Beatrice Offshore Windfarm

Atlantic Salmon *Salmo Salar* smolt movements in the Cromarty and Moray Firths, Scotland

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Beatrice
Offshore Windfarm Ltd

THE UNIVERSITY OF GLASGOW: THE SCOTTISH CENTRE FOR ECOLOGY AND THE NATURAL ENVIRONMENT

Atlantic Salmon *Salmo Salar* smolt movements in the Cromarty and Moray Firths, Scotland

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1. Project Background

The Beatrice Offshore Wind Farm (Beatrice OWF) and Offshore Transmission Works (OfTW) received consent under Section 36 of the Electricity Act 1989 from Scottish Ministers on 19th March 2014 ("the S.36 Consent") and was granted two Marine Licences from Scottish Ministers, for the Beatrice OWF and for the Beatrice OfTW respectively, on 15th August 2012 ("the Marine Licences").

Condition 27 of the Section 36 consent stated that the Project Environmental Monitoring Programme (PEMP) must cover, but not be limited to:

Pre-construction, construction (if considered appropriate by the Scottish Ministers) and post-construction monitoring surveys as relevant in terms of the ES and any subsequent surveys for....[5] diadromous fish...

Condition 31 the Beatrice OWF Section 36 consent stated that:

The Company must, to the satisfaction of the Scottish Ministers, participate in the monitoring requirements as laid out in the 'Scottish Atlantic Salmon, Sea Trout and European Eel Monitoring Strategy' so far as they apply at a local level (the Moray Firth). The extent and nature of the Company's participation is to be agreed by the Scottish Ministers in consultation with the MFRAG [the Moray Firth Renewables Advisory Group]. Further information on the Strategy was published by The Scottish Government (2014).

The requirements were repeated in Condition 3.2.1.1 and Condition 3.2.1.3 respectively of the OfTW Marine Licence.

Marine Scotland Licensing Operations Team (MS-LOT) confirmed that a proposed pre-construction study put forward by Beatrice Offshore Wind Ltd (BOWL) to acoustically track Atlantic salmon (*Salmo salar* L.) smolts in the River Conon and through the Cromarty Firth, and attempt to actively track smolts out from the Sutors would satisfy, in part, the requirements of S.36 consent condition 31 and deliver the required participation in the monitoring requirements as laid out in Marine Scotland's 'Scottish Atlantic Salmon, Sea Trout and European Eel Monitoring Strategy' to discharge consent condition 31. The agreed methodology is described in document LF00005-REP-598 BOWL Cromarty Firth smolt tracking study.

The study would also contribute to the discharge of consent condition 27 by investigation of coastal diadromous fish movements.

The study was undertaken by the Scottish Centre for Ecology and Natural Environment of the University of Glasgow and Marine Scotland Science (MSS) added value to it by installing a curtain of acoustic receivers from Tarbat Ness to Burghead, providing information out in the Moray Firth on tagged smolts. The receivers for this outer curtain were provided by the Ocean Tracking Network (http://oceantrackingnetwork.org/). MSS were responsible for the deployment and recovery of these receivers.

This report presents the results of both elements of this collaboration between the University of Glasgow and MSS.

2. Introduction

Little empirical evidence exists of the biology of Atlantic salmon (*Salmo salar* L.) as they enter the marine habitat or of the factors which influence their subsequent survival and migration. This is primarily due to the difficulties in locating and capturing individuals during this transit period. Mortality in the early marine stages of migration is thought to be high, reported mortality rates greater than 5% km^{-1} are not uncommon in estuaries and average approximately 1% km^{-1} in the early marine phase of migration (Thorstad *et al.*, 2012). Reported mortality of smolts is highly variable and application of mortality rates derived from one site and applied to another should be done with caution. Currently there is no estimate of mortality of migrating smolts in estuaries or the marine environment within Scotland. Smolt distribution at sea has previously been inferred from the recapture of fish in surface trawls within the Atlantic Ocean (NASCO, 2011). It remains to be seen if the capture of a few hundred individuals accurately represents the movements of, potentially, millions of individuals leaving European rivers each spring. As such, there is a keen interest in determining the offshore movements of fish as they enter the open ocean. Indeed, the first priority research need listed by Marine Scotland Science (MSS) in its national monitoring strategy for diadromous fish is “What routes and depths do salmon smolts use as they leave Scotland?” (The Scottish Government, 2017)

The use of electronic acoustic transmitters is a proven and effective technology for identifying movements and migrations of various aquatic species in coastal, estuarine and freshwater ecosystems (Cooke *et al.*, 2004, 2013). The developments and benefits of telemetry have previously been covered extensively by a number of authors (Lucas and Baras, 2000; Hodder *et al.*, 2007; Halttunen *et al.*, 2009; Cooke and Thorstad, 2011). Acoustic telemetry requires a transmitter, attached to an individual, which transmits information wirelessly to a receiver comprising a hydrophone and usually a data logger where information is recorded and stored. Acoustic tags are uniquely coded, able to determine and send information to the receiver on environmental parameters (e.g. depth and temperature) being experienced by the fish at that exact moment. Telemetry information can therefore be used to inform the position of the individual at a specific time and provide data on the environmental and physiological parameters of the fish (Thorstad *et al.*, 2013). By strategically deploying an array of receivers throughout the study system it is possible to monitor the behaviour and survival of fish in question. Alternatively, it is also possible to actively track fish with a mobile hydrophone beyond the range of a fixed receiver array.

The primary aims of this project are to quantify;

1) The rate of natural migration of salmon smolts in riverine habitats of the lower River Conon.

2) The natural mortality rate of smolts in the river habitats of the lower reaches of the River Conon.

3) The speed of estuarine passage of smolts in the Cromarty Firth.

4) The natural rate of mortality of smolts in the Cromarty Firth.

5) The route of estuarine passage of smolts in the Cromarty Firth.

6) The direction and speed of passage of smolts in the coastal zone.

7) The coastal features influencing the direction and speed of passage of smolts in the coastal zone (for example current speed and direction, coastal bathymetry and coastal topography)

3. Methodology

3.1. Study Area

The study was conducted in both the Moray and Cromarty Firths, Scotland. The Moray Firth lies on the North-East coast of Scotland and forms the largest single marine inlet of the North Sea on the Scottish east coast (Fig 1). The inner Moray Firth receives freshwater discharge from the Rivers Ness, Beauly and Conon which enter at its western side end via the Inner Moray, Beauly and Cromarty Firths respectively. Further large rivers, including the Spey, Deveron and Findhorn enter the southern side of the Moray Firth further to the east. The Moray Firth is classified as meso-tidal with a relatively uniform tidal range of less than 3.5m around its coastline; for further detailed information see Hansom and Black (1996).

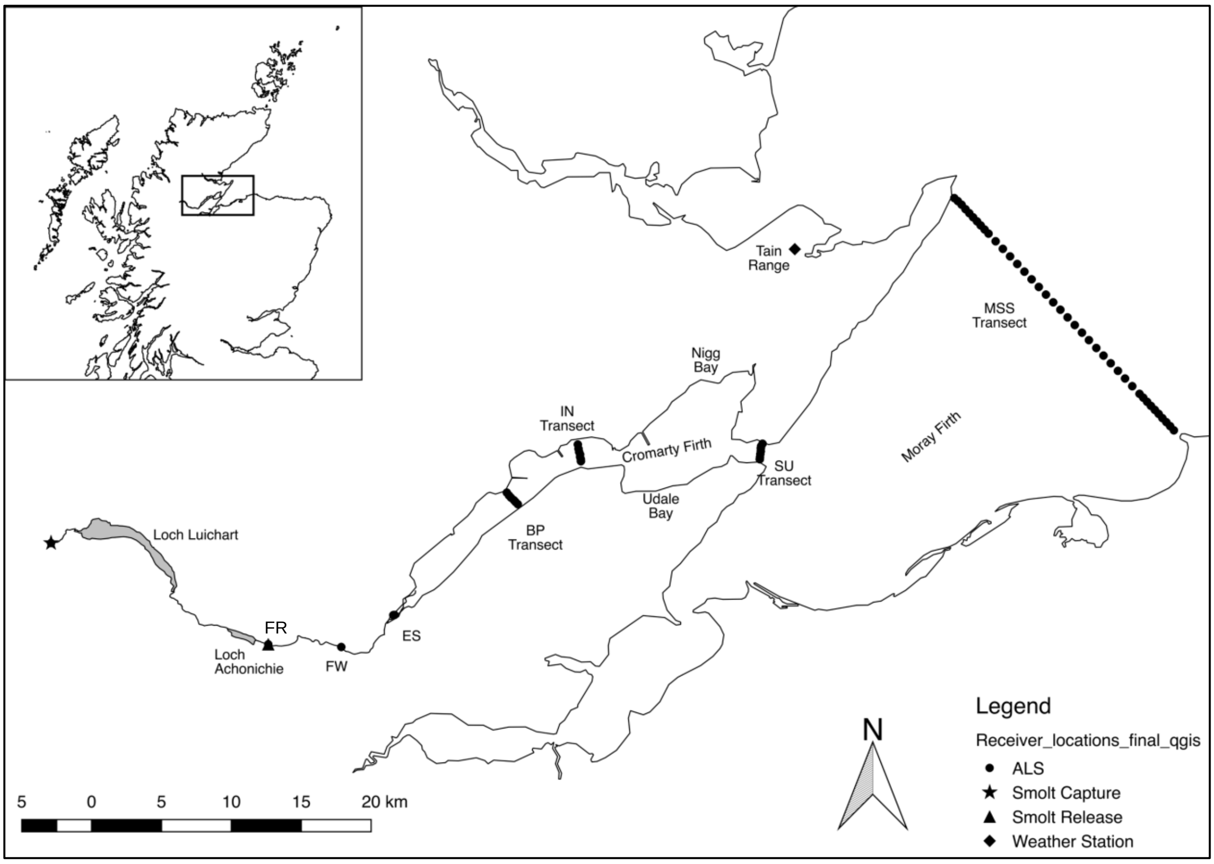

Figure 1: Top left: Cromarty firth in North East Scotland. Main: Deployment locations of ALS and individual transects within the acoustic array. Smolt capture and release sites are identified in the legend.

The Cromarty Firth is one of the major firths on the west shore of the Moray Firth. It is a meso-tidal estuary with a spring tidal range of 3.5m at its mouth. The firth consists of a narrow outer channel between the North and South Sutors of Cromarty, leading to a broad tidal basin with two large intertidal bays Nigg and Udale which in turn gives way to a long (approx. 18km) narrow (1-3km wide) corridor before the channel abruptly narrows forming the River Conon (Fig 1). For a detailed review of the Cromarty Firth see Stapleton & Pethick (1996).

