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This report presents the results of marine and freshwater scientific work carried out by Marine Scotland Science.

Using historic tag data to infer the geographic range of salmon river stocks likely to be taken by a coastal fishery

Helen Downie, Nora Hanson, Gordon Smith, Stuart J. Middlemas, Jackie Anderson, Dave Tulett and Hilary Anderson

Executive Summary

A review of both published material and Marine Scotland records was conducted to identify data available from historic tagging studies of salmon in Scotland. These data have been analysed with the aim of identifying those river stocks likely to contribute to the catches of individual coastal fisheries.

Two sets of tagging programmes were identified. The first consisted of salmon tagged as juveniles in-river and subsequently reported caught in coastal fisheries during their return adult migrations. The second comprised of adult fish tagged in coastal net fisheries during their return migration and recovered within rivers.

Juvenile salmon were tagged in four major East coast rivers (the Conon, the Aberdeenshire Dee, the North Esk and Tay) and a total of 576 were recaptured from 60 different coastal fisheries around Scotland. For each of these four major east coast river stocks, returning adults were taken in widely dispersed coastal fisheries. Fish from the rivers Tay and North Esk for example were recaptured in both west coast and Solway fisheries. Such data confirm that coastal fisheries throughout Scotland may exploit fish which originate from rivers some considerable distance from where they operate.

For the adult tagging programmes, data from 23 coastal fisheries were analysed and a total of 572 returning adult salmon were recovered from 59 rivers. The distances between coastal tagging sites and the mouths of those rivers where tagged fish were subsequently detected were estimated for each of these fish and the overall direction of travel (clockwise or anticlockwise) was also recorded.

Pooling the data across all tagging programmes, distances between adult release and in-river tag recoveries were fairly evenly distributed between anticlockwise and clockwise directions. Further, 50% of the tags were recovered within 15 km anticlockwise to 28 km clockwise from the fishery of release and 90% of recoveries were within 127 km anti-clockwise to 157 km clockwise from the fishery. Recoveries were occasionally very distant from the fishery of release; maximum distances observed were 571 km in an anticlockwise direction and 907 km in a clockwise direction.

The analysis presented does not provide the river stock composition of any given coastal fishery, nor can it assess the impact of a coastal fishery on any given river stock. However, assuming that in-river recovery of tags provides some indication of the river of origin of individual fish, these data do allow a more quantitative description of the relationship between coastal fisheries and the river stocks which comprise their catch than has been attempted previously. For all adult tagging data analysed here, for example, half of all recovered tags were recovered in rivers within tens of kilometres of tagging sites; 90% of tags were recovered within hundreds of kilometres and 100% of tags were recovered within several hundreds of kilometres of coastal fishery tagging sites. These range of distances, derived from substantial historic tag records, provide the best information currently available for identifying those river stocks likely to contribute to a coastal fishery in a given location.

Introduction

North Atlantic Salmon Conservation Organisation (NASCO) guidelines advise that salmon stocks and the fisheries which exploit them should be managed at the scale of individual rivers (NASCO, 2009). Mixed stock fisheries (MSFs), defined as fisheries that exploit significant numbers of salmon from two or more river stocks (NASCO, 2009), pose significant difficulties for such a management regime as some of those stocks which comprise the catch may be in poor conservation status.

NASCO guidelines further advise that management actions in respect of MSFs should aim to protect the weakest of the contributing stocks (NASCO, 2009). This provides a significant challenge for management where the stock composition of the catch is unknown or it is not possible to direct the fishery in order to target specific stocks (Ensing et al, 2013).

On their return migration the majority of Atlantic salmon, *Salmo salar* L., home to their natal rivers to breed; however some may enter other rivers for a short period or may even breed in non-natal sites (straying). As a consequence of straying all fisheries may, to some extent, exploit fish from more than one river stock (Youngson and Hay, 1996; Crawley et al, 2010). In this regard, fisheries in coastal waters or on the high seas are more likely to intercept significant numbers of salmon from two or more river stocks, whereas fisheries in estuaries and especially rivers are more likely to be dominated by individual river stocks (Potter and Ó Maoiléidigh, 2006; NASCO, 2009; Crawley et al, 2010).

Conservation regulations were introduced for the management of Scottish salmon stocks in 2016 (http://www.gov.scot/Topics/marine/Salmon-Trout-Coarse/fishreform/licence/status). Salmon fisheries in inland waters (rivers and estuaries) are managed according to the conservation status of the associated river stock. Retention of salmon in coastal waters is currently prohibited. Additionally, when the conservation regulations were introduced, a commitment was given that the moratorium on coastal fisheries would be reviewed (McLeod, 2015).

The analysis presented here has been conducted to support such a review. Salmon tagging data involving coastal net fisheries has been collated from both published and unpublished material. The distance and direction adult salmon travelled between coastal fisheries and river of recovery was estimated. To the extent the dataset permitted, spatial and temporal patterns in these metrics were analysed. A characterisation of the distances between coastal fisheries where returning adult fish were tagged and the rivers in which they were subsequently located is provided and could be used to infer those river stocks likely to contribute to the catches of individual coastal fisheries.

