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SPATIO-TEMPORAL VARIABILITY IN THE EMIGRATION TIMES AND SIZES OF SCOTTISH ATLANTIC SALMON (*SALMO SALAR*) SMOLTS

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Executive Summary

The Scottish Government has set ambitious targets for renewable power generation. Marine Renewable Energy, including wind, wave and tidal power are expected to contribute significantly to these targets. Information on the timing of Atlantic salmon smolt migrations is required for planning coastal development and the timing of particular activities. Information on smolt sizes is required to plan acoustic tagging studies aiming to improve understanding of fish movement and behaviour in the coastal zone. This report assessed pre-existing information on smolt migration timing and sizes. The commencement of migration was characterised as the day of the year (DoY) on which 25% of smolts had migrated (S25); the end of the migration period was characterised as the DoY on which 75% of smolts had emigrated (S75). The start and end of the migration period varied with elevation and over time, but not as a predictable function of geographical location (latitude and longitude). Thus, a single coastal migration DoY range (S25 to S75) was estimated for the whole of Scotland. By including uncertainty in the predictions it was possible to identify a “sensitive window” for development, where large numbers of migrating salmon smolts could be expected in the coastal zone. This window covers the period DoY 103-145. This envelope does not consider the time that smolts will spend in the coastal zone, so further work is required to adjust this window appropriately. It was not possible to model the spatio-temporal variability in smolt sizes given available data and resources. However, considerable inter-site and inter-annual variability was observed. The data presented here could be used to inform future acoustic tagging studies at existing sites, although it is suggested that pilot data should be obtained where work is to be carried out at new sites.

Introduction

The Scottish Government has set ambitious targets to meet Scotland's entire electricity needs from renewable power generation by 2020 (Scottish Government, 2011). Marine Renewable Energy, including wind, wave and tidal power are expected to contribute significantly to these targets. However, it is important that these industries are developed sustainably and that potential interactions with wildlife are assessed and mitigated where required.

Malcolm *et al.* (2010, 2013) scoped the research requirements for diadromous fish in the context of offshore renewables. This identified the need for greater information on the migratory timing and sizes of migrating salmon smolts to identify sensitive periods and locations for development, and to inform future acoustic tagging studies that aim to improve understanding of coastal movements and behaviour.

Previous research has investigated environmental controls on the timing of smolt migrations at a range of spatial and temporal scales from individual river systems (Youngson *et al.*, 1983; Jonsson & Ruud-Hansen, 1985; Byrne *et al.*, 2003; Kennedy & Crozier, 2010), to national (Antonsson & Gudjonsson, 2002) and international scales (Otero *et al.*, 2013). Within individual river systems, the timing of migration (also known as run timing) has been attributed to river and ocean temperature, discharge and lunar cycle. At larger spatial scales, the onset of smolt migration has been modelled as a function of latitude, longitude, river and ocean temperature and year (Otero, *et al.*, 2013). Although there have been previous investigations of smolt migration in Scotland these studies have either been focussed at a local level, in particular river catchments (Youngson *et al.*, 1983, Stewart *et al.*, 2006; Todd *et al.*, 2012) or at very large spatial scales across the whole Atlantic region (Otero *et al.* 2013). To date there has been no analysis of the timing of smolt migration at a national scale (Scotland) that could be used to inform risk assessments of development in near-shore areas.

There have also been a number of studies of smolt size at emigration. Differences in smolt size are often related to the age of emigrating fish (e.g. Gurney *et al.*, 2008; Todd *et al.*, 2012). However, size-at-age can also vary depending on changes in environmental conditions and competition (e.g. Gurney *et al.*, 2008). It has been hypothesised that salmon parr attain a critical size prior to emigration (Gurney *et al.*, 2008); in which case it could be expected that smolt sizes would be similar among rivers. However, other studies have suggested that size alone does not control the timing of

emigration and that rates of juvenile growth also have an influence, which could result in spatial and temporal variability in size at emigration (Okland *et al.*, 1993). Regardless of the precise mechanisms, there are relatively few studies that have investigated large scale spatial variability in the size of salmon smolts (Okland *et al.*, 1993), and none within Scotland that could be used to inform the likelihood of tagging opportunities, which require larger smolt sizes (Lacroix *et al.*, 2004).