3.2.Smolt Capture and Tagging

Salmon smolts (n = 120) were captured in a fixed trap in the middle reaches of the River Bran (Fig 1; Smolt Capture), a tributary of the River Conon 33km upstream from the Cromarty Firth. Fish deemed large enough (Fork length > 130mm) for tagging and which were also clearly smolting were anaesthetised with clove oil (0.5mg per litre); mass (M, g), fork length ($L_{F,}$ mm) and fat content (%) (Distell fish fat meter FM 692) were recorded prior to the fish being placed on a v-shaped surgical pillow saturated with river water. An incision 11-14mm was made along the ventral abdominal wall anterior to the pelvic girdle. A coded acoustic transmitter (Model LP-7.3, 7.3mm diameter, 18mm length, 1.9g mass in air, Thelma Biotel AS, Trondheim, Norway) was inserted into the peritoneal cavity. The incision was closed with two independent sterile sutures (6-0 ETHILON, Ethicon Ltd, Livingston, UK). Fish were aspirated with 100% river water throughout the procedure. Tags were programmed to have an acoustic transmission repeat cycle of 25s ± 50%, giving a tag life span in excess of 90 days. The acoustic tags also transmitted the depth and temperature of the tag every 25 seconds ± 50%. On completion of tagging, fish were placed in a recovery bucket filled with aerated river water and allowed to recover. Fish were then transported downstream (20 river kilometres) to the release site (Fig 1: Smolt Release), 13km upstream from the tidal limit of the Cromarty Firth. Trap and transport of migrating smolts is routinely conducted by the Cromarty District Salmon Fishery Board (CDSFB) because many smolts fail to locate the upstream entrance to the Borland lift at Luichart Dam. This was recognised as an issue shortly after the scheme was constructed in the early 1960s. This trapping and release procedure has resulted in significant increased survival of translocated smolts as determined by ~20 years data from a tagging study which PIT (passive integrated transponder) tagged smolts and quantified the rate of returning adults (between 3 and 6%) (unpublished). Fish tagged with acoustic transmitters were released into the river in a small, calm, back eddy in the River Conon at the same time as untagged fish were released approximately 200m upstream. All work was conducted under Home Office Licence.

3.3.Acoustic Tracking

Movement of tagged smolts was determined by using fixed position automatic listening stations (ALS) (Vemco VR2W-tx/ VR2W-AR). All ALS were deployed prior to tagging and release of fish. ALS were recovered in August (22nd – 23rd) 2016 i.e. post migration and expected tag life. One ALS (FW) was positioned within the freshwater part of River Conon. Two ALS were positioned at the tidal limit of the River Conon at the upstream limit of the Cromarty firth Estuary. Twenty receivers were positioned in three transects dissecting the Cromarty Firth. The inner transect (BP), consisted of six ALS between Balconie Point and Castlecraig, the centre transect (IN) of seven ALS, between Invergordon and Newhall Point, the outer transect (SU) also of seven ALS, between the North and South Sutors where the Cromarty Firth discharges into the Moray Firth. Maximum distance between any two receivers in the SU array was 231m with average distance between receivers of 190m. Average distance between receivers in IN and BP transects was 203m (max = 307) and 226m (max = 244) respectively. A marine transect (MSS marine) of 40 ALS was also deployed within the Moray Firth and extended from Tarbat Ness to Burghead. Receivers within 5km from either shore line were spaced at 400m intervals, increasing to ~750m further offshore.

Moorings within the Cromarty Firth consisted of a 70kg weight, with a 2.5m length of rope to a subsurface float. The receiver was attached midway between the weight and the float approximately 1m from the seabed, receivers were recovered by an underwater remotely operated vehicle. Receivers on the marine transect were moored in a similar manner, although the length of rope between weight and subsurface float was approximately 5m, with receivers suspended 2m from the seabed. Acoustic releases within the receivers enabled recovery of the mooring system from a surface vessel.

3.4.Range Testing

Range tests were undertaken prior to deployment of the final array for Cromarty Firth ALS transects. Two transects of six receivers were deployed for one week in the vicinity of the BP and SU transects in the Cromarty Firth. Locations were selected to be representative of hypothesised final array positions. The use of surface buoys was required by Marine Scotland Licencing for short term deployments and thus areas of heavy shipping were avoided. The data obtained indicated an acoustic detection efficiency in excess of 75% at 200m (Fig 2), thus receivers were deployed so as to create overlap in detection ranges of ALS. An extra receiver was added to the SU and IN transects from the initially planned 6 ALS per transect to 7 ALS per transect. Maximum distance between any two ALS on a single transect within the Cromarty firth was 231m. Range tests were conducted continually throughout the study period. Determining effective range at the SU transect was needed to allow the total number of tagged smolts reaching this point to be accurately estimated. All receivers also recorded tilt and background noise every 15 minutes, “sync tags” comprising transmitters built into each ALS were programmed to transmit on all receivers to enable detection efficiency testing throughout the study period. Data collected from this set up enabled post processing of data to identify potential non-detection of migrating smolts. Detection efficiency of the sync tags at the SU transect remained high throughout the study (Fig 2), with detections recorded at distances in excess of 800m.

More specifically, at the SU transect an acoustic tag (model LP-7.3, 139dB 1 μPa power, Thelma Biotel AS, Trondheim, Norway) was suspended at 3m depth and allowed to drift, at approximately maximum distance, between each ALS to test for acoustic breaches i.e. the non-detection of a transmitter as it transits through the receivers. No acoustic breach occurred during these tests. Tag failure rate reported by the manufacturers is low (<2%). For tags of the same model used in this study, Gauld *et al.*, (2013) reported control tag failure rates of 0% in field test environments.

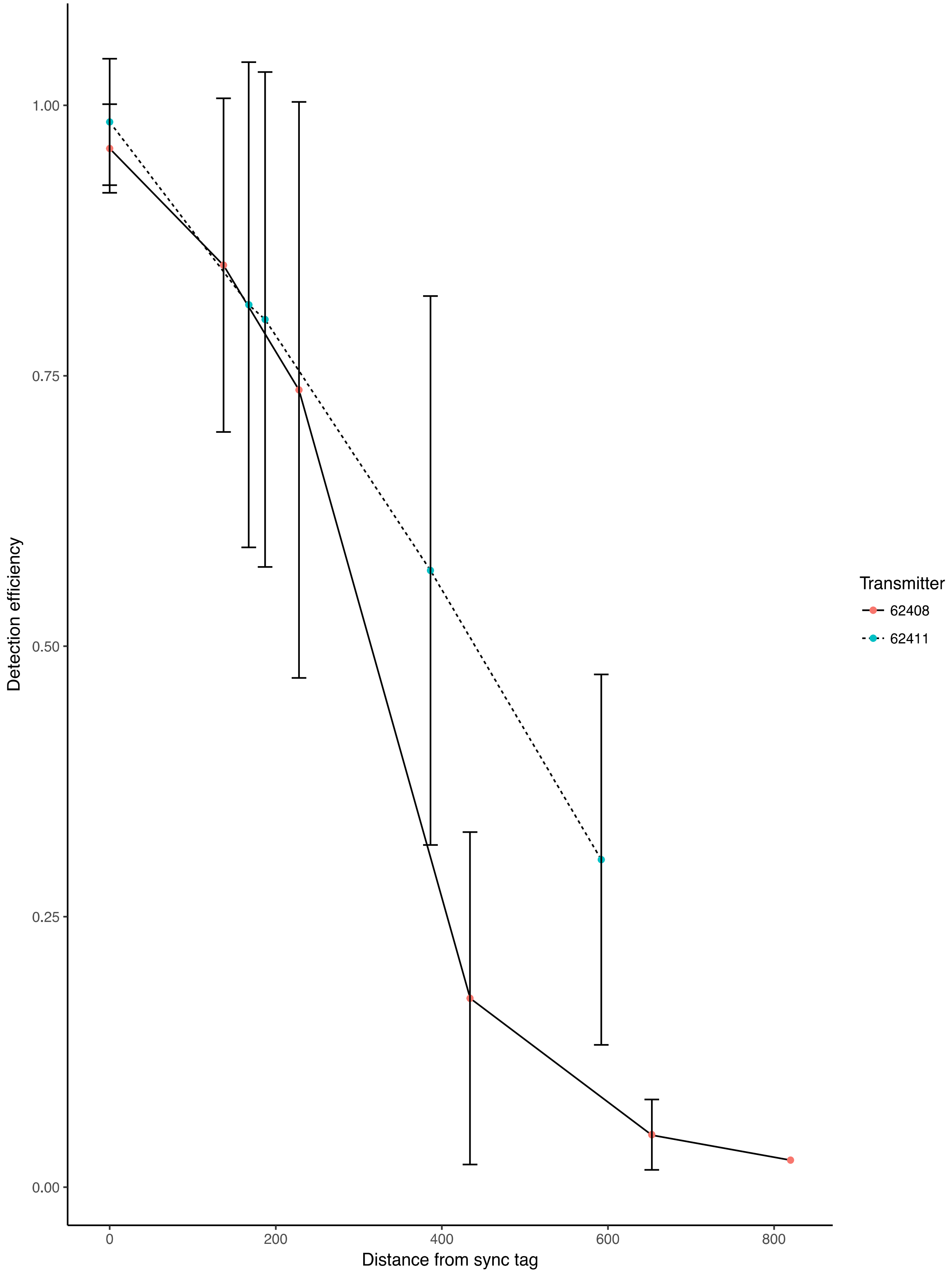

Figure 2. Mean detection efficiency of a single transmit within each 15-minute period for two sync tags (Power output [dB re 1 uPa at 1m] 142) between 02/05/2016 – 15/05/2016, when fish were actively migrating through the transect. Error bars indicate one standard deviation.

3.5. Fish behaviour

Fish behaviour was determined from the detections of tagged fish at the fixed arrays. Details of the behaviour and movement of fish out with detection zones cannot be identified by the study design used here, however it can be inferred through the detection sequence of fish as they move through the fixed array of receivers. Residence and non-residence events are identified from the data which enables subsequent behavioural responses to be calculated. A *residence event* is defined as a continuous detection of a fish at an individual transect. A new residency event is assigned when a fish has not been detected for a period of 60 minutes or the fish is detected at a new transect. A fish may have consecutive residency events at a single transect due to detections occurring more than 60 minutes apart. Each residency event required a minimum of two consecutive detections. A *non-residency* event refers to the period between two residency events which have occurred due to a fish being detected at different transects. A non-residency event records the time and location of the start of the event (i.e. the time and location where a fish was last detected) and the end of an event (i.e. the time and location where the fish was subsequently detected). A non-residency event is not assigned for periods between two consecutive residency events if they occur at the same transect.

The rate of movement (ROM) is the ground speed of an individual between two transects. The ROM is also assigned a *movement direction*. The movement direction is determined from where the non-residency event started and ended. For example, the ROM between BP and IN transects was calculated as the time difference between the last detection at BP and the first detection at IN divided by the distance between receivers to give ROM in metres per second, the movement direction is referred to as BP IN (i.e. the two transects, in order, between which the movement occurred). Distance travelled between detection at transects was calculated using the centre line of the river/estuary with QGIS software (QGIS Development Team, 2009). Distance travelled between the SU and MSS marine transects was determined via straight line distances between each individual ALS where fish were detected within the transects to account for the difference in travel distance between the eastern edge and western edge of the array. It is recognised that this is unlikely to be the exact route taken by individual fish, however it is likely to be indicative of the actual migration distance and enables comparisons to be made between individuals.

Swimming depth is determined as the mean depth of a fish during a residency event. Each tag detection indicates the depth of the tag at that point in time, the mean of all detections during a single residency event is recorded as the swimming depth of the individual at the specific transect it was detected at for the residence event. The acoustic tags have a depth resolution of 10cm up to a maximum depth of 25.5m.

Successful migration and survival was determined by detection of individuals on successive downstream receivers. It is assumed that fish which were detected at an upstream receiver but not at the subsequent downstream receiver, died within that intervening area. Survival results are reported on a percent per kilometre (% km^{-1}) loss basis to enable comparisons between sites and studies.

