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EXPLORING THE MOVEMENTS OF ATLANTIC SALMON AROUND SCOTTISH COASTS, USING HISTORICAL TAGGING DATA AND A SIMPLE AGENT-BASED MODELLING APPROACH

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ABSTRACT

Meeting targets for green energy generation will involve marine renewables. To ensure that this development is environmentally sustainable, it is necessary to assess potential interactions between renewable energy arrays and marine organisms.

One species that may be affected is the Atlantic salmon (*Salmo salar*). Salmon undertake extensive migrations which pass through Scottish coastal waters, where they may encounter renewable energy developments. To assess possible risks to migrating salmon, it is important to understand how many fish may encounter devices. This requires knowledge of how many migrating salmon pass through areas where renewables development is taking place, but there are few data available.

One potential resource in Scotland is a historical archive of tagging study data. We use these data, in conjunction with an agent-based modelling approach, to simulate movements of fish around Scotland. This approach works by representing the coastal seas as a linear series of 'cells' corresponding to salmon fishery districts, and a parallel series of cells representing the salmon home rivers. At each time step, fish can migrate along the coast, or move into their home rivers. This model can be parameterised using data on coastal fishing effort, productivity of home rivers, and other factors, in order to explore potential influences on patterns of recaptures, and to test hypotheses about coastal movements of salmon.

INTRODUCTION

The European Union has committed to producing 20% of EU-wide energy consumption from renewable sources by 2020.[1] The UK intends to generate 15% from renewables by this date,[2] while Scotland is aiming for production of the equivalent of 100% of Scotland's electricity demand (and 11% of its heat energy demand) from renewables on the same timescale.[3] Marine renewables – offshore wind, wave and tidal power – will play a role in meeting these targets. Since these technologies are still relatively new, the potential environmental implications of industrial-scale deployment are not well understood. However, in order to be sustainable, these and future developments must be partnered with robust assessment of any risks to the natural environment. This includes potential effects on sensitive stocks of Atlantic salmon.

The Atlantic salmon, *Salmo salar*, is a species of high conservation significance and considerable socio-economic importance in Scotland.[4] Atlantic salmon stocks are considered to have declined throughout their range, particularly since the mid- to late- 1980s.[5] Salmon are anadromous; they spend the majority of their adult lives in the oceans but return to freshwater to reproduce. After hatching, young fish spend 1-4 years living in the river before migrating to sea as 'smolts'). Post-smolts then migrate long distances to feeding grounds in the North Atlantic.[6] After 1-3 years at sea, adult fish return to their rivers of origin to spawn.

The migrations of Scottish salmon include periods of time spent in coastal waters;[7] fish may pass through renewable energy development areas during these times. To estimate potential impacts on salmon, we need to understand not only the possible interactions between devices and fish (disturbance, displacement, etc.) but also the numbers of fish that may encounter arrays of devices. In order to do this, we need to answer two key questions. Firstly, what proportions of salmon from Scottish rivers pass through areas (such as the Pentland Firth) where renewable energy developments may occur? Secondly, what proportion of these fish may pass through actual arrays of devices? This paper will focus on the first question, which requires information on the coarse scale movements of fish around the coasts of Scotland, and will only consider the migration of adult fish returning to Scotland to spawn. This migration can be thought of as being divided up into three phases:

1. **Oceanic**. Fish cross the North Atlantic from their feeding grounds and arrive at the coasts of the UK and Ireland.
2. **Coastal**. Fish move around the coastline, searching for their home rivers.
3. **River**. Having reached the entrance to their home river, fish move upstream to their spawning grounds.

Here we are mainly concerned with the second, coastal, phase. One way to model movements of fish during migration around the coasts is using particle-tracking models to simulate individual trajectories of individuals within hydrodynamic models. However, a detailed model of Scottish coastal seas, capturing

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all features of interest at suitable resolution, would be complex and expensive to build and validate. Furthermore, such models are very sensitive to the 'behaviour' of individual particles, and currently there is insufficient data on salmon migratory behaviour to allow meaningful parameterisation.

As an alternative, or complementary, approach, we have developed a simple 'cellular' model which allows us to simulate the movements of salmon through Scottish coastal waters. The outputs of this model can be compared with the results of a range of historical salmon tagging studies carried out in Scotland from the early 20th Century onwards.

METHODOLOGY

For administrative purposes, Scotland is divided into 109 salmon fishery districts (Fig. 1), for which catch and effort data are reported. If we assume that fish, once they arrive in coastal waters, move along the coast without heading back offshore, then we can represent the coastline of Scotland as two linear series of cells (Fig. 2). Each pair of cells represents the salmon rivers (lower cells, green) and coastal waters (upper cells, blue) of each district.

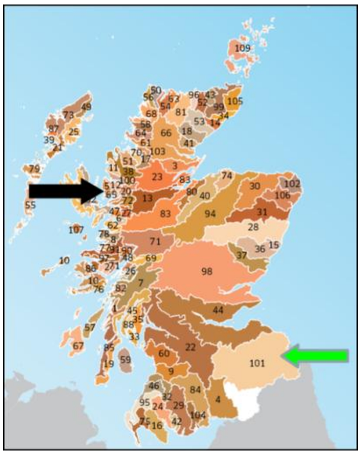

Figure 1 Scottish salmon fishery districts. Arrows indicate corresponding positions in model 'world' (Fig. 2)

The model 'world' was coded using NetLogo.[8] Modelled fish can be placed in the coastal waters (blue cells) of any fishery district, and individual fish are assigned a 'home river identity' which would correspond (in the real world) to the river in which they hatched. For this iteration of the model, these home river identities were set proportional to the productivity of the rivers in each fishing district, such that relatively large river systems (eg. the Tweed) contribute proportionally more to the overall population of fish in the model. At each time step, there are four possible outcomes for each fish:

1. All fish in coastal waters have a (globally fixed) probability of being captured in coastal fisheries.
2. Any fish in coastal waters (blue cells) that is not captured has a 50% chance of moving into the adjacent river (green cell), ***if*** it is in the fishery district that matches its 'home river identity'.
3. Any fish that is not captured and has not moved into its home river, has a 15% chance of moving one district (cell) towards its home district.
4. Any remaining fish move randomly either left or right along the sequence of cells, (with a 0.5 probability of moving either way). They do not move into river cells.