Materials and Methods

Data collation

A review of both published material and Marine Scotland records was conducted to identify data available from historic tagging studies of salmon in Scotland. These data were compiled into two separate databases. The first consisted of salmon tagged as juveniles in-river and subsequently reported caught in coastal fisheries during their return adult migrations. The second dataset comprised of adult fish tagged in coastal net fisheries (Fig.1) during their return migration and recovered within rivers. In both cases, data was restricted to recoveries in Scottish waters. Biologists across Scotland's fisheries trusts were also given the opportunity to contribute local data from unpublished tagging studies, although none were able to supply data suitable for analysis.

Four juvenile tagging data sources were identified, all as part of Marine Scotland records. Sample sizes and tagging methods were not available for all studies. Data collated was therefore limited to reports of the location of those tagged fish caught as returning adults in coastal fisheries.

Adult tagging programmes have been reviewed previously in relation to the coastal migration patterns of returning adult salmon (Shearer, 1992; Malcolm et al, 2010). Original sources from these reviews were collated together with Marine Scotland records (Appendix 1). Information from more recent tagging studies was also included (Godfrey et al, 2015; Orpwood et al, 2016). Again, sample sizes and tagging methods were not available for all studies. Data collated was limited to reports of the location of in-river returns of tagged adults. Adults were tagged by a variety of methods in these studies including both transmitting and numbered tags; recovery was by rod anglers, adult monitoring traps, or via detection of transmitting tags. For the present analysis, records were restricted to observations where recovery occurred in rivers (excluding estuaries) to maximise the likelihood that a given recovery represented a member of that river stock.