3.6. Environmental data

Meteorological data were obtained from a weather station located at Tain Range (57.817 ^{o}N, -3.967^{o}W) approximately 14 km north of the study site (Fig 1). Data from the weather station used in the analysis included cloud cover, total daily precipitation and wind speed. Tidal height data was provided by SEPA from a monitoring station located at Cromarty (Fig 1) and was used to investigate tidal impact on behaviour. Diurnal conditions were determined via the sunrise and sunset times calculated from the maptools package in R (Bivand and Lewin-Koh, 2016; R Core Team, 2016)

3.7. Statistical analysis

3.7.1. Rate of Movement

The mean ROM for each non-residency event was regressed on four explanatory variables (Movement direction [the two stations between which the movement occurred], wind speed, L_F and fat content) using a general linear model (GLM), for Gamma distributed data. The variables Length, Weight and Tag mass: body mass ratio were not included due to violation of collinearity with L_F. Due to individual fish generating multiple measures of ROM throughout the array, a mixed modelling approach was conducted with the fish ID included as a random effect (GLMM). All explanatory variables were treated as fixed effects. A maximal statistical model with all fixed effects was created. A minimum maximal model was selected using a top down strategy as described by Zuur *et al*., (2009) and the elimination of non-significant terms. The stepwise process of significance testing between models (ANOVA), and a sequential stepwise elimination of non-significant terms was also conducted. The final model contained only significant predictors of the ROM for each non-residence event. Tukey's HSD Post-Hoc tests were conducted to determine the significant differences in ROM between movement directions.

3.7.2 Swim depth model

The mean swimming depth for each residence event was regressed against five explanatory variables (diurnal condition (day or night), wind speed, cloud cover, daily precipitation and transect) using a general linear model (GLM) for Gamma distributed data. Due to individual fish generating multiple measurements of mean depth for each residence event at each receiver and throughout the array, a mixed modelling approach was conducted with the fish ID included as a random effect. All explanatory variables were treated as fixed effects. A maximal statistical model with all fixed effects was created. A minimum maximal model was selected by a top down strategy as described by Zuur *et al*., (2009) and the elimination of non-significant terms. The stepwise process of significance testing between models (ANOVA), and a sequential stepwise elimination of non-significant terms was also conducted. The final model contained only significant predictors of the mean swimming depth for each residence event.

3.7.3 Residence event duration

The duration for each residence event was regressed against five explanatory variables (tide state [ebb or flood], mean swimming depth, fat content, F_L and transect) using a general linear model (GLM) for Gamma distributed data. Due to individual fish generating multiple residence events throughout the array and at each transect, a mixed modelling approach was conducted with the fish ID included as a random effect. All explanatory variables were treated as fixed effects. A maximal statistical model with all fixed effects was created. A minimum maximal model was selected by a top down strategy as described by Zuur *et al*., (2009) and the elimination of non-significant terms. Stepwise significance testing between models (ANOVA), and a sequential stepwise elimination of non-significant terms were also conducted. The final model contained only significant predictors of the mean swimming depth for each residence event.

3.7.4 Within Group Survival

The proportion of within group survival (total survive/group total) was regressed on the day of year at release (DOY) and the total of number of fish in the release group using a logistic regression model for binomial distributed data. All explanatory variables were treated as fixed effects. A maximal statistical model including all fixed effects was created. A minimum maximal model was generated by the stepwise process of significance testing between models (ANOVA), and a sequential stepwise elimination of non-significant terms. The final model contained only significant predictors of within group survival.

3.7.5 Individual Survival

The binary response of survival (Yes/No) to the MSS transect (determined by detection of the individual at this outer transect) was regressed against five explanatory variables: mean fork length (L_F), ROM through Cromarty firth (ES to SU), fat content, DOY, total fish within release group. All explanatory variables were treated as fixed effects. A maximal statistical model including all fixed effects was created. A minimum maximal model was generated by the stepwise process of significance testing between models (ANOVA), and a sequential stepwise elimination of non-significant terms. The final model contained only significant predictors of the dependent variable.

3.8 Detection Error Estimates

Since there is potential that some tagged fish were not detected as they traversed an ALS transect, estimates on survival may be confounded and rely on the probability of transmitter detection. Knowledge of the detection probability parameter is an essential element in obtaining unbiased estimates of the survival rate of migrating smolts. Survival estimates in each segment of the migration between successive ALS transects are highly dependent on the probability of tagged fish being detected at each ALS as they cross.

The mean probability of detecting a single transmission of two sync tags (142dB 1 μPa power) located within the SU transect within each three hourly interval for the period of when fish were in the vicinity (as determined by detections on previous transect at IN [03/05/2016 – 12/05/2016]) is in excess of 0.75 (75%) at 200m and >0.87 (87%) at 100m. Transmissions are detected in excess of 400 and 800 metres although efficiency is low indicating zones of detection which are covered by two or more receivers.

Where there are additional receiver transects downstream of the one of interest, transect efficiency is estimable as the ratio of fish detected after the line of interest but not at the line of interest. Despite data supporting high detection probability at the SU transect, three fish were not detected which were subsequently detected at the MSS marine transect, indicating an error in detection of fish at SU of 3.9 %.

Where additional downstream receiver transects are not available, it is possible to estimate the potential detection error from known detection efficiency data. Range testing at the MSS marine transect identified detection efficiency estimates for the receivers. These efficiency estimates can be used to model the likelihood of a smolt managing to migrate through a receiver array without detection. Thus, smolts were simulated passing through a grid with a receiver at its centre. Simulated smolts were modelled moving at a random speed between min and max ROM for fish travelling between SU and MSS marine, and random straight-line trajectories originating in the lower portion of the grid and ending in the upper portion. Simulated smolts were assumed to be tagged with a transmitter that transmitted every 25 seconds (as per the tag specifications used in this study). Thus, it is possible, using this simulation, to estimate the numbers of smolts which pass through the grid undetected. This simulation was run with 2,000 fish across a 750m x 750m and 400m x 400m grid to represent the close spaced receivers near to shore, and wide spaced receivers in the centre of the transect (Fig 3).

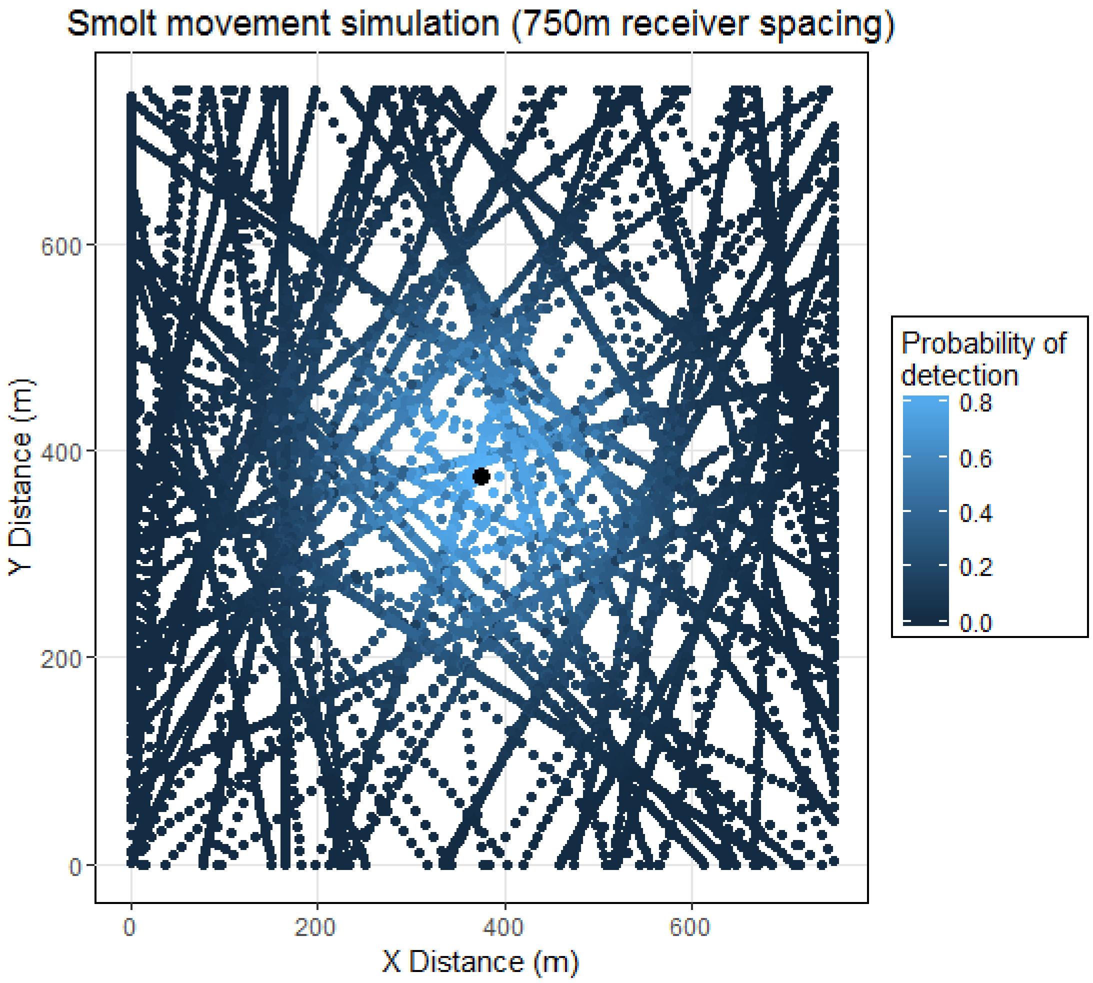

Figure 3: Plotted simulated smolt movements (small blue dots) passing a receiver (black dot) across a 750m grid. Probability of detection increases closer to the receiver as indicated by shading. 100 simulated movements are plotted.

3.9 Particle Tracking

A particle tracking model was used to explore where passive, neutrally buoyant, particles released in the Cromarty Firth could travel to under the influence of the natural hydrodynamics in the Moray Firth region. A hydrodynamic model of the Moray Firth has previously been developed by Marine Scotland Science. For the purpose of this work the model was run for the period March – August 2016. The hydrodynamic model was based on the Scottish Shelf model (SSM) (Wolf *et al.*, 2016). The SSM is a high resolution hydrodynamic model of the wider Scottish Shelf, and is an implementation of the Finite Volume Community Ocean Model (FVCOM). The Moray Firth model was forced at the boundary by data from the Atlantic Margin Model (AMM) which is an operational forecast model run by the UK Met Office. The forcing parameters at the boundary were current speeds, water elevation, temperature and salinity. The wind and atmospheric properties for the model were forced by modelled data from the European Centre for Medium Range Weather Forecasts (ECMWF) ERA-Interim reanalysis. The freshwater river input for the model used here included five dominant rivers (Conon, Ness, Findhorn, Spey and Deveron). The river discharge data was provided by SEPA for the appropriate gauging stations during the time of interest. The hydrodynamic model has been validated against a number of tide gauges in the region, and a further more rigorous validation is planned for the future.

The Lagrangian particle tracking model solves a nonlinear system of ordinary differential equations in order to update the particle position as it changes with time due to the hydrodynamic environment. For a more detailed description of the Lagrangian particle tracking model see the FVCOM manual (Chen *et al.*, 2011). The particle tracking code that was used here includes no biological behaviour, and simulates purely passive, neutrally buoyant, particles. The particle tracking code was performed *offline* using stored output from the Moray Firth hydrodynamic model as input.

4. Results

In total, 120 downstream migrating Atlantic salmon smolts were tagged with acoustic tags and released in the study. These fish had a mean fork length (L_F) = 144.3 ± SD 6.7mm, mean mass (M) 29.4 ± SD 4.2g, mean fat content 2.7 ± SD 1.2%. Fish were detected on every transect within the array with a total of 59,248 detections from study fish and >1,500,000 detections from sync tags. Fish were detected at the first ALS in the array (FW) on average 3.9 ± SD 5.3 days after release (distance from release site to FW = 6.1km). Confirmation of downstream migration occurred by detection of a fish at FW. Subsequently, movement was generally rapid, taking on average 8.1 ± SD 3.5 days to travel from the most upstream ALS (FW) to the most downstream marine transect (MSS), a distance of around 62 km (Fig 1). Despite tagging and releasing fish over a period of around 30 days, the majority of the fish passed through the array within a 10-day period (Fig 3).