This report aims to characterise and model the spatial and temporal variability in (1) smolt migration times and (2) sizes, at the national (Scotland) scale using simple spatial predictors that can be readily obtained from a Geographical Information System (GIS) thereby negating the need for local site specific information which is frequently unavailable (e.g. river temperature, sea surface temperature, discharge, etc.). The start and end of the smolt migration period are considered with the aim of identifying a “window of sensitivity” for activities that have the potential to harm migrating smolts. The analysis of smolt sizes focusses on identifying the proportion of emigrants exceeding a size threshold of 135mm, which corresponds to the recommended size for tagging using VEMCO V7 acoustic tags (Lacroix *et al.*, 2004; Middlemas *et al.*, 2009). This information can subsequently be used to identify opportunities for studies of smolt movements and behaviour in the coastal zone. The information in this report contributes towards the National Research and Monitoring Strategy for Diadromous fish (NRMSD; <http://www.scotland.gov.uk/Topics/marine/marineenergy/Research/NatStrat>).

Methods

Data Collation

Data on smolt emigration times and sizes were obtained from fisheries trusts, fisheries boards, universities and private companies and compiled under a Marine Scotland contract to the Scottish Fisheries Coordination Centre (SFCC, 2014). This was supplemented by monitoring data from Marine Scotland Science Freshwater Fisheries Laboratory. A map showing the locations of the sampling sites in the final dataset is shown in Figure 1. Smolt data were collected by a wide range of methods including fixed and temporary, partial and full river traps and rotary screw traps. It is important to note that these data were collected for varying purposes, but that the objectives of these studies were not necessarily the same as those of this

report. Although this is inevitable in any large scale opportunistic meta-data analysis, it should be borne in mind.

To facilitate analysis, a number of assumptions were made about the data. Firstly, it is assumed that fish are caught in proportion to the numbers of emigrating fish and thus that capture efficiency remains constant within years. Secondly it is assumed that the captured fish provide a representative sample of migrating fish and there is no size selection in the capture process.

Data Analysis

Emigration Time

The temporal distribution of smolt migration times was visualised by plotting smolt counts against Day of the Year (DoY) for each Site and Year. The onset of smolt migration was characterised as the DoY on which 25 percent of emigrants had been captured (S25). The end of the smolt migration was characterised using the 75th percentile (S75). These definitions of the start and end of the smolt run were chosen to allow comparison with previous studies (Antonsson and Gudjonsson, 2002; Otero *et al.*, 2014) and because more extreme percentiles would be more variable and challenging to model.

S25 and S75 were modelled as a function of plausible environmental predictors obtained from a GIS including Latitude, Longitude, Coast (whether rivers drained to the east, west or north coasts), Distance Around Coast, Elevation (the altitude of the trapping site), Distance From Sea (a river network distance from the trapping site to the sea) and Year, assuming normally distributed errors. Preliminary investigations revealed that Distance From Sea and Elevation were highly correlated, so only Elevation was included in model fitting. Site was modelled as a random effect to account for inter-site variation. Smoothers were used to investigate non-linearity. Where there was no evidence of non-linearity, linear effects were investigated. Model selection was undertaken using a step down procedure using likelihood ratio tests.