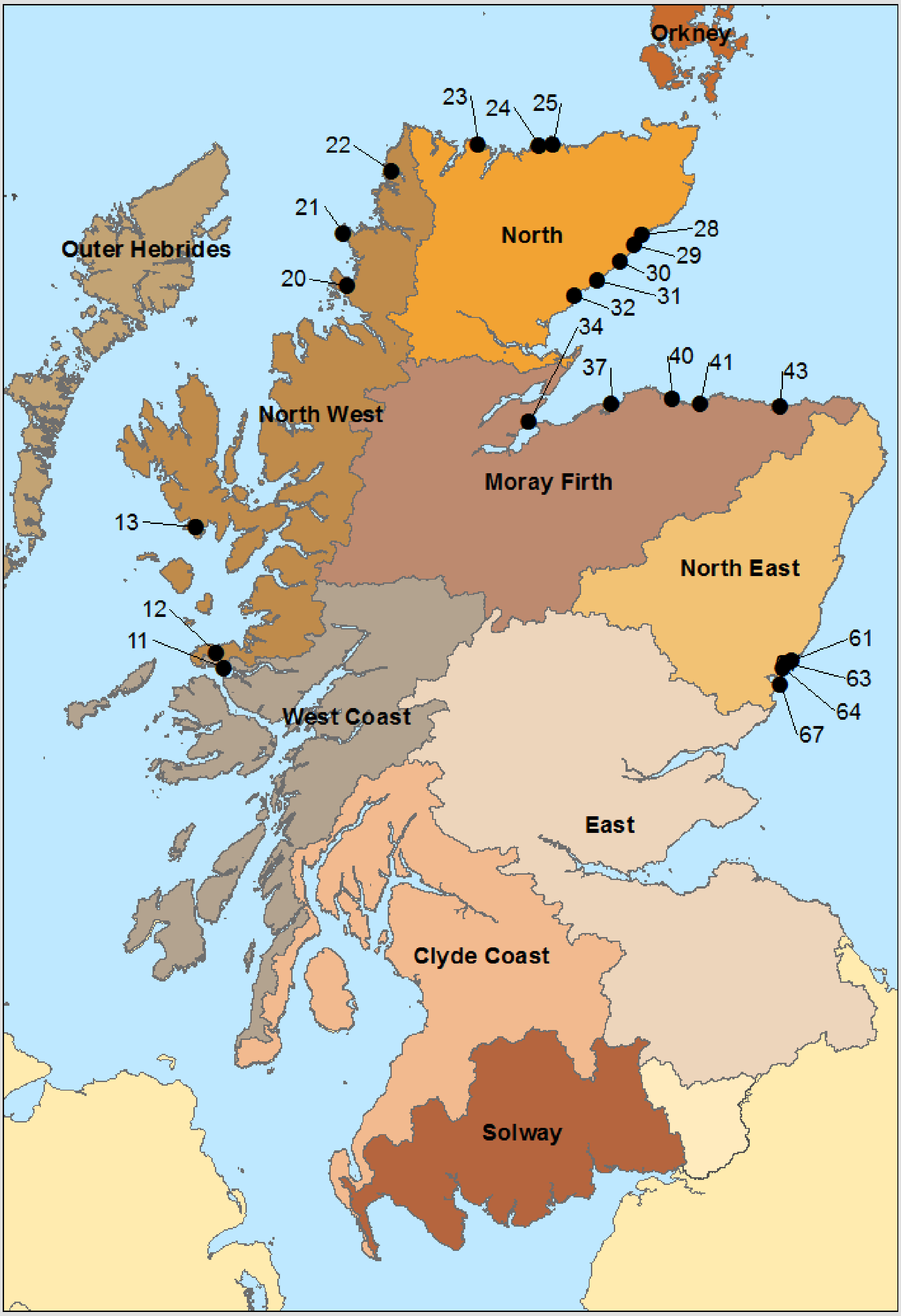


Figure 1: Locations of coastal fisheries where adult tagging programmes were carried out. Fishery labels and region names and colours correspond to those in Figure 3.

Estimating the distance between tag and recovery locations

For the data from the adult tagging programmes, a geographic information system (GIS) model was developed to measure the distance between coastal tagging sites and the mouths of those rivers where tagged fish were subsequently detected. This method involved constructing an “artificial street network” in the sea, and using the ESRI ArcGIS Network Analyst OD (Origin-Destination) Cost Matrix tool to calculate inter-site distances across this network.

An artificial street network was constructed using a utility developed within the Marine Scotland GIS Team. This produced a network from a fixed grid of points (at 5 km intervals) by connecting adjacent points (chess Queen moves), ‘2 along + 1 across’ points (chess Knight moves) and ‘3 along + 1 across’ points (‘elongated Knight moves’) in all directions from each point across the grid. This method gave a dense network able to generate reasonably smooth routes in all directions. The Knight and elongated Knight lines were included to better approximate direct routes in simple orthogonal grids. The network was then erased in GIS using an Ordnance Survey 1:50,000 coastline to remove the land, and cleaned so that all line intersections were calculated and stored within the GIS.

For this review, two networks were created. One was limited to a 1 km strip around the coastline to provide distances between any two sites on the Scottish mainland. A second network covering the whole sea-space across the study area was developed to allow rivers in the Outer Hebrides to be connected to mainland tagging sites. The appropriate network was then used to calculate the distance between any pair of sites.

Data analysis

All data analyses were performed in the R statistical package (R Core Team; www.rproject.org).

For the adult tagging data set, individual coastal fisheries may intercept fish from river stocks located in both a clockwise and anticlockwise direction from the fishery. To preserve directional information, distances (km) between tag and recovery locations were coded as positive when the river of capture was located clockwise (around the Scottish coastline) from the fishery. Distances were coded as negative when the river of capture was located anticlockwise from the fishery. Keeping a directional component to the data was important to allow variations in clockwise/anticlockwise movement among tagging locations to be analysed.

The distribution of distances from tagging to recovery locations was summarised for each fishery by 7 indices: minimum distance, 5th percentile value, 25th percentile value, median distance, 75th percentile value, 95th percentile value and maximum distance. Together these metrics describe the central tendency and spread of distances associated with each fishery. Similarities in these characteristics among fisheries could indicate groups of fisheries that share characteristics affecting the distances between those fisheries and the rivers where tags were subsequently located. A cluster analysis was therefore used to search for the presence of any groups of fisheries sharing similar distributions of distance data. The gap statistic method (Tibshirani et al, 2001) was used to test if there were clusters of observations in the distribution metrics that were more similar to each other than could be expected by chance.

We also explored whether the timing of tag release was related to the average distance/direction to the river where the tag was subsequently recovered. This was undertaken by constructing generalised additive models which allowed distances to vary as a smooth function of the day of the year of tag release.

Results

Juvenile tagging

Juveniles tagged in four major East coast rivers were recaptured from a total of 60 different coastal fisheries around Scotland (Fig.2).

Adult returns from the Conon were recorded between 1970 and 1971 (n = 15), from the Aberdeenshire Dee between 1969 and 1981 (n = 174), the North Esk between 1991 and 2007 (n = 290) and the Tay between 1969 and 1987 (n = 97). These studies were carried out over a lengthy period, during which coastal fisheries reported major declines in the fishing effort deployed and a reduction in the geographical range of the fisheries (Marine Scotland, 2017). Taking this together with the limited information on sample sizes and tagging methods we present this information as a description of the range of coastal fisheries which may exploit salmon from known river stocks, but do not seek to analyse these data further.

Adult tagging

Coastal net fisheries for available adult tag data were distributed primarily along the north and east coasts of Scotland (Figure 1). The majority of tag releases were from fisheries in the North coast region (n = 8 fisheries), followed by the North West and Moray Firth regions (n = 5 each), the North East (n = 4), and a single release site in the West Coast region. In total tags were released from 23 fisheries and release years ranged from 1913 to 2014, most commonly occurring in July (Appendix 2).