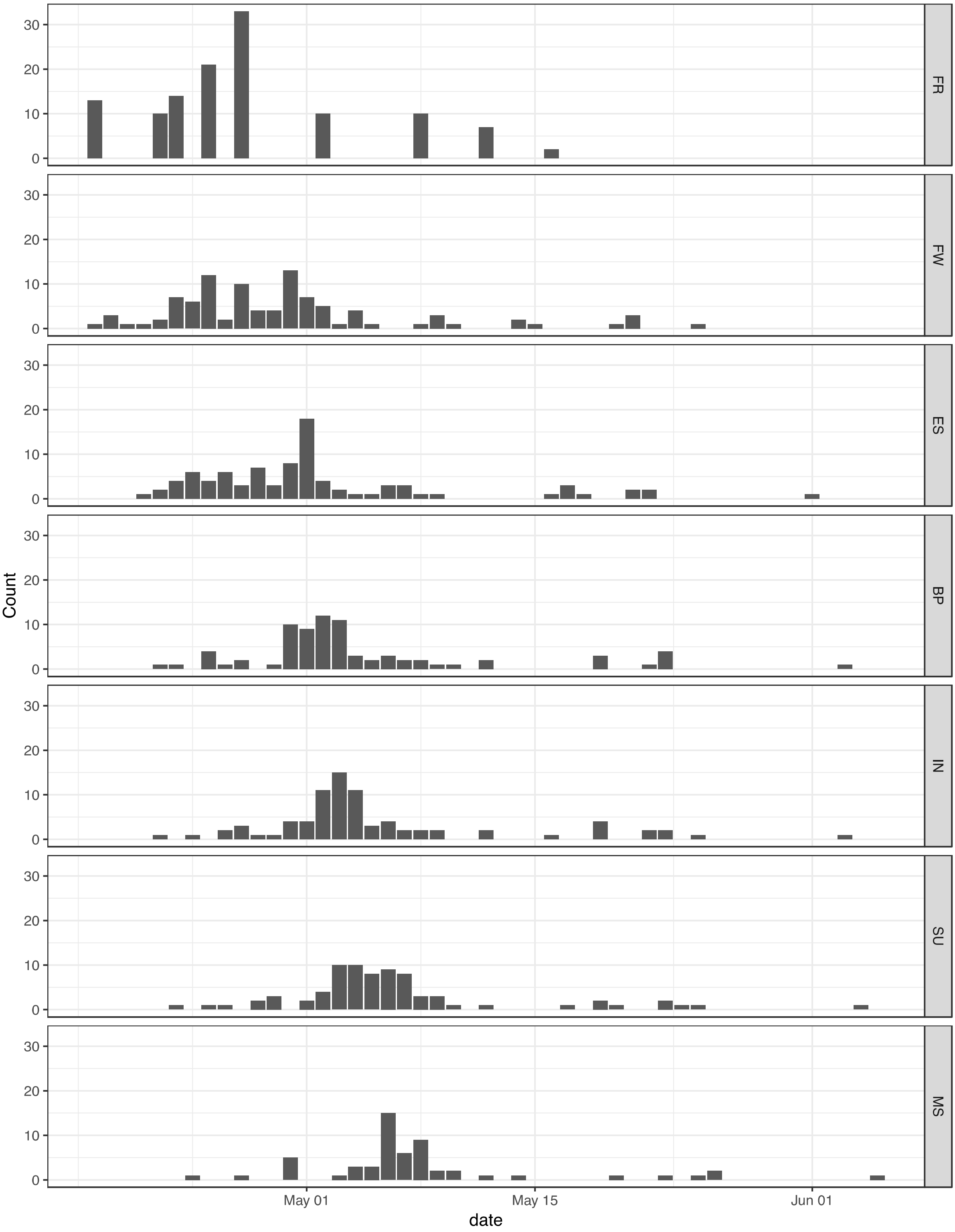

Figure 4: Counts of numbers of fish detected by date on each receiver transect. ‘FR’ indicates freshwater release site

4.1.Direction of Travel

Progress through the firth was generally in an outward direction. Fish appeared to be influenced by tide, with multiple residence events occurring for individuals at transects. This indicates fish periodically moving in and out of detection zones over an extended (hours) period. Some individuals were detected moving back upstream from IN to BP and subsequently returning from BP to IN. This movement pattern was detected by 19 individuals, three of which exhibited this pattern of detection on two occasions, such movement is expected to be a result of tidal influences as opposed to a behavioural response.

Fish were detected across all ALS within each transect with no clear route preference across transects. At the MSS marine transect, a route preference was observed. Fish were detected predominantly on the south-eastern ALS within the MSS marine transect, with the majority of first detections of fish at the transect occurring within 5km from the south-eastern shore of the Moray Firth (Fig 5). No detections of tagged fish occurred on the north-western portion of the transect. Some fish had multiple residence events in the MSS marine transect indicating potential tidal influence on their migration direction.

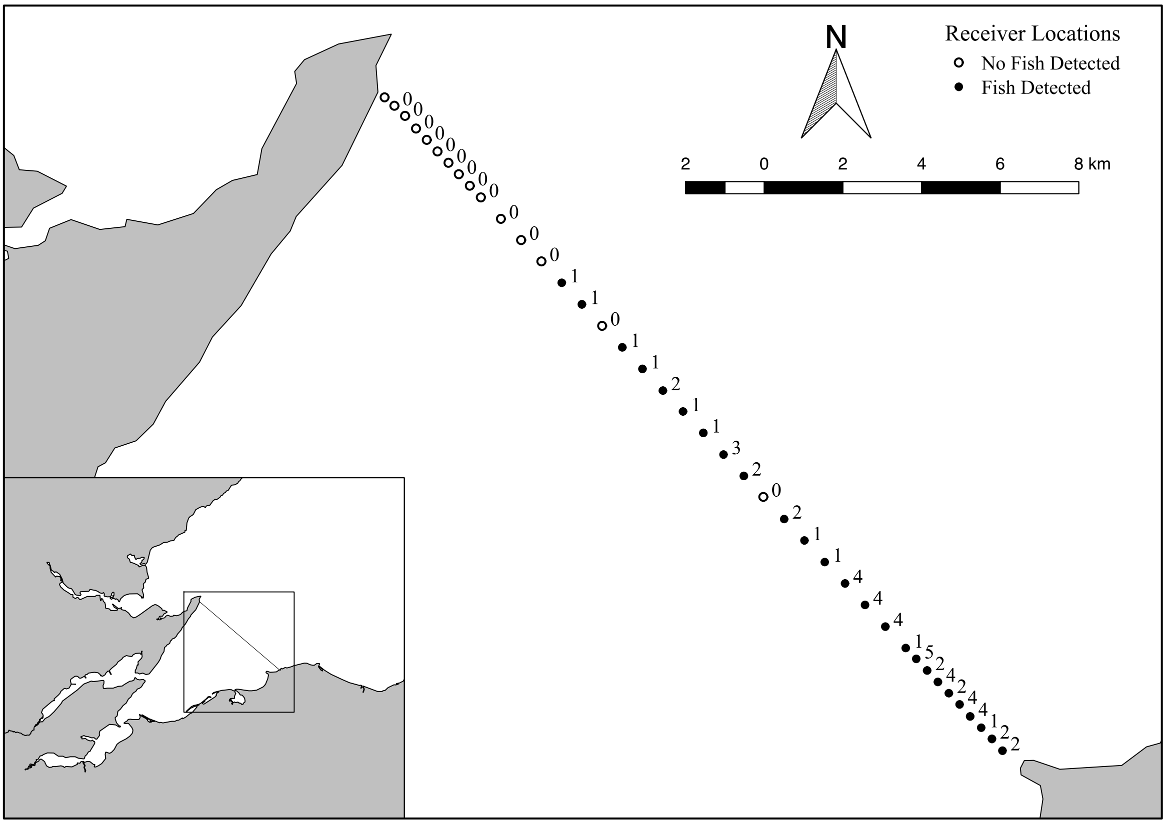

Figure 5: Numbers of fish detected by individual ALS within the MSS marine transect. Only the first detection of each individual fish is recorded to identify directionality. Numerous fish were detected on multiple receivers

4.2.Survival

Total escapement of tagged fish from the Cromarty Firth (detected at SU transect) was thus 65.8% (n = 71) of tagged fish with 46.7% (n = 56) detected at the MSS transect (Fig 6). Relative mortality rate (Table 1) was highest between release and FW (3.1%/km) followed by marine migration between SU and MSS (1.2%/km). Mortality through the Cromarty Firth was similar between transects at 0.2-0.4%/km. The exact fate of tagged individuals cannot be determined. No tags were detected with temperatures higher than the surrounding water temperature and no tags were detected continually deeper than the depths of the other tagged fish; scenarios that may be interpreted as indications of predation by other fish or mammals. One fish indicated depth readings at the maximum range of the tag at 25.5m deep as it traversed the SU transect, but was subsequently detected at the MSS marine transect within the top five metres of the water column suggesting the depth recording at SU was natural swimming and thus reliable data.

Model simulations based on 2,000 simulated fish passing a receiver (Section 3.8) indicate 29% of fish were missed passing between the receivers spaced at 750m and 2.4% of fish missed between the 400m spaced receivers. Based on the numbers of fish detected passing through the MSS array, an estimate of up to 10 fish which may have successfully reached the array may not have been detected but successfully reached the array.

For fish detected at SU, there were, on average 26 detections per fish. Given the receiver spacing of 200m and the detection probability of a single transmission supporting the hypothesis a fish would be detected by multiple receivers (overlapping detection array), the probability that all detections from an individual tag were missed is likely to be low. Similarly, at the MSS marine transect, despite increased receiver spacing, fish were detected multiple times (mean – 19 detections per fish). It is expected that all fish passing between

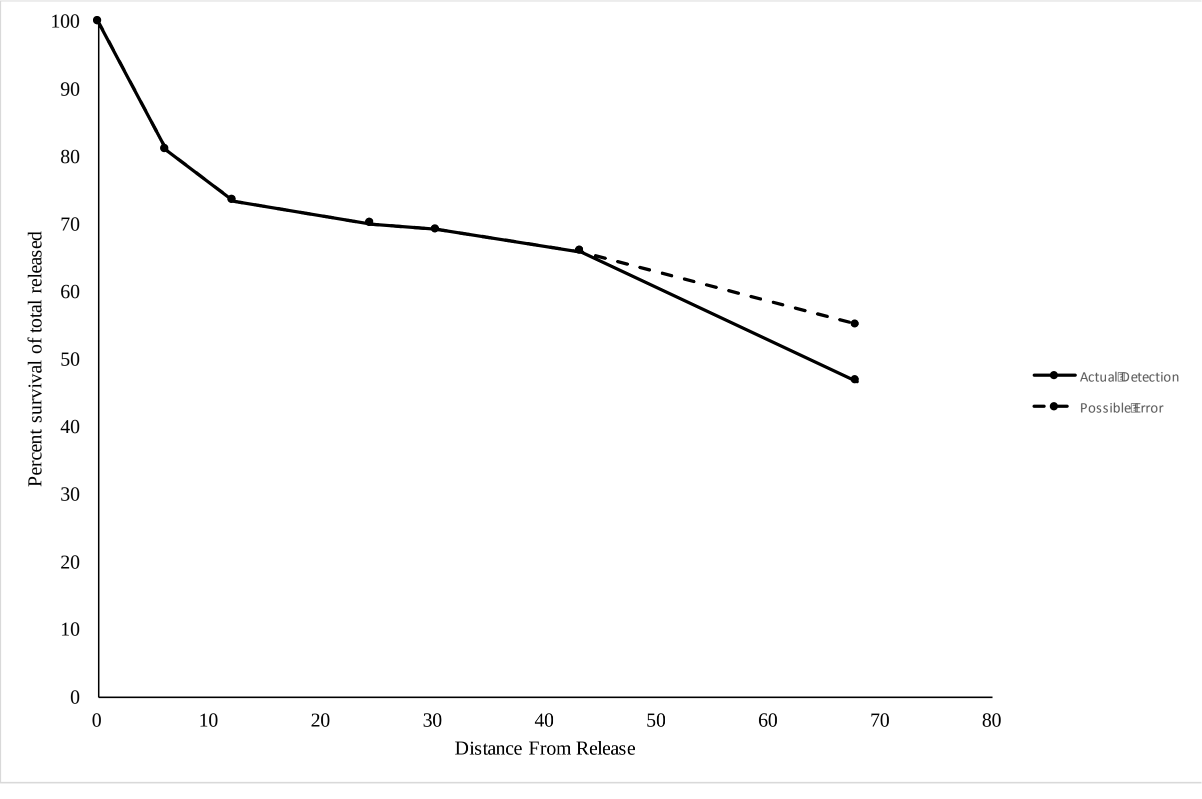

Figure 6: Survival curve for fish within the study. Transect locations are identified by black dots and labelled. Possible error identifies detection error estimates calculated for MSS marine transect by simulated trials

receivers will be reliably detected unless they pass at the midpoint between two receivers, **and** they pass rapidly enough so that there are few transmissions whilst in range of the receivers, **and** acoustic conditions are close to the worst found during testing. Intuitively this would represent a small percentage of missed fish.