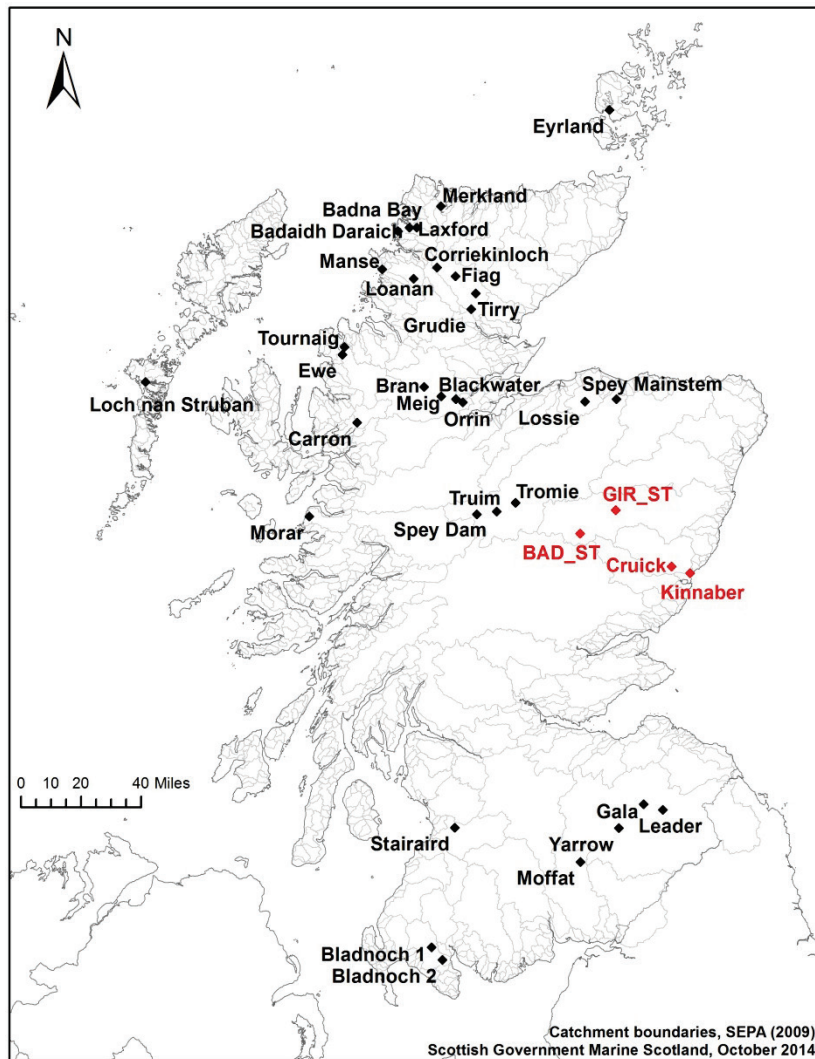


Figure 1 Map showing the spatial distribution of sites where data on salmon smolts was collected. MSS sites are shown in red. Sites provided by the SFCC data collation contract (SFCC, 2014) are shown in black.

Smolt size

Given the limited number of sites for which high precision (1mm) smolt size information was available, a formal statistical analysis was not performed. Instead, the distribution of fish sizes was plotted for each Site and Year, along with the 135mm size threshold. The percentage of fish exceeding this threshold was then summarised and tabulated for each site and year where data were available.

Results

Emigration time

The spatial and temporal variability in smolt emigration times is shown in Figure 2. There was no indication of non-linear effects in any of the models investigated. Following step down model selection, the final model for both S25 and S75 included Site as a random effect and Elevation and Year as fixed effects (Figure 3). This indicated that there was no significant spatial variability in the timing of smolt migration to sea (zero metres elevation), that could be predicted from simple GIS metrics. There was however, considerable inter-site variability that was unrelated to geographic location. There was also substantial inter-annual variability at individual sites and significant long-term trends in migration time with migration advancing by ca. 7 and 14 days for S25 and S75 respectively over the last 47 years. To identify a “sensitive window” for salmon smolt migration, predictions of S25 and S75 were made for zero metres Elevation and the Year 2014. The lower (S25) and upper (S75) 95% confidence intervals were then used to bound the sensitive period, considering uncertainty in the predictions. This results in a period that runs from day 103 to 145.