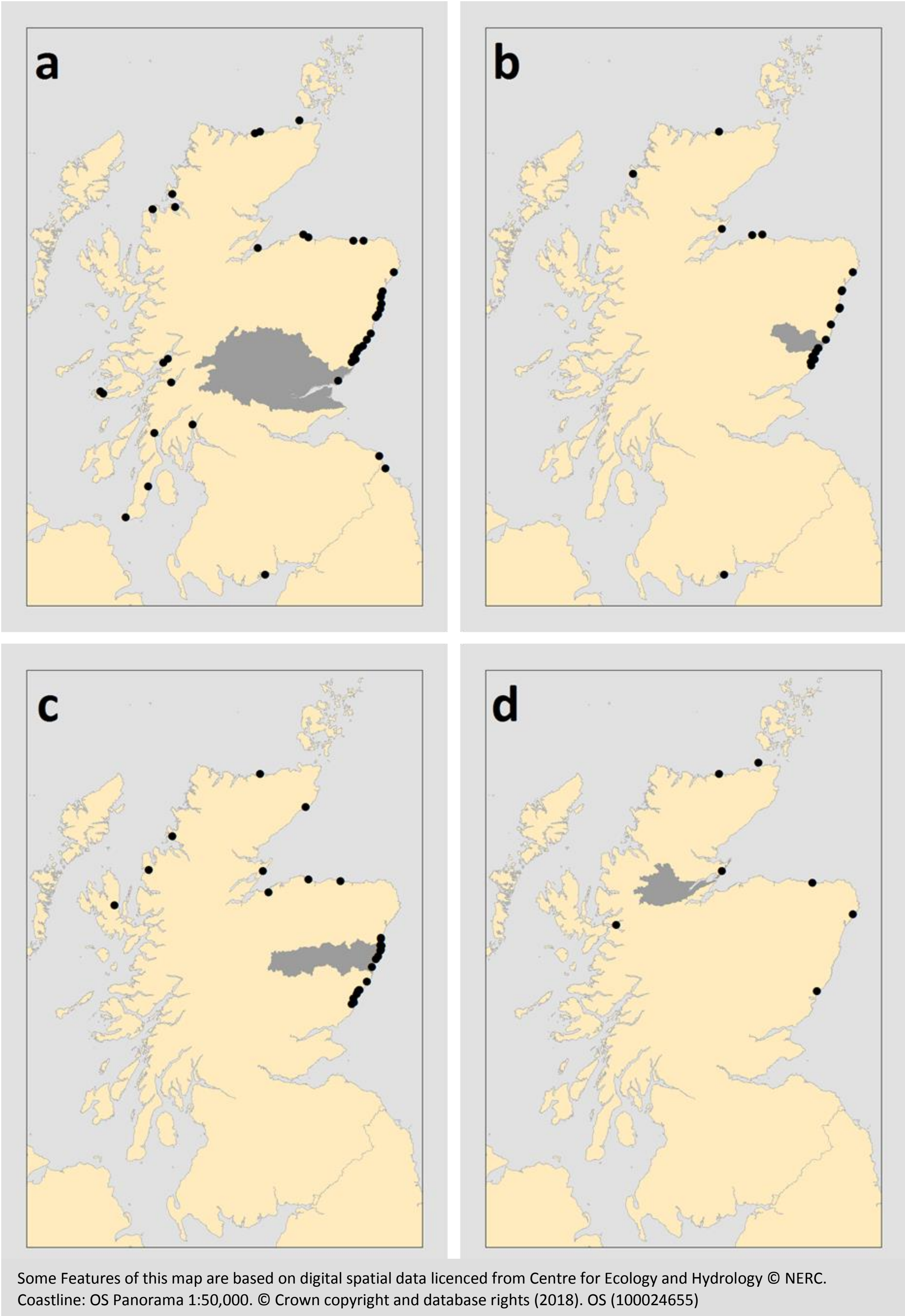


Figure 2: Locations of coastal fisheries (dots) reporting captures of returning adult salmon tagged as juveniles in 4 Scottish rivers, the Tay (a), the North Esk (b), the Dee (c) and the Conon (d). Tag and recapture data for each river tagging programme is shown separately together with the river catchment (shaded region).

The number of tags recovered varied among the fisheries (1 to 83 recovered tags per fishery (Fig.3)). The distances estimated between the fishery of tagging and river of tag recovery varied considerably among fisheries (Fig.3), but the cluster analysis detected no significant grouping on the basis of distance metrics. Furthermore, there was little evidence that the seasonal timing of tag release was related to the average distance/direction (p = 0.641). Data from all tag recoveries was therefore pooled to describe the distribution of distances (Fig.4).