Thus, actual escapement of fish tagged in the River Conon (i.e. fish passing to the MSS marine transect) in 2016 is likely to lie between the 47% (based on actual detections) and 55% accounting for missed fish.

4.3. Rate of Movement (ROM)

The mean ROM for non-residence events was significantly predicted by two variables. The final model accounts for 25.0% of variation in the data, 24.6% of this variance is explained by the movement direction (χ^2_5=111.38, p= <0.001) and 0.4% of the variation in the mean ROM is explained by wind speed (χ^2_1=5.61, p= 0.002) (pseudo R^2 calculated by r.s quaredGLMM function in the MuMln package on models generated without gamma distribution (Bartoń, 2016)). A post-hoc Tukey test showed that the ROM differed significantly ($p < 0.05$) between zones. However, there was no significant difference ($p > 0.05$) in ROM for movement between; BP IN, IN SU, SU MSS marine, or between IN BP and BP IN. There was no significant effect of F_L, Fat content, or Tag mass: Body mass ratio on ROM. In general, the rate of movement between all ALS was highly variable (Fig 7). The highest recorded ROM for a single fish outwith the riverine habitat was 1.29 m.s^{-1} for a fish moving between BP and IN transects, similarly the lowest rate of ROM was recorded in the same transitional section 0.01 m.s^{-1}.

Table 1: Mean and Standard deviations of rate of movement and the duration for fish moving between each transect. * denotes upstream movement from IN to BP. This is not an outward migration movement.

Movement Location	Mean ROM $m.s^{-1}$	S.D. ROM $m.s^{-1}$	Mean Duration (Hours)	S.D. Duration (Hours)	Mortality % per km
Release (FR)	0.08	0.09	90.69	127.11	3.14
FW → ES	0.26	0.38	46.32	54.76	1.55
ES → BP	0.13	0.15	52.79	43.77	0.37
BP → IN	0.53	0.34	6.63	15.02	0.21
IN → BP	0.62	0.13	2.50	0.68	0.00
IN → SU	0.29	0.30	25.45	22.04	0.37
SU → MSS	0.27	0.14	37.39	20.84	1.18

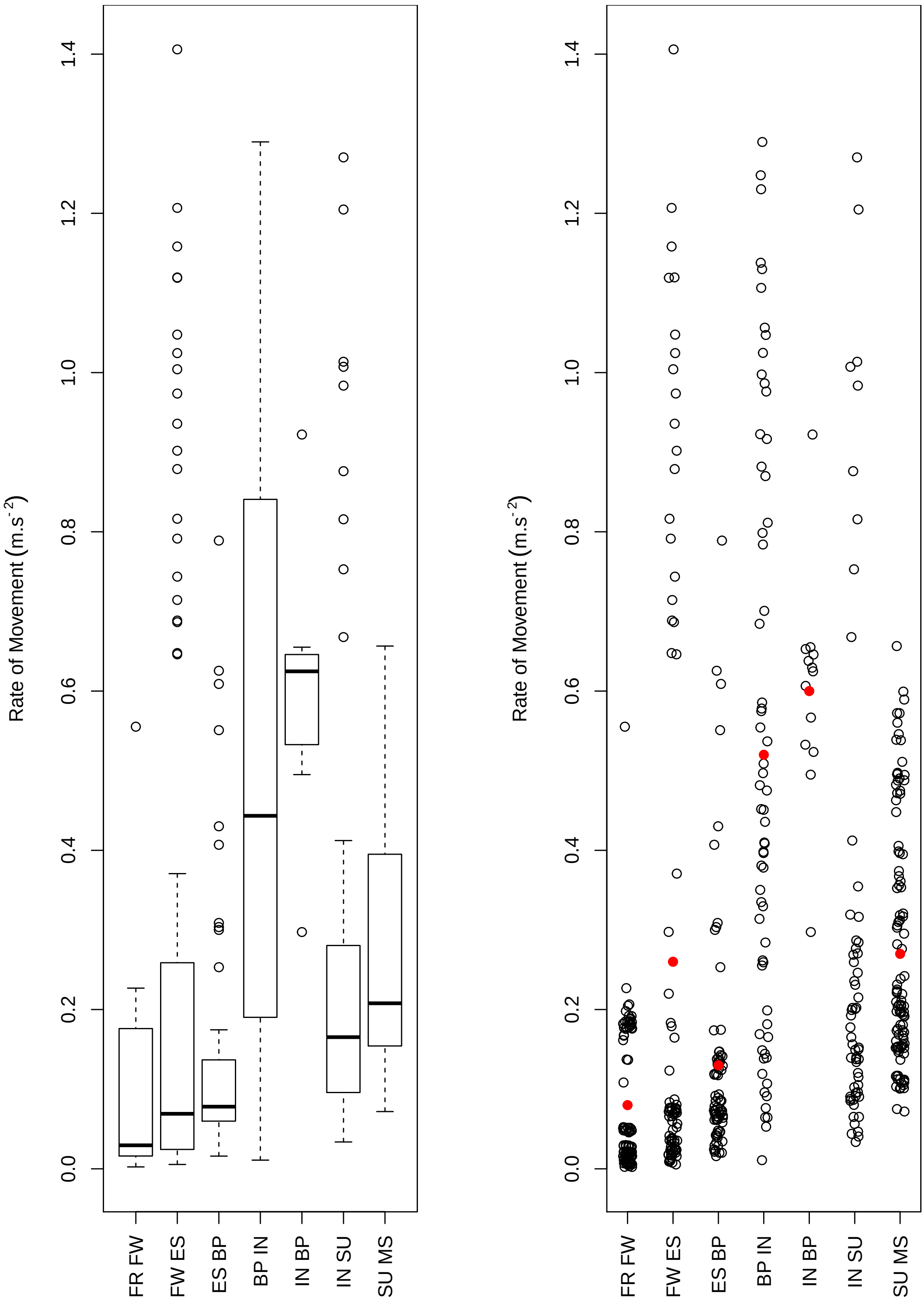

Figure 7: Boxplot, and spread of data for the rate of movement (m.s^{-1}) for each movement direction. Red points indicate mean ROM for each transect

4.4. *Swimming Depth*

Mean depth of fish during a residence event was highly variable at both FW (mean = 1.6 ± SD 0.5m) and ES (mean = 2.2 ± SD 0.8m) receivers. Throughout the Cromarty firth and marine environments, fish were predominantly recorded within the top metre of the water column (mean = 0.8 ± SD 0.6m), although fish were recorded throughout the top five meters of the water column (Fig 9). One individual recorded the maximum depth allowed by the tag recording of 25.5 metres at the SU transect. This individual was removed from depth analysis of fish at the SU array due to the exact depth of the fish being un-identifiable. Mean swimming depth of fish during a residency event exhibited a significant diurnal pattern (χ^2_1=210.19, p= <0.001, Fig 8). No other variables had a significant effect on the mean depth of fish during residency events. The mean swimming depth had a significant diurnal pattern, mean depth during residency events occurring at night were significantly shallower than those occurring in day. However, for residency events at FW and ES this pattern was reversed with fish being detected shallower in the day as opposed to night (Fig 8).

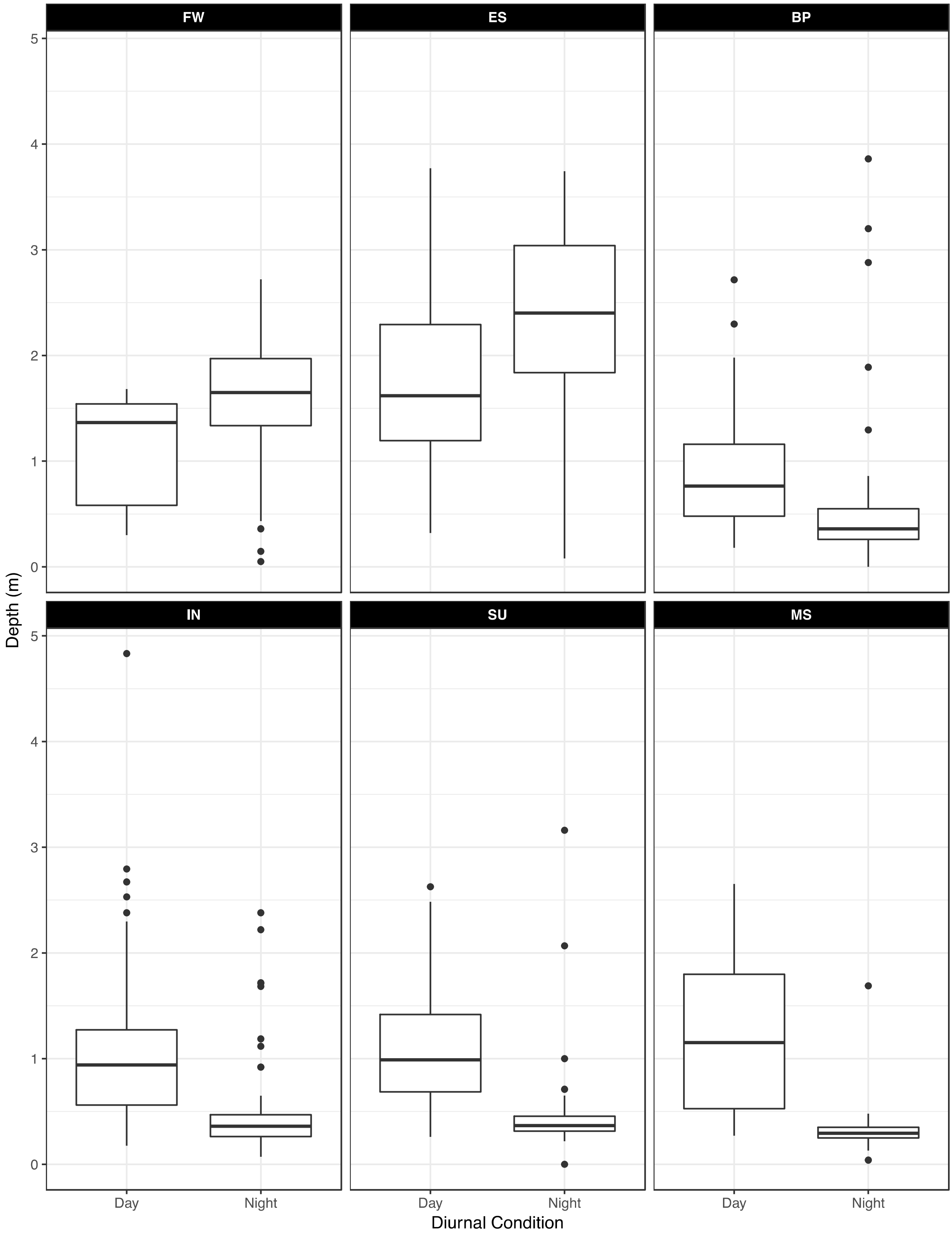

Figure 8: Boxplots of mean swimming depth (m) for each resident event by transect. Data is grouped by light condition.