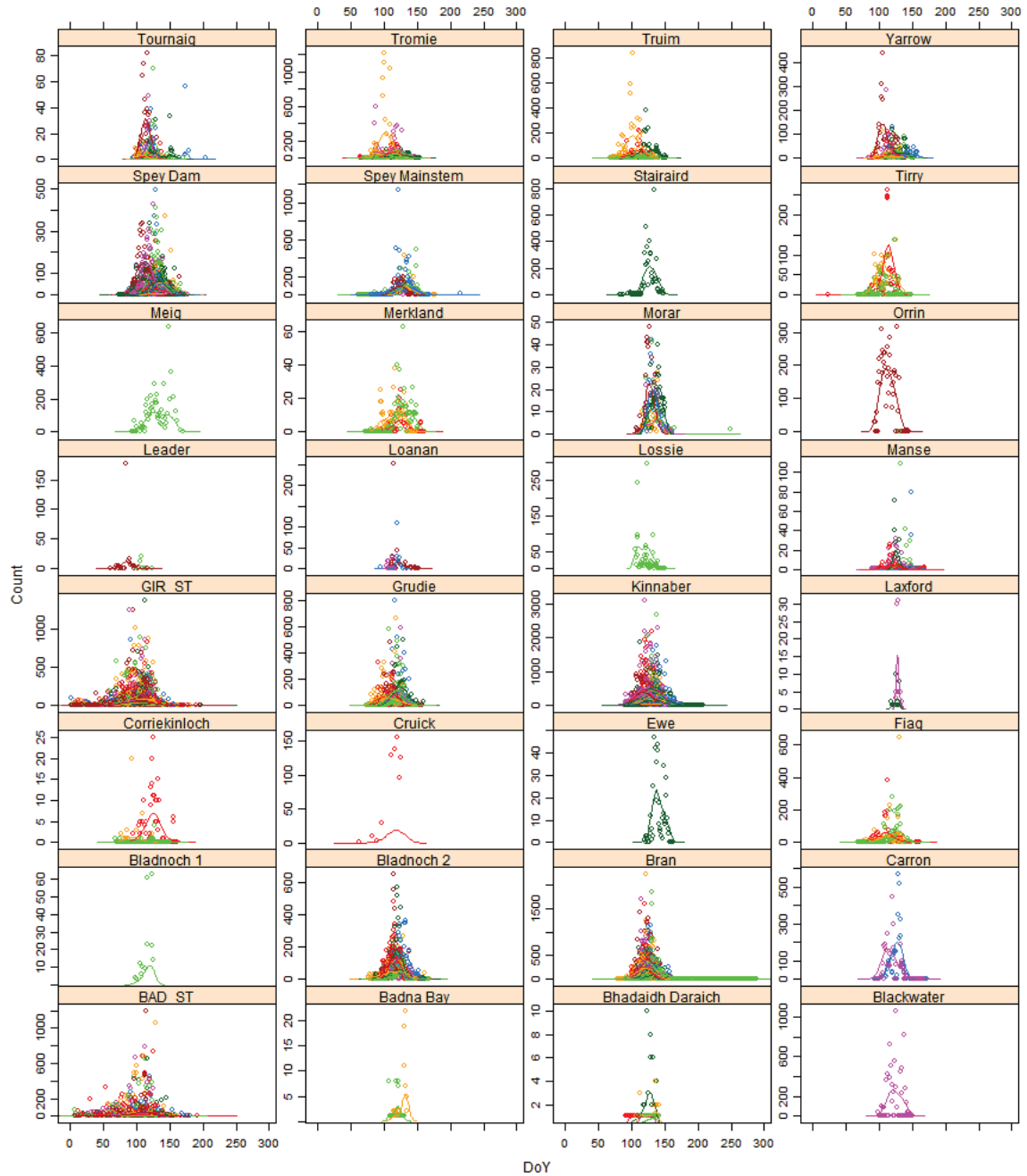


Figure 2 Temporal variability in smolt emigration times as indicated by counts of juvenile Atlantic salmon caught on each day of the year (DoY). Points show individual counts obtained from a site visit, lines provide a kernel density estimate of the distribution of emigration times. Individual years are indicated by separate colours.