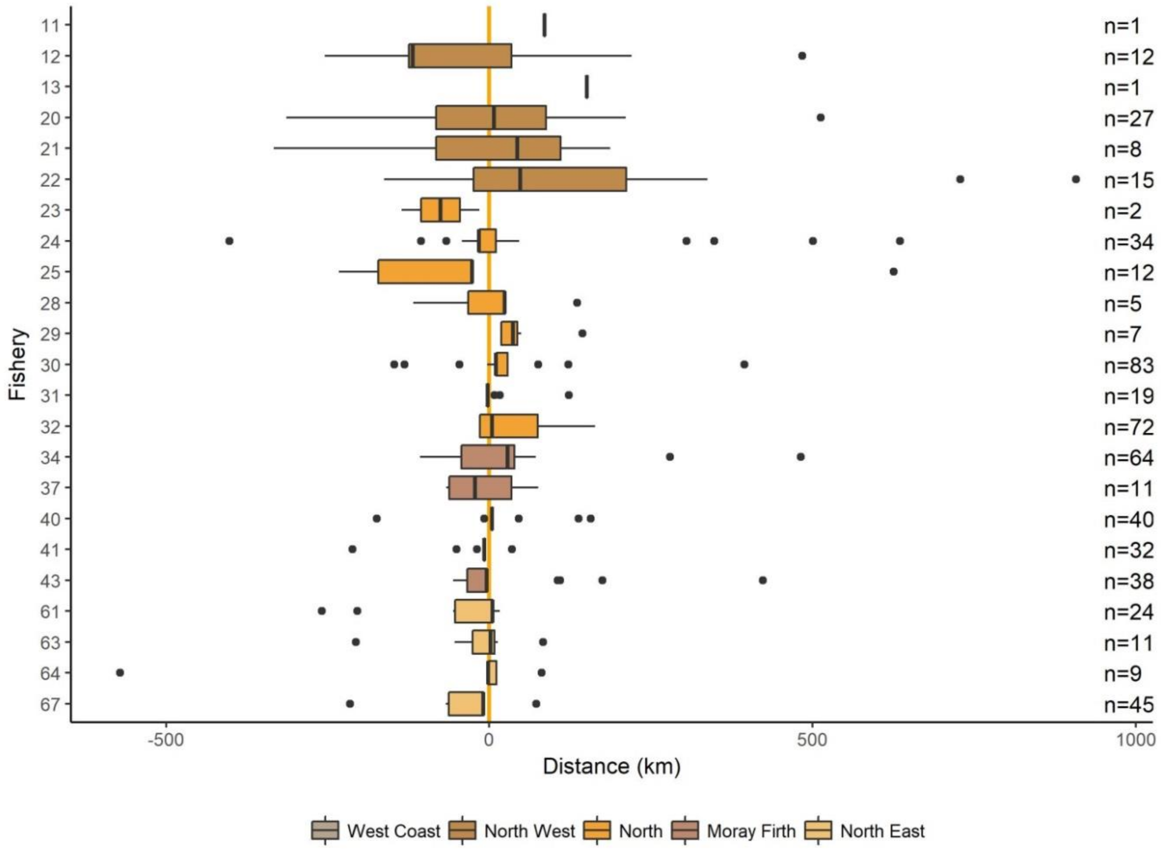


Figure 3: Summary boxplots showing the distribution of distances between tagging site and recovery river. The box region encompasses 50% of the observed distances with the vertical line showing the median (middle) distance. The horizontal lines extend to 1.5 times the range of the middle 50% of the data and any data falling outside these limits are represented as points. The number of tags recovered from each fishery are given on the right. Fisheries are coloured by management region (Fig.1) and ordered clockwise from the west to the east coast of Scotland.

Across the pooled dataset, distances between adult release and in-river tag recoveries were fairly evenly distributed between anticlockwise and clockwise directions (Fig.4). Median recovery distance was 2 km. 50% of available recovered tag data was within -15 km to 28 km from the fishery of release and 90% of the distances were within -127 km to 157 km from the fishery. Recoveries were occasionally very distant from the fishery of release; maximum distances observed were 571 km in an anticlockwise direction and 907 km in a clockwise direction. Figure 5 illustrates these distances from a given point on the north coast of Scotland.