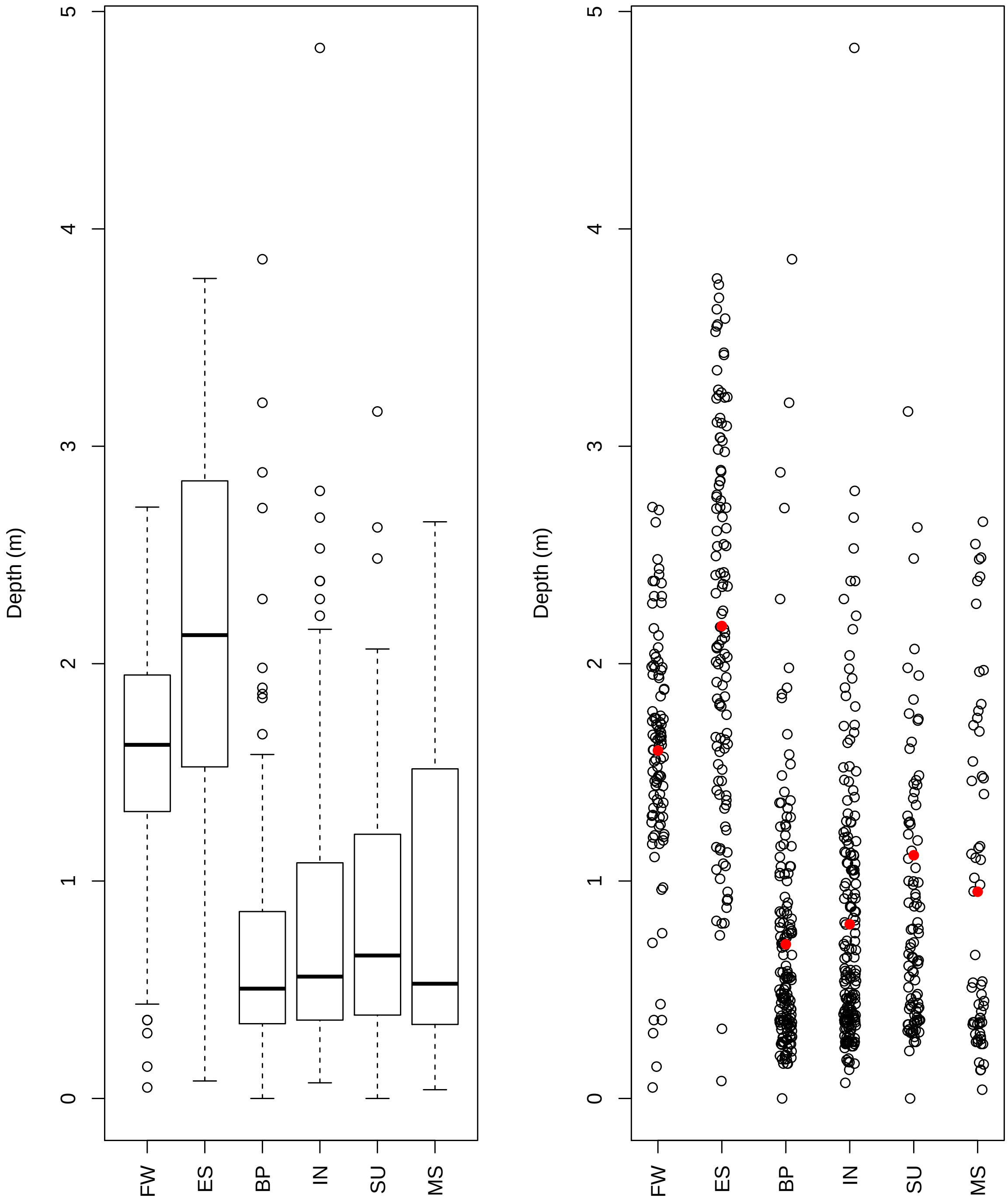

Figure 9: Boxplot and spread of data for mean swimming depth during each residence event by station. Red points indicate mean depth for each transect

4.5. *Residence event duration*

The mean duration of a fish at an individual ALS was significantly predicted (χ^2_2=46.65, p= < 0.001) by the additive effects of tidal state (χ^2_1=27.60, p= < 0.001) and mean depth χ^2_3=14.91, p= <0.001) during the residence event. Mean duration of fish in ALS was significantly higher when the residence event occurred in a flooding tide (mean = 27.9 ± SD 50.75 minutes) as opposed to an ebbing tide (mean = 15.44 ± SD 30.63 minutes). Mean duration also increased with mean depth of the fish during a residence event.

4.6. *Group Survival*

The proportion of within group survival to MSS marine was significantly predicted by both day of year (DOY) and the total number of individuals within the release group (Table 2). The odds ratio and model summary indicate that as DOY of release increases, survival decreases, and as group number increases so does survival. This is also an additive effect in that larger groups migrating earlier in the migration period have better survival than larger groups migrating later in the migration period (Fig 10).

Table 2: Beta, Standard error and confidence intervals for a logistic regression model which determines group survival (section 3.7.4)

		95% CI for odds ratio		
	B (SE)	Lower	Odds ratio	Upper
Constant	9.8 (4.61)			
DOY	-0.08 (0.04)	0.86	0.92	0.99
Group number	0.08 (0.04)	1.01	1.08	1.17

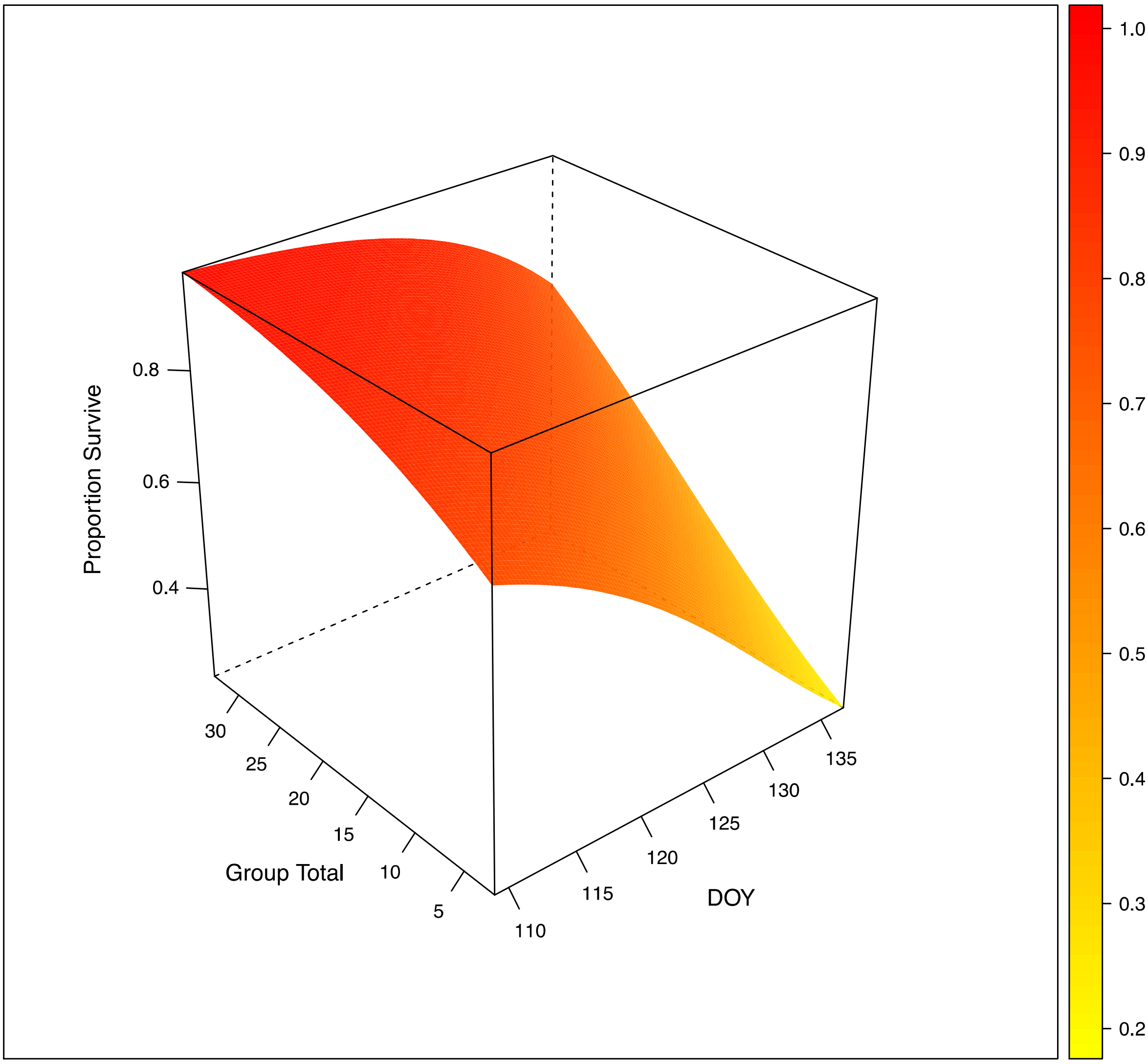

Figure 10: Graphical representation of logistic regression model. Proportion of within group survival represented by colour.

4.7.Individual survival

There was no evidence to suggest that mean fork length (L_F), ROM through Cromarty firth (calculated from ES to SU), fat content, DOY of release or total fish within release group were significant in determining survival on an individual basis. Although it is possible to predict within group survival (section 4.6) it is not possible to predict which individual fish within the specific groups will survive.

4.8.Particle Tracking

The aim of this particle tracking work was to simulate the release of particles at times corresponding to the times at which the smolts passed the receiver line in the Cromarty Sutors. The particles were released at the surface, at locations corresponding to the receiver location at which the smolts were detected before crossing the receiver line. The particle location and time of release are listed in table 3. These correspond to approximately 1/10 of smolt recordings at the Cromarty receiver line (every 10th in temporal order was chosen to simplify the analysis).

The particles were tracked for 39 days, as this was considered a substantial time to establish their trajectories past the MSS marine receiver line. The particle positions were recorded hourly from the points of release. The resulting particle tracks for the ten released particles are plotted within the Moray Firth domain in figure 11 Here the solid lines correspond to the particle track while the filled circles correspond to the location each 24 hour period after release. For this small set of tracked particles the particles tend to circulate in the inner Firth before crossing the MSS receiver line. After crossing the MSS line there appears to be a trend towards travelling along the southern coast (Figure 12). Of the ten particles released, four intersect the MSS marine array in a similar location to the naturally dispersing smolts but not in comparable times. The particle tracking work provides strong evidence that there is a clear active migration in an easterly direction out from the Sutors.