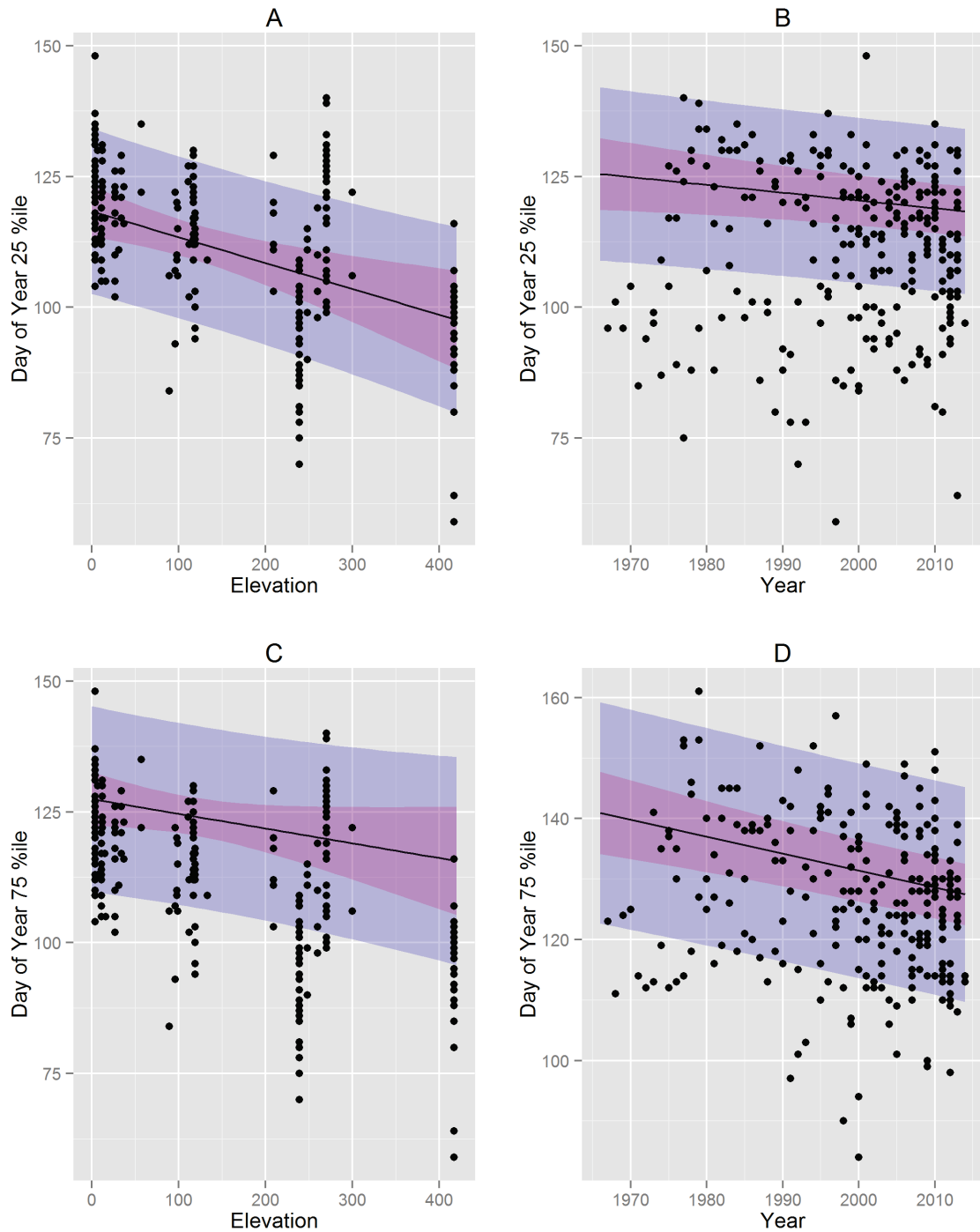


Figure 3 Model predictions of the effects of Elevation (metres) (A,C) and Year (B,D) on the timing of S25 (A,B) and S75 (C,D). Predictions of the effects of elevation are made for year 2014. Predictions of the effects of Year are made for an elevation of zero metres. Points show individual observations, black lines indicate the estimate of an effect, purple shading indicates uncertainty in the fixed effects, while blue shading indicates uncertainty in the fixed effect, combined with variance from the random effect (i.e. includes inter-site variation).

Emigrant size

There was substantial temporal and spatial variability in the size of emigrating salmon (Figure 4, Table 1). Across all sites and years, the proportion of emigrants >135mm ranged from 0-92%. Within sites, the proportion exceeding the threshold varied by as much as 92% between years. The mean percentage of emigrants exceeding the threshold at individual sites varied between 6 and 29% for sites with ≥ 10 sampling years. Unfortunately it was not possible to model the spatial and temporal variability in smolt sizes given the small number of sites with high precision (1mm) size data and the time available for analysis.