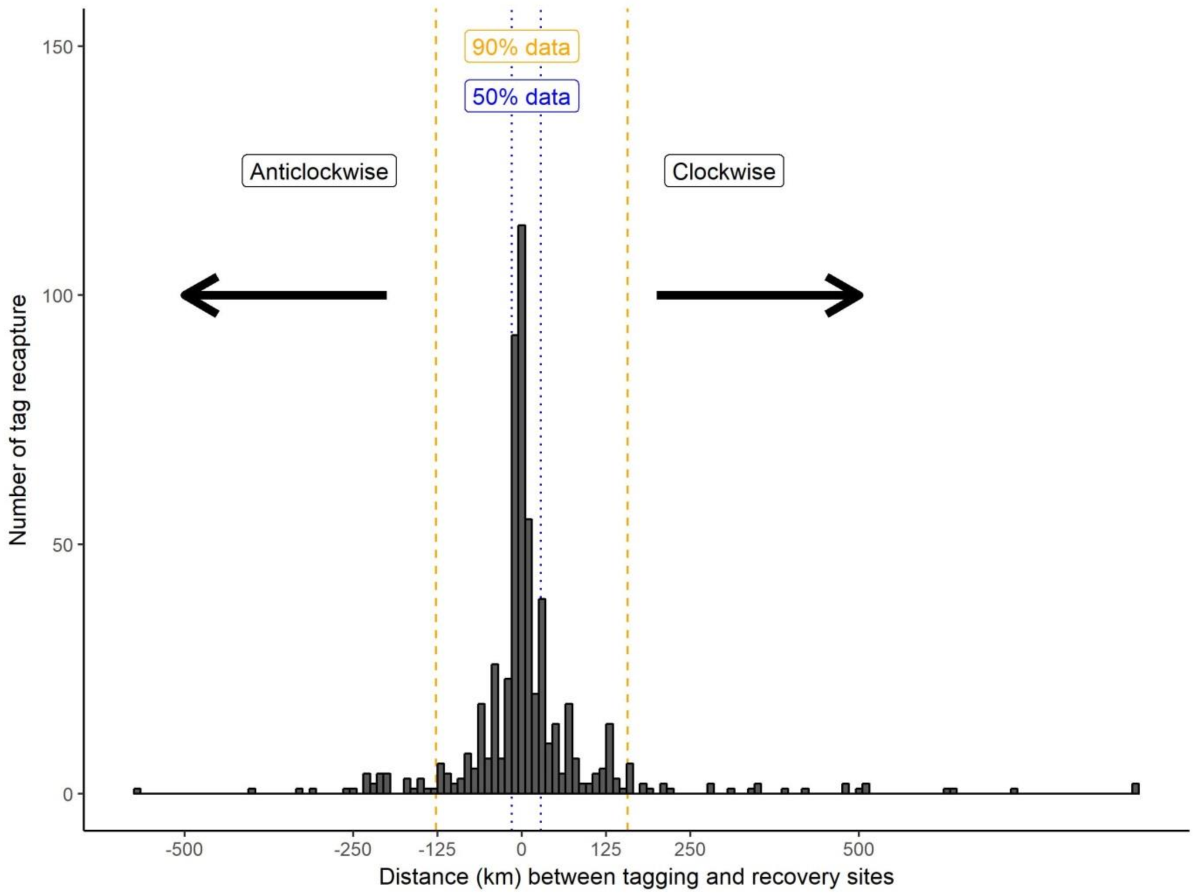
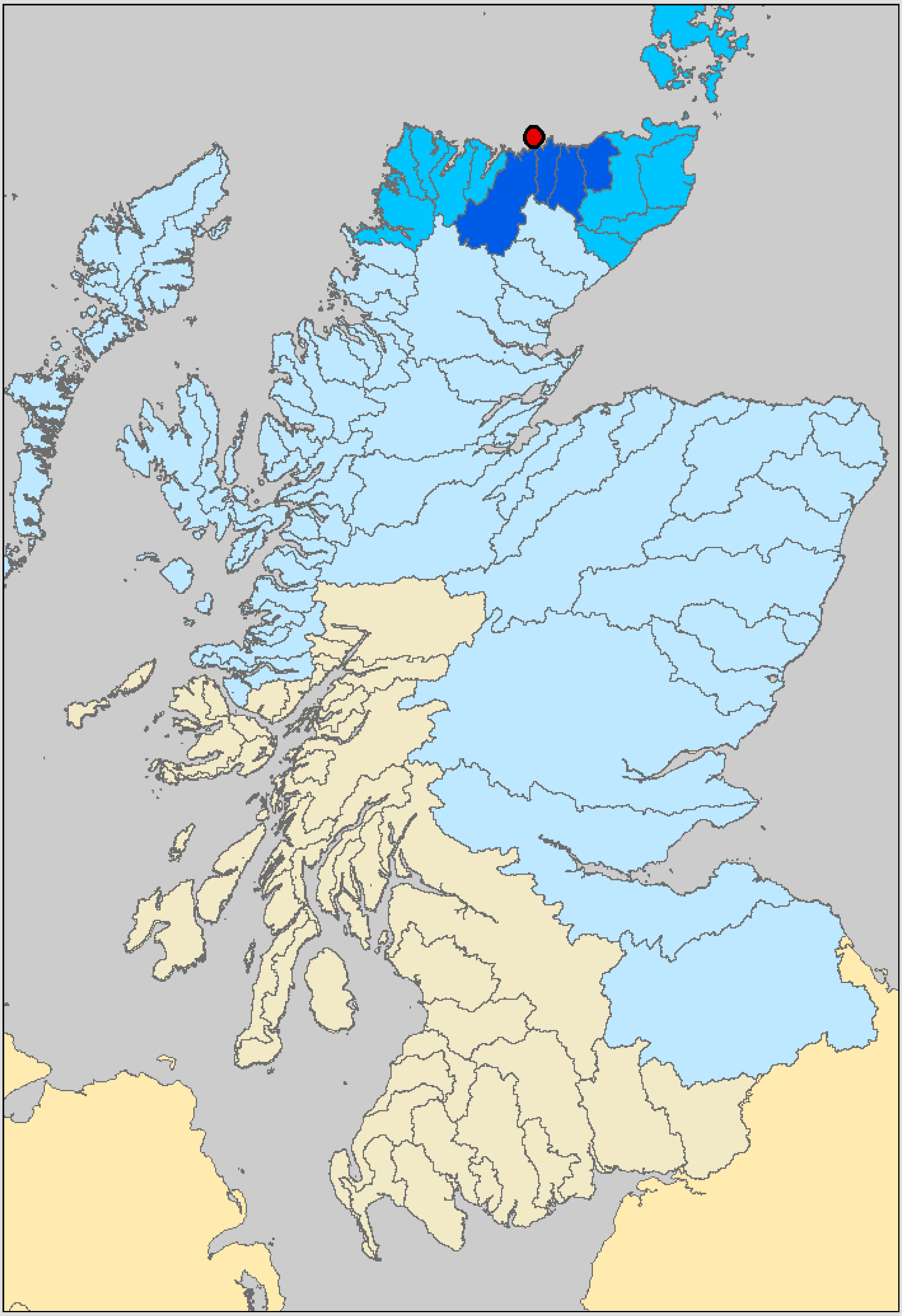