Table 3: Release location and time for the passive particle simulation in the Moray Firth as well as location at which the passive particles pass the array of receivers further out in the Moray Firth. The elapsed time corresponds to the time passed from release time to the crossing of the MSS line.

Particle	Transmitter	Lon (° E)	Lat (° N)	Release Time	Lon crossing (° E)	Lat crossing (° N)	Elapsed time (hours)
1	12	-4.0008	57.6864	23/04/2016 05:00	-3.5166	57.7127	275
2	5	-4.0017	57.6813	29/04/2016 22:00	-3.6969	57.8102	224
3	37	-4.0008	57.6864	03/05/2016 12:00	Did not cross	Did not cross	
4	120	-4.0005	57.6899	04/05/2016 00:00	-3.7122	57.8185	115
5	116	-4.0009	57.6884	04/05/2016 13:00	-3.5005	57.7039	336
6	88	-4.0015	57.6826	04/05/2016 17:00	-3.6965	57.8100	26
7	191	-4.0005	57.6899	05/05/2016 22:00	-3.6939	57.8086	19
8	194	-4.0015	57.6826	06/05/2016 16:00	-3.5004	57.7039	284
9	149	-4.0015	57.6826	08/05/2016 14:00	-3.5264	57.7180	250
10	177	-4.0015	57.6826	19/05/2016 23:00	-3.5287	57.7192	87

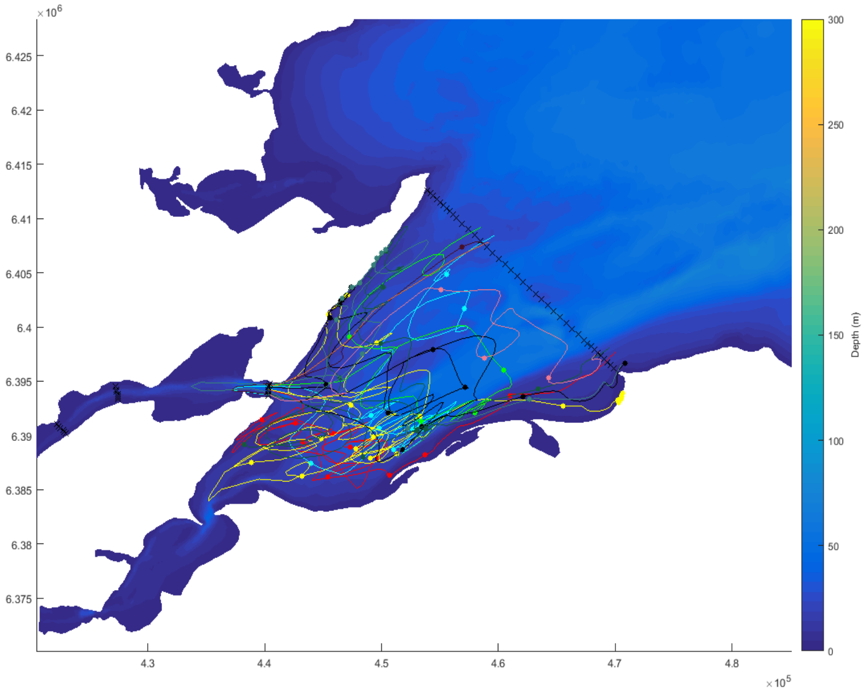

Figure 11: Figure showing the particle tracks between release location in the Cromarty Firth until they cross the MSS marine receiver line (black crosses across the Moray Firth).

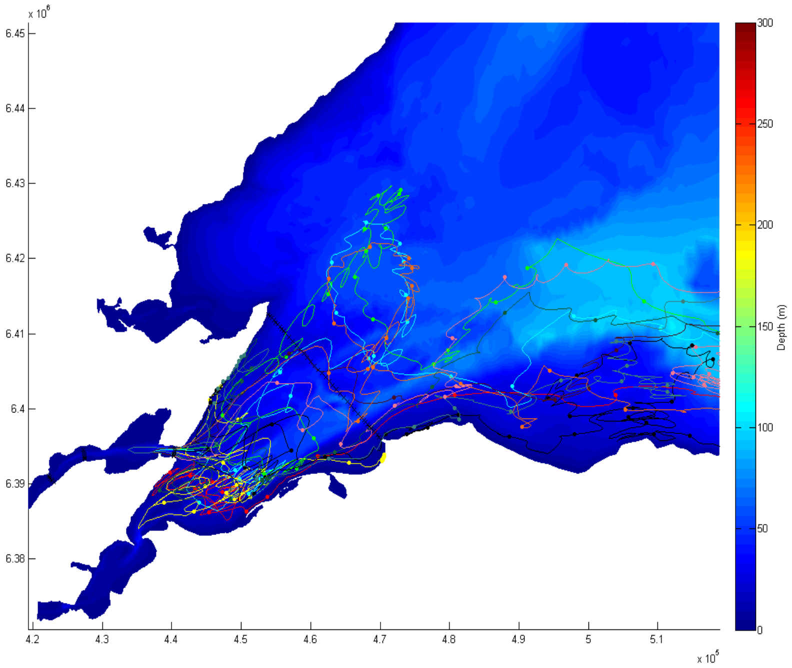

Figure 12: Figure showing the tracked particles from release location in the Cromarty Firth (by the Sutors), passed the MSS marine receiver line and further into the Moray Firth.

5. Predation

The non-detection of an acoustic transmitter at successive transects identified a mortality event. However, the exact fate of each “missing” tagged fish cannot be determined. Acoustic tags utilised in this study were selected for their ability to return information on depth and temperature, and such data would be used to identify potential predation events. For example, if a mammal consumed a tagged fish, the temperature would increase due to the internal body temperature of the mammalian predator and thus a predation event identified. Similarly, it was expected that a predation event by a fish would result in variable depth recordings substantively different to the population of migrating smolts. No tag was detected with abnormal temperature readings or abnormal tag depth. With acoustic telemetry, data on the tagged individuals is only recorded when the tag is within a detection zone of a receiver, if a predation event occurred and the predator did not transit through a transect, no definitive predation event would be identified. A single tag transiting through the SU array was recorded at the maximum depth of the tag (25.5m) but subsequently detected within the surface layers at the MSS array thus not providing evidence for a predation event. One tag from the active tracking releases (See Appendix) did record a high temperature reading shortly after release. A seal was observed within the vicinity of the release site and thus it is hypothesised the high temperature was a result of the smolt being consumed by the seal. A single tag was also recorded at the ES receivers after transiting through the firth and at the MSS array. The fish was not recorded transiting back upstream through the array and thus we hypothesise avian predation at a location outwith the MSS marine transect. Although only two tags were identified as having been predated, it is not unrealistic to assume that lost fish were predated on between transects.

6. Discussion

This study is the first to identify the migration direction and swimming depths of downstream migrating salmon smolts in both estuarine and marine environments in Scotland. Smolts were successfully tracked up to 30km from shore within the open marine environment, and >60km from the river mouth. Contrary to the general hypothesis (pers.comms) that smolts would migrate in a northerly direction close to the coast, the location of detections across the MSS transect would indicate an eastward movement of individuals from the Cromarty Firth. This study is the first to track fish in the marine environment where their movement is unconstrained by a land narrowing. Smolt swimming direction does not appear to be aligned with tidal currents, passive particle tracking does not provide a good tool for predicting smolt migration routes. It is reported (Hansom and Black, 1996) that tides flood down the Caithness coast, and then eastwards along the southern coast of the Moray Firth. Current reversal during the ebb tide sees water flow westwards along the southern coast of the Moray Firth and northwards towards Caithness. Along the southern coast of the outer Moray Firth, an easterly flowing current is the predominant water flow. Initial passive particle tracking models do not accurately represent natural dispersing smolt movements. The directionality of smolt movement when compared to the direction of passively tracked particles raises questions in the ability for tracking models, based on tidal currents, to accurately identify smolt migration routes out with telemetry arrays (Fig 11). Although no biological data were assigned to the particles, even assigning a swimming vector may not be simple given the unexpected directionality of naturally dispersing smolts.

Mortality rates within the study (Table 1) were relatively low when compared with other studies. Atlantic salmon smolt mortality has been shown to range between 0.3 – 5% km^{-1} in fresh water, 0.6-36% km^{-1} in estuaries and 0.8 – 3.4% km^{-1} in the marine environment (Thorstad *et al.*, 2012). Mortality may occur for a variety of reasons during smolt migration, but the most commonly cited are a lack of physiological preparedness (for transition between fresh and marine water) and predation. Should a lack of physiological preparedness be responsible for mortality (as determined by gill Na^+, K^+-ATPase), survival is expected to be positively correlated with day of year as later migrating smolts are more physiologically prepared for migration in the marine environment as reported by Stich *et al.*, (2015). Data presented here supports the hypothesis that mortality was caused by predation. Fish have been shown to learn about the location of food socially, along with the ability to learn novel food types (Brown and Laland, 2001, 2002). As a new resource becomes available (e.g. migrating smolts) it is at first minimally exploited (high prey survival) as predators take time to adjust and increase foraging efficiency. As time passes, predators learn and increase their foraging efficiency of that resource, leading to low prey survival. Migration in numbers as employed by migrating smolts decreases predation risk (Furey *et al.*, 2016), thus the positive relationship between within group survival, early migration and increased group size strongly supports that predation as the primary cause of mortality in this study.

Changes in swimming depth has also been strongly related to temperature and salinity (Plantalech Manel-La *et al.*, 2009), and light conditions (Davidsen *et al.*, 2008). Smolts were predominantly detected within the top metre of the water column, and were detected shallower in the water column at night than during the day. There are few studies which explore the diurnal effect in coastal migration, those that have report results similar to this study (Reddin and Short, 1991; Davidsen *et al.*, 2008; Richard D Hedger *et al.*, 2008). It is hypothesised that smolts are found deeper in the water column in daylight to avoid avian predators (Reddin and Short, 1991), and that the higher variability in depth during daylight is due to fish actively foraging since they rely on visual cues to identify prey (Davidsen *et al.*, 2008; Richard D. Hedger *et al.*, 2008).

The rate of movement was different between various transects and is likely to be a result of tidal influences. Rate of movement was highest within the inner firth (BP to IN) where tidal influences are likely to have the strongest effect (Stapleton and Pethick, 1996). The duration of a residency event was significantly longer under a flooding tide as opposed to an ebb tide, potentially indicating fish actively swimming against the current in an outward direction. The rate of movement has previously been correlated with tidal cycle, wind induced currents (Fried, McCleave and LaBar, 1978; Lacroix, McCurdy and Knox, 2004; Stich *et al.*, 2015), barometric pressure, lunar illumination, cloud cover and wave height (Fried, McCleave and LaBar, 1978), and such relationships vary across studies. Given that tagged smolts are only tracked for a relatively short period of time, combined with the heterogeneity of the environment variables and small-scale localised changes in conditions, behaviour such as rate of movement and swimming depth, regardless of whether the mechanism was active (smolts adjusting behaviour to conditions) or passive (smolts displaced by currents), will be effected to some extent (Richard D. Hedger *et al.*, 2008). Fried *et al.*, (1978) also report that environmental variables were correlated with behaviour in their study due to smolts being transported by differing current vectors at the same time that changes in environmental conditions occurred. As with all smolt migration studies, the time an individual is within a detection array is limited and behaviour is not exposed to a range of conditions. Hence it is likely the major driver of behaviour, be it a passive or an active effect masks the effects of other more subtle variables (Thorstad *et al.*, 2012).