Site	Maximum	Minimum	Mean	Number of Years
BAD_ST	35	0	12	25
Badna Bay	64	43	54	2
Bhadaidh	92	0	43	4
Daraich				
Bladnoch 1	26	26	NA	1
Bladnoch 2	48	14	29	11
Bran	32	4	11	15
Carron	10	9	9	2
Cruick_RST	5	5	NA	1
GIR_ST	30	0	6	48
Kinnaber	42	8	20	35
Laxford	20	10	15	2
Lossie	11	11	NA	1
Manse	65	0	40	6
Morar	37	22	29	6
Spey	21	11	17	4
Mainstem				
Stairaird	66	66	NA	1
Tirry	67	0	34	4
Tournaig	52	0	30	9
Tromie	13	5	8	5
Truim	5	4	4	4

Table 1 The percentage of fish exceeding the 135mm size threshold required for tagging with a VEMCO V7 acoustic transmitter.

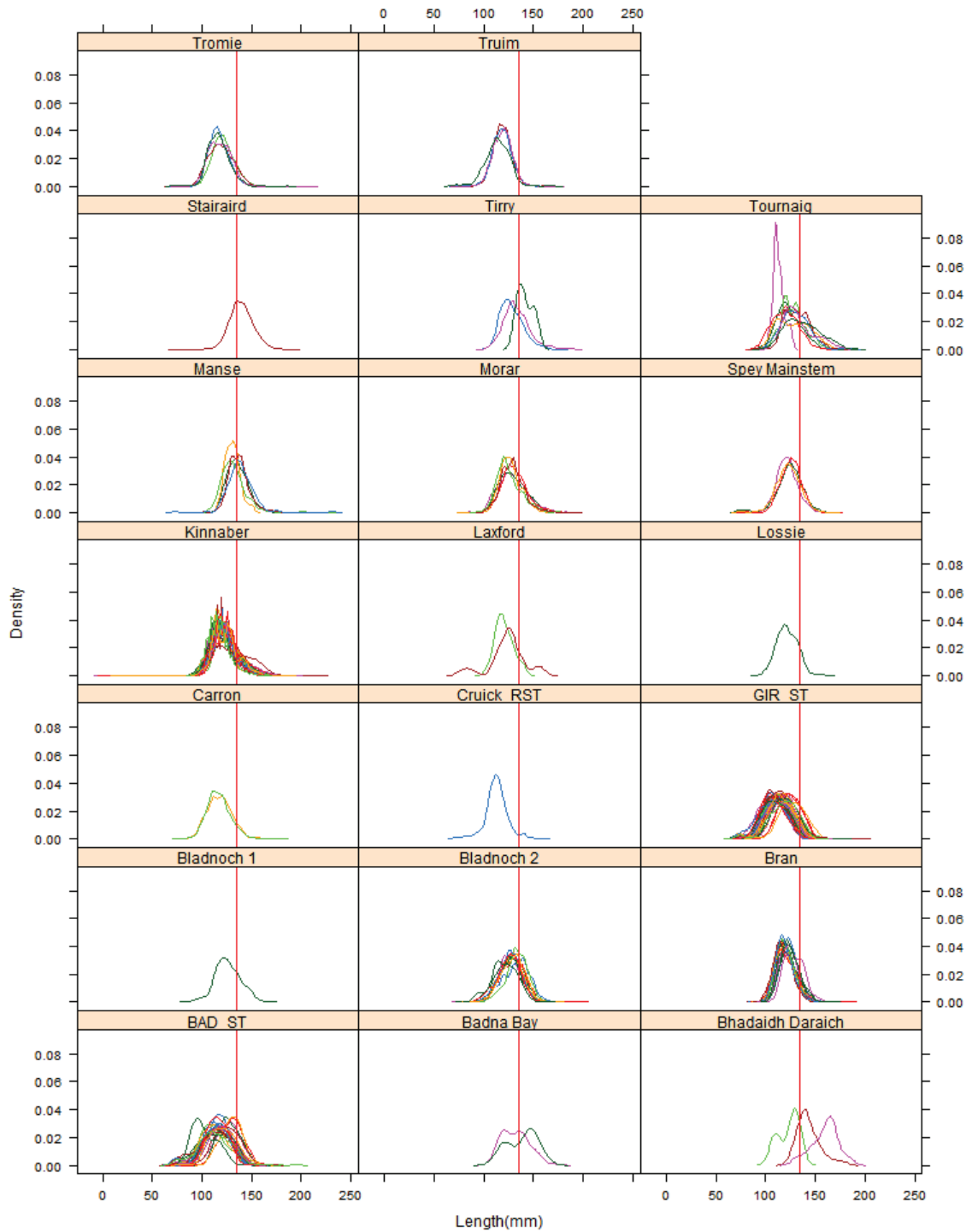


Figure 4 Kernel density estimates of the distribution of smolt sizes. Colours indicate individual years. Vertical red line indicates the threshold size required for tagging with a VEMCO V7 acoustic tag.

Summary and Discussion

This report analysed pre-existing information on the timing of migration and sizes of Atlantic salmon smolts leaving Scottish rivers and attempted to predict emigration time using spatial covariates readily obtained from a GIS. The final model included Elevation and Year as fixed effects and Site as a random effect. A single estimate of S25 (DoY 118; 95% CL 103-134) was obtained for the entire Scottish coast. This was broadly consistent with that reported previously (Otero *et al.*, 2014). However, there was no evidence of an effect of Latitude, Longitude, Coast or Distance Around Coast that would indicate predictable spatial variability at the Scottish scale. This likely reflects the limited and patchy availability of data (over time and space), and considerable inter-site and inter-annual variability in emigration time. In common with Otero *et al.* (2014), this study also observed a significant long-term decline in S25 (i.e. earlier migration), although the estimated effect of ca. -1.5 days per decade was considerably lower than the -2.5 days reported by Otero *et al.* (2014) for the Atlantic region as a whole. This study also extended previous studies by modelling S75 (DoY 127; 95% CL 110-145), thereby characterising a “sensitive window” for development activity (103-145) where large numbers of smolts are likely to be migrating into coastal waters. However, this window provides no information on the amount of time that fish will spend in the coastal zone and thus further information on coastal behaviour and migration would be required to further qualify this window appropriately.

