An agent-based model of Atlantic salmon migration in Scottish coastal waters

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INTRODUCTION

Atlantic salmon, *Salmo salar*, are economically important in Scotland,[1] but populations may be in decline.[2] Relatively little is known about their migration, or their behaviour in coastal waters. This makes it difficult to predict the effects of changes such as the development of marine renewable energy arrays.

Over 100 years of data collection and tagging experiments conducted in Scotland do allow some insights into salmon movements.[3] Our aim is to use these data resources to develop an 'agent-based' model of fish movements around the coast.

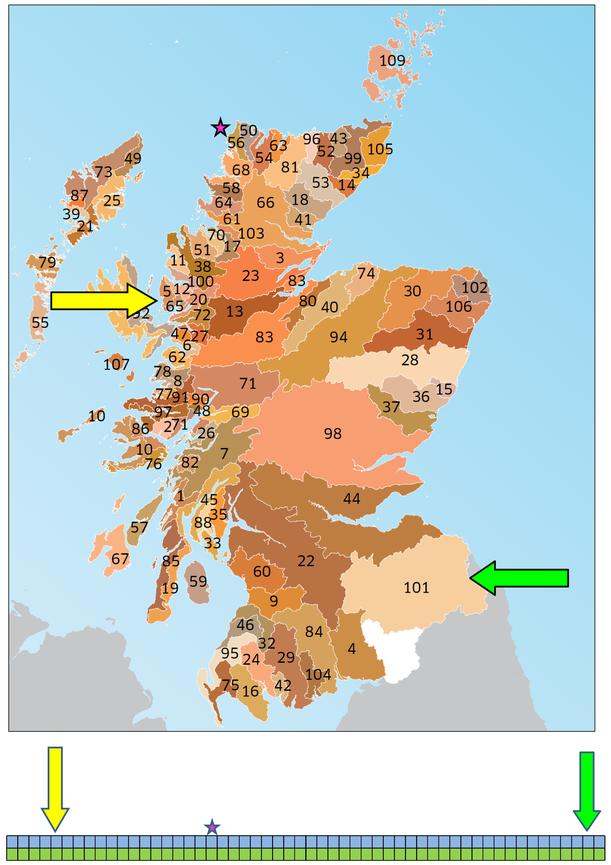

Figure 1. Scottish Fishery Districts (upper) mapped to a 2 x 54 NetLogo 'world' (lower). Arrows indicate Kishorn district (65, yellow arrow, left) and Tweed district (101, green arrow, right). Star indicates starting position of modelled fish – Inchard (56). Green squares represent the home rivers of each district, and blue squares represent adjacent coastal waters. Image from [6].

THE MODEL

An agent-based model was coded using NetLogo.[4] Scotland is divided into 'Fishery Districts' (Fig. 1); these are represented as pairs of 'patches' in the model, arranged in a linear sequence (Fig.1, lower). Green patches represent 'home rivers' and blue patches are the adjacent coastal waters. 141 fish are placed in the coastal waters of 'Inchard' district (recreating a 1936 tagging study[5]). Each fish has a 'home river' to which it is trying to return – these are assigned proportional to the relative salmon production of each of the districts (based on 2011 and 2012 rod catch data[7]). Individual fish move through coastal waters, searching for their home rivers (Fig. 2). At each time step fish in coastal waters also have a 1% chance of being captured in coastal fisheries. At the end of the model run, coastal catches and river returns are examined.

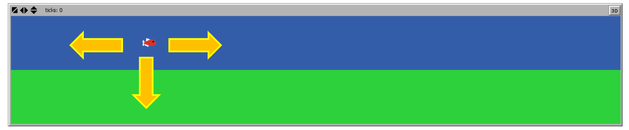

Figure 2. An individual fish in a small 'world' only 10 patches long. At each time step the fish, if it is in coastal waters adjacent to its home river, may move into the river. If it does not, it moves either towards its home river, or randomly left or right. Once fish have 'homed' to a river, they no longer move.