In order to reveal the migration patterns of Atlantic salmon smolts in the open ocean, detailed information relating to the drivers of their emigration routes is required to populate predictive models. The study presented here is the first to identify migration routes in the open ocean within Britain, and has also successfully tracked smolts further from shore than any previous UK study. Although the direct drivers of smolt movement remain unknown, and that fish do not appear to be driven directly by tidal currents, the large spatial scale of detections presented here paves the way for future modelling research into the paths and vectors of smolts in the marine environment. It is likely that smolt movements are influenced to some extent, by marine currents, and potentially by salinity plumes or even magnetic fields, but such analyses of the underlying mechanisms behind movement paths lie outwith this report. The work presented here demonstrates the ability to tag and track wild salmon smolts in the ocean, at spatial scales which would enable further smolt movements and drivers of swimming vectors to be identified. Future collaborations between particle tracking modellers and smolt telemetry projects such as this will enable greater insight into the mechanisms and pathways behind Atlantic salmon smolt migration in the ocean.

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Appendix

Development of an active tracking methodology

In addition to the fixed acoustic array, this project aimed test new methodologies and provide proof of concept for active tracking of acoustically tagged smolts at sea to be applied elsewhere to enable accurate, real-time swimming vectors of fish. This would specifically provide data to enable improved design of future studies of coastal migration by fish. The further method development aims of this study include:

1) Validating the potential for active tracking of coastal released fish as a methodology for determining coastal habitat use.

2) Testing the validity of using near-shore coastal swimming vectors as a description of fish behaviour for input to particle tracking models exploring potential marine migration pathways; a method for generating very high resolution temporal and spatial data compared with the current alternatives of using fixed position receivers.

1. Introduction

There is a need for high spatio-temporal resolution data to determine potential environmental drivers (tide, currents, wind speed & direction) of fish movement speed and direction for subsequent modelling of smolt migration and improved understanding of environmental drivers of migration parameters. Fixed acoustic arrays within transects enable effective data collection on survival and rates of movement within rivers, estuaries and to a certain extent the marine environment. Such arrays however do not enable the fine scale, continuous movement of fish to be identified over large spatial scales, but enable a snapshot of behaviour as fish transit through detection zones. Mobile tracking, the continuous monitoring of an individual from a boat with a hydrophone has the potential to bridge the gap between autonomous data collection from fixed arrays and the requirement for high resolution spatial data.

2. *Methodology*

Fish capture and tagging follows the methodology outlined in section 3 (main report). Following tagging and recovery, fish were placed into a transport bag filled with river water and oxygen and transported to a holding box (2m x 1m x 0.65m). The box was filled with freshwater and aerated continuously with three air pumps, fish were allowed to settle for two hours. Following acclimation, salinity within the box was gradually increased through the addition of sea water (35 psu) over a 16h period. Fish were exposed to full strength sea water (35 psu) for six hours prior to release (total time in release box 24h). The following day fish were transported onto a boat prior to release for active tracking. This process was repeated six times with five fish per group (total 30 fish) throughout the smolt run. Tags used in this methodology also transmitted a non-coded pulse every five seconds in addition to coded depth and temperature transmits every 25 seconds.

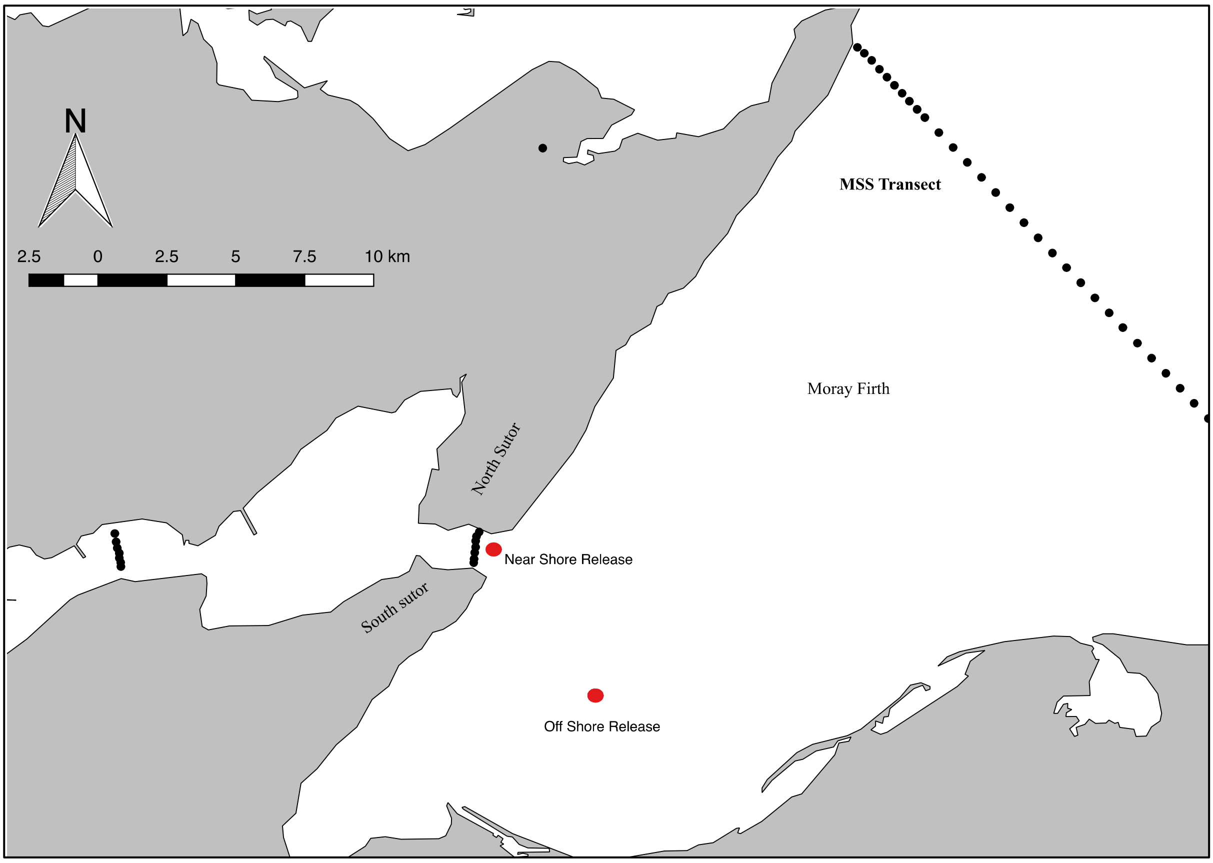

Figure A1: Map of release locations used in active tracking

Fish were released individually within the Sutors (Fig A1) on an ebbing tide, and tracked via an omni-direcional and directional hydrophone. Initially the directional hydrophone was utilised to identify the swimming direction of the released individual. The directional hydrophone was used to identify the vector from which the strongest signal strength was detected. The boat was then manoeuvred so as to stay in contact with the fish. If the fish was not detected for a period of three minutes the omni-directional hydrophone was used to identify if the fish was still within detection range, if so, the directional hydrophone was then utilised to determine the swimming vector of the fish. If the fish was not detected on the omni-direction hydrophone, a grid search pattern was undertaken in an attempt to locate the fish. If the fish was not relocated within 30 minutes a new fish was released and tracked from the initial release location.

The first three release groups yielded extremely poor data and the decision was taken to change methodology:

The remaining 15 fish were released in the Moray Firth approximately 30km south-west of the MSS transect (Fig A1), comparable to the distance between SU and MSS transects. This methodology was devised to test the hypothesis that mortality in smolt migration occurs relatively close to shore as opposed to open ocean. The two different release sites effectively created a near-shore and an off-shore release group. Active tracking was initially employed to follow the off-shore release groups, however similar results were encountered to the near shore release and the ability to active track these fish significantly compromised.

3. *Results*

Of the 15 fish released in three groups at the Sutors release location, one fish was detected for a period of 20 minutes. The fish did not move any significant distance from the release location. The remaining fish were tracked for a period of less than five minutes. No fish were re-detected following loss of initial detection post release. There was insufficient data to determine swimming trajectories of any of the fish. Of the fish released within the Sutors, non-were re-detected on the SU transect indicating movement was in an easterly direction initially, away from the firth. Of the 15 fish released within the Moray Firth, no individual was tracked for greater than five minutes.

Of the 15 fish released in the near-shore release groups, three were redetected at the MSS transect, similarly of the 15 fish released in the off-shore release groups three were also detected indicating a mortality rate of 0.6% km^{-1} for each group. The sample sizes of survival within each group prevent any robust statistical analysis being conducted. We hypothesised that smolts stayed within the same relative location of release for a brief period of time (1-3minutes) before directional movement was made. Given that the tidal currents and potential active swimming, fish were likely out of detection range within a matter of minutes before directionality could be inferred.

One fish indicated a mammalian predation event within two minutes of release at the offshore location identified by the temperature reaching the maximum allowed by the tag (25.5^oc) only possible from the ingestion by a mammal, in this case, a seal.

4. Discussion

Although the tracking results of the fish were poor, the methodology testing revealed significantly useful aspects of the work which could be taken forward to future research programmes.

A combination of factors within this study limited the effectiveness of the work.

- Tidal currents within the Sutors and immediate area are relatively high, drift speed of the boats used regularly exceeded $2m.s^{-1}$. Even if only passively drifting, fish would cover more than 100m per minute and be out of effective detection range within 5 minutes. Due to the novelty of the project, no a priori information was available to the direction of smolts leaving the Sutors, thus the potential of re-locating a fish was significantly reduced.
- Acoustic noise within marine environment was high and masked the high frequency non-coded five second pulse transmitter designed to enable active tracking. To increase the detection range of the receiver, gain on the receiver was increased however this resulted in further reducing the ability to identify the high frequency transmitter due to increased background noise. It was possible to determine the coded transmits of the depth and temperature, however these were too in-frequent to enable effective tracking.
- Acoustic noise generated from the boat engines also affected detection ability. The boat engine was required to hold station against the tide and/or to follow moving fish,

however this increased noise and decreased detection efficiency. On occasions where the engines were turned off, the boat drifted rapidly under the influence of the tidal current and out of detection range of the tagged fish.

- The tags used are of very low power output (dB re 1 uPa at 1m 139) which is limited by the tag size required to enable the acoustic tagging of Atlantic salmon smolts. Such low power output reduces the ability to 'hear' these tags in the given conditions

Despite the issues identified here, active tracking has been undertaken, successfully, in other smolt migration studies (Lacroix and McCurdy, 1996; Lacroix, McCurdy and Knox, 2004; Thorstad *et al.*, 2007). The environmental conditions of the study site strongly influence the effectiveness of such a methodology. In areas of slow moving water, relatively free of current, active tracking may be accomplished. Similarly, the use of larger higher powered tags enables more efficient tracking; however, such tags would not be recommended for use with smolts.

Considering the results from the methodology development we highlight some recommendations for future acoustic tracking work:

- Active tracking should be conducted in environments/locations relatively free of strong tidal currents.
    - Acoustic noise created by currents reduces detection efficiency.
    - The boat used for tracking will not drift away from the released fish, thus greater opportunity to enable detection of the individual.
- Tracking should be conducted on calm days, with no/little wind or rain.
- The boat used should the smallest feasible (following health and safety guidance) and if possible use an electric motor whilst tracking is being undertaken. This reduces excess noise generated by the boat and engines.
- Two boats maybe used to triangulate the tagged fish so a more informed estimation of position and swimming direction maybe generated, thus informing subsequent boat movements.
- Use highest power tag output (and thus tag size) available relative to fish size.
- High frequency non-coded pulses may not be best suited to tracking in the marine environment and consideration for higher ping rate of coded data may be of benefit.

Active tracking has the potential to identify localised movements of individuals however, care should be taking when identifying the study location to ensure the points outlined above are considered. Further developments of such methodologies would be welcome.