Figure 4: The distribution of distances between tagging site and recovery river for all wild Atlantic salmon tagged in coastal net fisheries in Scotland.



Some Features of this map are based on digital spatial data licenced from Centre for Ecology and Hydrology © NERC.
Coastline: OS Panorama 1:50,000. © Crown copyright and database rights (2018). OS (100024655)

Figure 5: An illustrative example showing districts (Marine Scotland, 2015) included within those distances associated with 50% (dark blue), 90% (intermediate blue) and 100% (light blue) of adult tag recoveries analysed in this review. Distances are shown from a point on the north coast indicated by a red dot.

Discussion

In this analysis, a combination of qualitative and quantitative assessments of historic Atlantic salmon tagging studies provided some insight into the interaction between coastal fisheries and river stocks. Other techniques, such as genetic assignment, have also been used to provide useful information in this regard. In the North Atlantic, genetic analyses indicate considerable variation in the geographic range of river stocks exploited by salmon fisheries in coastal waters and on the high seas depending both on the location of the fishery and on the migration routes of the stocks exploited by those fisheries.

For example, high-seas fisheries at West Greenland exploit fish of both North American and European origin (Bradbury et al, 2016b), while the catches of fisheries occurring in the waters surrounding St. Pierre and Miquelon off southern Newfoundland comprised largely of fish from three regions of Canada; Southern Gulf of St. Lawrence, Gaspe Peninsula, and Newfoundland (Bradbury et al, 2016a). Gilbey et al, (2012) showed that of the fish taken in the coastal fisheries on the north east of England between 40 and 80% were of Scottish origin and that, of these, a small proportion may have originated from north and west coast Scottish rivers.

While providing valuable insights into the broad geographic range of river stocks exploited by a given fishery, such genetic techniques are often unable to assign individual fish to a single river stock. Assignment units for Scottish stocks, for example, range from a single river to groups of 13 adjacent rivers (Gilbey et al, 2012; Gilbey et al, 2016).

In contrast, tagging studies have the advantage of providing discrete locations of fish at tagging and again later at tag recovery or detection. In the present analysis, river of origin was known for those fish tagged as juveniles and recaptured in coastal fisheries as returning adults. For each of the four major east coast river stocks for which we have data, returning adults were taken in widely dispersed coastal fisheries. Fish from the rivers Tay and North Esk for example were recaptured in both west coast and Solway fisheries (Fig.2). Such data confirm that coastal fisheries throughout Scotland may exploit fish which originate from rivers some considerable distance from where they operate.

Analysis of the adult tag data develops this analysis further. The collation of 572 tag recovery observations provided a robust sample size; however, the geographical coverage of coastal tagging sites was incomplete. Much of the North West and West Coast regions were poorly represented while the Clyde Coast, Solway, Outer Hebrides and East regions were not represented (Fig.1). The unbalanced nature of the dataset was due to this analysis being a meta-analysis of historic tag data rather than a designed experiment. Notwithstanding this limitation, analysis of the available data provided little evidence for a broad geographic pattern in the relationship between the location of coastal fisheries and the relative positions of the rivers in which they were subsequently recovered. Further, both the juvenile tag and recapture data noted above and the adult tag recovery data indicate that while we may have no detailed information on the composition of river stocks contributing to the catches of these western and north-western fisheries, they nevertheless exploited stocks at some distance from their locations.