INITIAL SENSITIVITY ANALYSES

The behaviour of individual fish is controlled by two parameters:

1. *home-sense* –the probability that a fish will move into its home river when in adjacent coastal waters.
2. *loc-sense* –the probability that fish can tell which way they need to travel to reach their home rivers. If it is zero, fish always move randomly along the coast. If it is 1, then fish always move towards their home rivers.

home-sense seems to have little effect on model behaviour. Increasing *loc-sense* reduces run length (Fig. 1), but increases numbers of fish moving east and successfully getting 'home'.

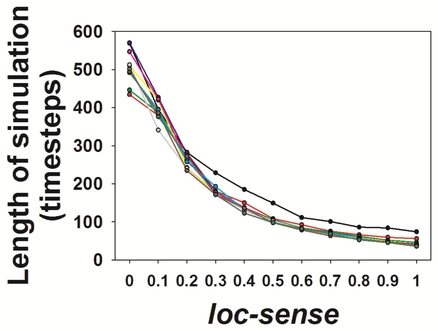

Figure 3 (left). Effect of *loc-sense* and *home-sense* on the length of simulations (number of timesteps until all fish have either returned to home rivers or been captured in coastal fisheries). Plotted curves are for individual values of *home-sense* – changes in this parameter have little effect

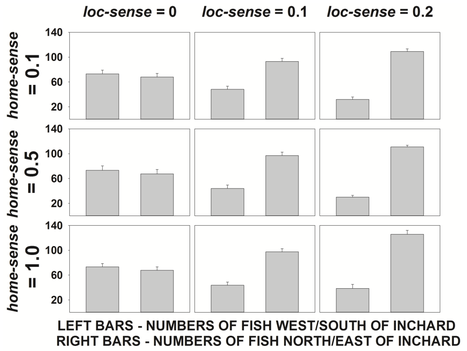

Figure 4. Effect of *loc-sense* and *home-sense* on numbers of fish moving west/south and north/east) of the starting point (Inchard). Averaged over 10 runs, error bars ± S.D.

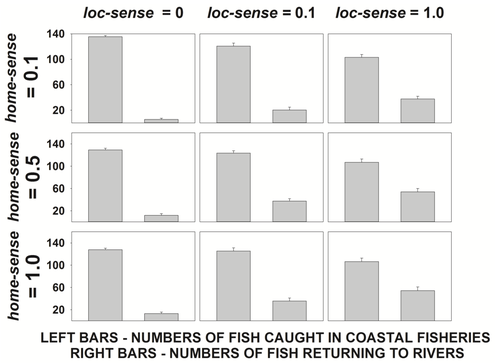

Figure 5. Effect of *loc-sense* and *home-sense* on numbers of fish captured in coastal fisheries or returning to rivers. Averaged over 10 runs, error bars ± S.D.

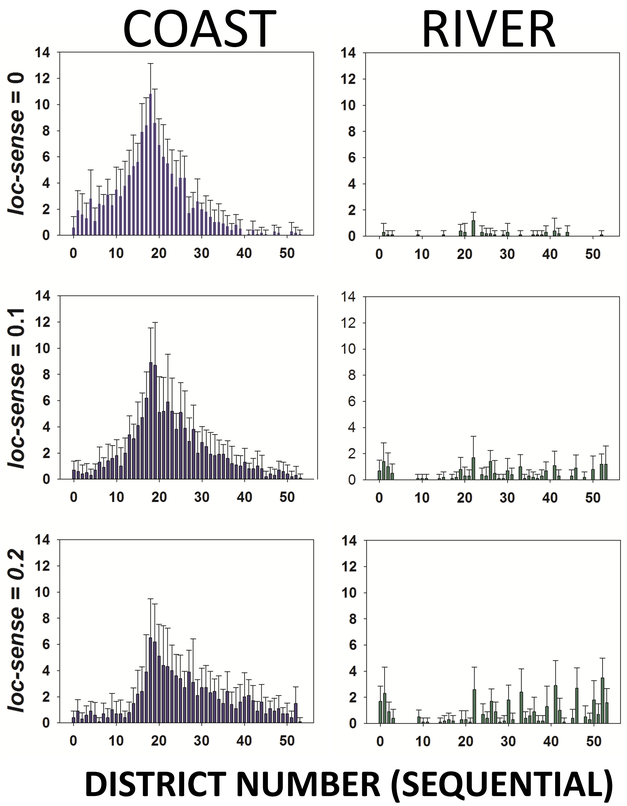

Figure 6. Distribution of fish at the end of simulations using three values of *loc-sense* (*home-sense* = 0.1). Left panels: numbers of fish captured in coastal fisheries of each district. Right panels: numbers of fish returning to home rivers. Averaged over 10 runs, error bars + S.D. Districts in this case numbered 1-53 starting at the left of the NetLogo world (Fig.1, lower). Inchard is district 18 in this case.

