

after 50 year, region 1 will have the most population compared to other regions. And it would take fish a very long time to go far from R1 region .

In addition to this, small fishing companies also have to worry about the total population of fishes decreasing every year. From the graph on page 11, we can see that initially we had a total fish population of 2735k, but after 50 years, we only 1671k left. Roughly 40% of the fishes have gone. With both population migration and population decreasing, it will be hard for small fish companies in north scottish to survive in the future.

4) In this model, we do not assume fishes will move to other territorial waters. If we take the moving rate from outside sea area, that could be more accurate, but we do not know under what condition fishes will move in or move out. Also, we already have the moving rate for the inner north scottish sea, adding two might produce some error.
5) If the small fishing firms relocate fishing ports in 2031 after the migration trends of herring and mackerel stabilized, they will incur one year of losses for £244 million, but the loss will be quickly recovered by high profits in consecutive years. Therefore, We suggest the fishing firms relocate the fishing ports to shetland in 2031 to adapt the migration of fish.

Work Cited

Wikipedia contributors. (2021, May 7). *Sea surface temperature*. Wikipedia. https://en.wikipedia.org/wiki/Sea_surface_temperature

Oeberst, R. (2009). *Mean daily growth of herring larvae in relation to temperature over a range of 5–20°C*. OXFORD ACADEMIC. https://academic.oup.com/icesjms/article/66/8/1696/677425

Ventusky - Wind, Rain and Temperature Maps. (n.d.). Ventusky. Retrieved June 10, 2021, from https://www.ventusky.com/?p=55.1;-0.1;4&l=temperature-2m

The Marine Life Information Network. (n.d.). *MarLIN - The Marine Life Information Network - Atlantic herring (Clupea harengus)*. Marine Life. Retrieved June 10, 2021, from https://www.marlin.ac.uk/species/detail/45

Map. (n.d.). Google Map. https://www.google.com.tw/maps/place/%E8%8B%B1%E5%9C%8B%E8%8B%B1%E6%A0%BC%E8%98%AD/@53.8629096,-8.7459822,6z/data=!4m5!3m4!1s0x47d0a98a6c1ed5df:0xf4e19525332d8ea8!8m2!3d52.3555177!4d-1.1743197?hl=zh-TW

The Scottish Government. (2020, September 28). *Scottish Sea Fisheries Statistics 2019*. Gov.Scot. https://www.gov.scot/publications/scottish-sea-fisheries-statistics-2019/pages/15/

The Scottish Government. (2021, May 18). *Provisional Scottish sea fisheries statistics 2020*. Gov.Scot.https://www.gov.scot/publications/provisional-scottish-sea-fisheries-statistics-2020/