Much of the data derived from adult tag and recovery programmes were from fish tagged during the summer months (Appendix 2). Analysis of the available data suggested no significant seasonal pattern in the distance between coastal fisheries and the locations of the rivers in which they were subsequently recovered. While the lack of a seasonal relationship may be due to the limited data available outwith the summer months, this limitation may not compromise the overall value of the data for providing management advice. Historically, the main effort deployed by coastal fisheries occurred in the summer months (Shearer, 1992). More particularly, in the 20 years before the conservation regulations came into effect in 2016 between 61% and 81% of reported annual salmon and grilse catch was taken in the months from July onwards (Marine Scotland, 2017).

The adult tagging data may be taken to indicate a collection of river stocks exploited by a series of known coastal fisheries. This interpretation is based, however, on the assumption that the rivers where tagged fish are subsequently recovered should be considered as their rivers of origin. Homing to river of origin is well documented for returning adult Atlantic salmon (for example, Hansen et al, 1993) and, although there is also evidence of straying in returning adults (Quinn, 1993), the data analysed here are nevertheless the best currently available upon which to assess the relationship between coastal fisheries and the river stocks which are likely to comprise their catch.

The analysis presented does not provide the river stock composition of any given coastal fishery, nor can it assess the impact of a coastal fishery on any given river stock. Estimates of the return rates of tags from given river fisheries would be required before reliable assessments of these parameters could be made. The lack of uniformity among tagging studies and the absence of original tagging numbers in many cases further limits the analyses which may be undertaken.

Analysis of these data do, however, allow a more quantitative description of the relationship between coastal fisheries and the river stocks assumed to comprise their catch than has been attempted previously. The recovery locations from a given coastal fishery may be used to infer how river stocks at varying distances from that fishery may contribute to the catch (Fig.3). Amalgamating the data across all fisheries generalises the analysis and provides successive distances from coastal fisheries which encompass increasing proportions of the tags recovered from these fisheries (Fig.4).

It may be inferred that the total range of distances associated with all recoveries provides a minimum estimate of the geographic range of river stocks likely to contribute to the catch of a coastal fishery, particularly as the analysis is restricted to recoveries in Scottish waters. On the other hand, it is possible to set a threshold value for the proportion of tags recovered which identifies a boundary within which river stocks are likely to contribute to the catch of a coastal fishery. The greater the threshold value, the greater the geographic range of river stocks identified as likely to contribute to the catch. For all adult tagging data analysed here, for example, half of all recovered tags were recovered in rivers within tens of kilometres of tagging sites; 90% of tags were recovered within hundreds of kilometres and 100% of tag were recovered within several hundreds of kilometres of coastal fishery tagging sites (Fig.4). Figure 5 illustrates these distances from a given point on the north coast of Scotland.

A recent study (Armstrong et al., 2018) provided information on movements of specific individual salmon captured in a coastal net fishery with findings that are coherent with the general analysis of historic data provided here. This analysis provides the best information currently available for identifying those river stocks likely to contribute to a coastal fishery in a given location. In doing so, these data could be used to help manage mixed stock fisheries in Scottish waters according to NASCO guidelines, protecting the weakest of the contributing stocks (NASCO, 2009).

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Appendix 2: Details of tags recovered in the adult tagging studies

The number of adult Atlantic salmon tags recovered by the year and month in which they were released from coastal fisheries tag sites.

NA – month or year data not available.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	NA	Sum
1913	0	0	0	0	2	2	1	0	0	0	**5**
1914	1	0	0	0	5	15	31	7	0	0	**59**
1915	0	0	0	1	14	31	26	0	0	0	**72**
1936	0	0	0	0	0	0	0	0	0	1	**1**
1977	0	0	0	0	0	6	13	0	0	0	**19**
1978	0	0	0	0	0	7	5	0	0	0	**12**
1979	0	0	0	0	0	15	14	0	0	0	**29**
1980	0	0	0	0	0	1	15	0	0	0	**16**
1981	0	0	0	0	0	3	14	8	0	0	**25**
1982	0	0	0	0	0	0	43	0	0	0	**43**
1983	0	0	0	0	0	10	17	3	0	0	**30**
1984	0	0	0	0	0	0	46	0	0	0	**46**
1985	0	0	0	0	0	0	41	2	0	0	**43**
1986	0	0	0	0	0	0	44	3	0	0	**47**
1987	0	0	0	0	0	2	5	0	0	0	**7**
1988	0	0	0	0	0	0	17	0	0	0	**17**
2012	0	2	7	7	12	3	0	0	4	0	**35**
2013	0	0	0	10	1	4	0	0	0	0	**15**
2014	0	0	0	0	1	15	1	0	0	0	**17**
NA	0	0	0	0	0	0	0	0	0	34	**34**
Sum	**1**	**2**	**7**	**18**	**35**	**114**	**333**	**23**	**4**	**35**	**572**