The model runs until all fish are either captured in a fishery or have returned to their home river. The probability values used for options 2 and 3 above (50% and 15% respectively) were selected following a simple sensitivity analysis using data from a tagging study (see below). The final positions of all fish are recorded and output.

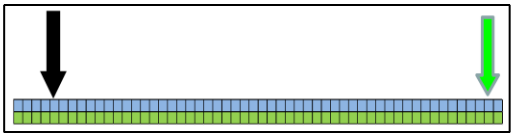

Figure 2 NetLogo model 'world'. Green cells are the rivers of each fishery district; blue cells are associated coastal waters. Arrows indicate correspondence with locations of real fishery districts in Fig. 1

A number of tagging studies have been carried out on Scottish salmon; in the early part of the 20th Century this work was mainly carried out by the Inspector of Salmon Fisheries of Scotland. These experiments were conducted by tagging returning adult salmon, captured at coastal netting stations, and recording the pattern of recaptures by commercial fisheries and recreational anglers[7]. We took data from ten of these studies (Fig 3a) and used our model to 'recreate' each tagging study. A number of fish equal to the number actually recaptured were placed in the model at the coastal cell representing the location where the real study took place. Ten replicate model runs were executed for each experiment.

RESULTS AND DISCUSSION

The initial results to be considered are the proportions of fish that, at the end of the simulation, are found to the left and right of the tagging location in the model world (corresponding to anti-clockwise and clockwise movement around the coast of Scotland respectively, Fig. 3b). Fish that are recaptured within the tagging district are not considered here, as these recaptures are not informative regarding fish movements.

The outputs of the model show some correspondence with the results of the real tagging studies, while in some cases there are clear differences. For the Raffin 1937 study, the model successfully predicts that most fish will move clockwise around the coast. Similarly, the model is correct in forecasting that more fish will head anti-clockwise (moving northwards) than clockwise (southwards) after tagging at Rockhall; however, the proportion of fish heading anti-clockwise in the real study was much greater than in the model.

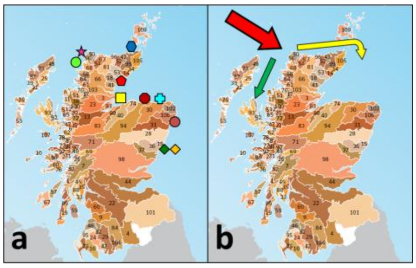

Figure 3 a) locations of historical tagging studies replicated using the model. b) potential migration of fish arriving on the North-west of Scotland (red arrow). Fish can move clockwise (yellow arrow, rightwards movement in the model world) or anti-clockwise (green arrow, leftwards movement in the model world).

When simulating tagging and release of fish at Macduff, the model estimates an approximately even distribution of fish heading each way, but this differs from the actual results. Finally, for the Learnie 1914 study, the model does not correctly predict either the direction or the magnitude of the trend. These patterns are representative of those observed for the other tagging studies; the model often correctly predicts which direction the greatest proportion of fish will move in, although it is sometimes wrong about the magnitude of the difference in proportions moving in each direction. In some cases (as with the Learnie 1914 study) the actual data show that the bulk of migratory movement at that location is actually opposite to that predicted by the model.

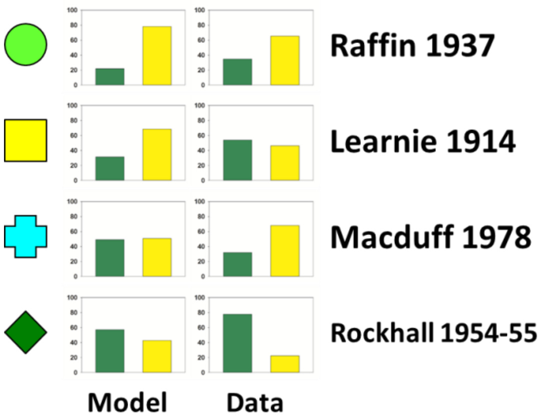

Figure 4. Comparisons of model outputs with real tagging results for four selected experiments; proportions of fish recaptured to the left (green bars) or right (yellow bars) of the tagging location in the model world (Fig. 2). Symbols indicate location of tagging experiment in Fig. 3a.

Cases where the model predictions are incorrect are perhaps the most informative outputs. They reveal that there are aspects in which this very simple model structure is not a good representation of the movements of returning adult *S. salar* and that adjustments to the model are necessary. Potential reasons for the lack of correspondence between model and data include: oversimplification of the model structure (a linear series of cells could be too simple); erroneous assumptions regarding river productivity and arrival points of fish at the coast (which are used to determine the mixture of 'home river identities' of fish); and temporal mismatch between tagging data and other data used in the model. These, and other potential flaws, will be addressed in future versions of the model.

CONCLUSIONS

A simple ABM can reproduce some features of adult salmon return migration around the coast, but does not yet capture all significant features of salmon movement around Scotland. Ultimately it is intended that the model should allow us to examine hypotheses about salmon migration around Scotland, particularly with regard to estimating numbers that may pass through renewable energy sites.

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