REAL DATA

Simulation runs with *loc-sense* set to 0.1 produce results similar to real recapture data in terms of proportions of fish moving in each direction, and proportions captured in coastal fisheries versus rivers (Fig 7a and 7b). Actual distributions of recaptures match less well (Fig. 7c and 7d).

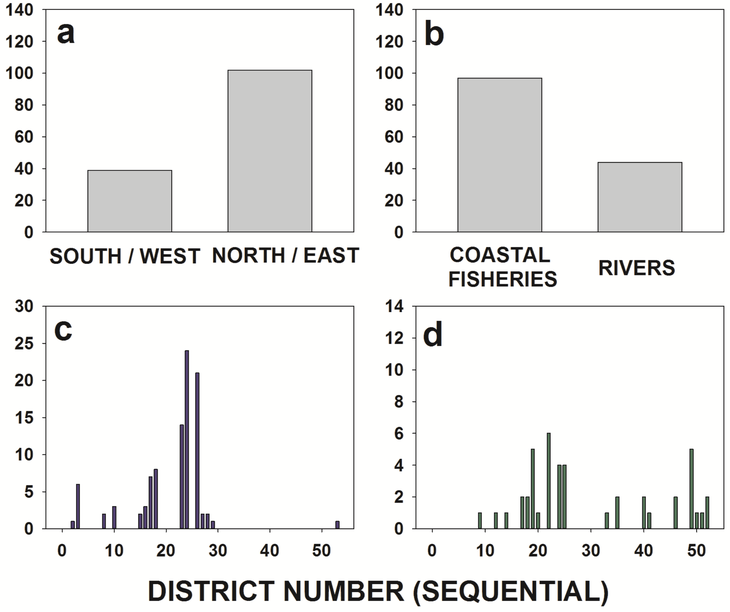

Figure 7. Data from 1936 tagging experiment at Inchard.[5] **a:** numbers of fish recaptured south/west and north/east of Inchard (cf. Fig. 4). **b:** proportions of fish recaptured in rivers and coastal fisheries (cf. Fig. 5). **c and d:** actual distribution of recaptures by district in coastal fisheries and rivers respectively (cf. Fig. 6).

CURRENT LIMITATIONS

- The model captures some features of coastal migration, but is clearly oversimplified in its current version.
- Not yet parameterised with real effort data (uniform fishing effort is not realistic).
- Mismatch between relative river productivity estimates (based on 2011-2012 catch data) and tagging study used for model testing (1936 data).

NEXT STEPS

- Obtain and test other proxies for district productivity.
- Obtain appropriate fishing effort data.
- Further sensitivity analyses and scenario-based testing (using data from Marine Scotland tagging records).
- Test effect of 'short-cuts' and alternative routes on model output (Fig. 8).
- Initiating model with fish spread across multiple districts, rather than starting from single point.

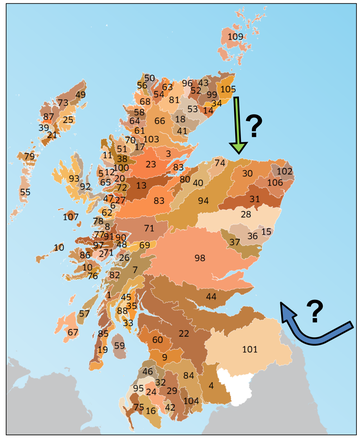

Figure 8. Fish may arrive at the coast at various locations, and may not proceed along the sequence of districts in a strictly linear fashion. For example, fish might cut directly across the Moray Firth (green arrow), or arrive in large numbers directly on the east coast.

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