Unfortunately it was not possible to model spatio-temporal variability in smolt sizes. However, the preliminary analysis presented here identifies considerable inter-site and inter-annual variability in the percentage of fish that would exceed the investigated tagging threshold. Given the lack of a robust spatial model, it is suggested that the data presented here are used to guide future tagging studies, but that where new sites are to be used, then pilot work should be carried out to identify the likelihood of catching sufficient numbers of large smolts in advance of any large scale resource investment. Even where pilot data can be collected there is still a risk that sizes could be markedly different between years. This is likely to be especially true in smaller rivers, where returner numbers can vary markedly from year to year affecting competition, growth and subsequently smolt age.

Recommendations

There are a number of limitations with this study (1) there are relatively few sites where smolt data has been collected from which to make spatial predictions (2) there are very few sites where data has been collected over long-time series (3) current analyses do not consider temporal or spatial auto-correlation. Future analyses of these data could be improved by addressing these issues. Specifically, it is worth considering (a) the inclusion of additional historical data from MSS which was not possible within the timescales of this report, (b) strategic collection of new data to improve understanding of spatial patterns e.g. high altitude sites close to the sea, additional west coast locations and locations in the central belt (c) consideration of spatial and temporal correlation.

Finally, the data analysed in this report came from a range of different sources in a variety of formats reflecting the different objectives of the original studies and availability of resources. These data thus required considerable resource to collate and quality control. Future analyses would benefit from central data collation and storage with associated meta-data on collection methods. This would be possible using the existing MSS FishObs database or through additional development of the SFCC database. These and other issues relating to strategic data collection and storage are central to the Report of the Wild Fisheries Review Panel (e.g. Recommendations 12, 13, <http://www.scotland.gov.uk/Resource/0046/00460195.pdf>) that will be considered in due course.

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