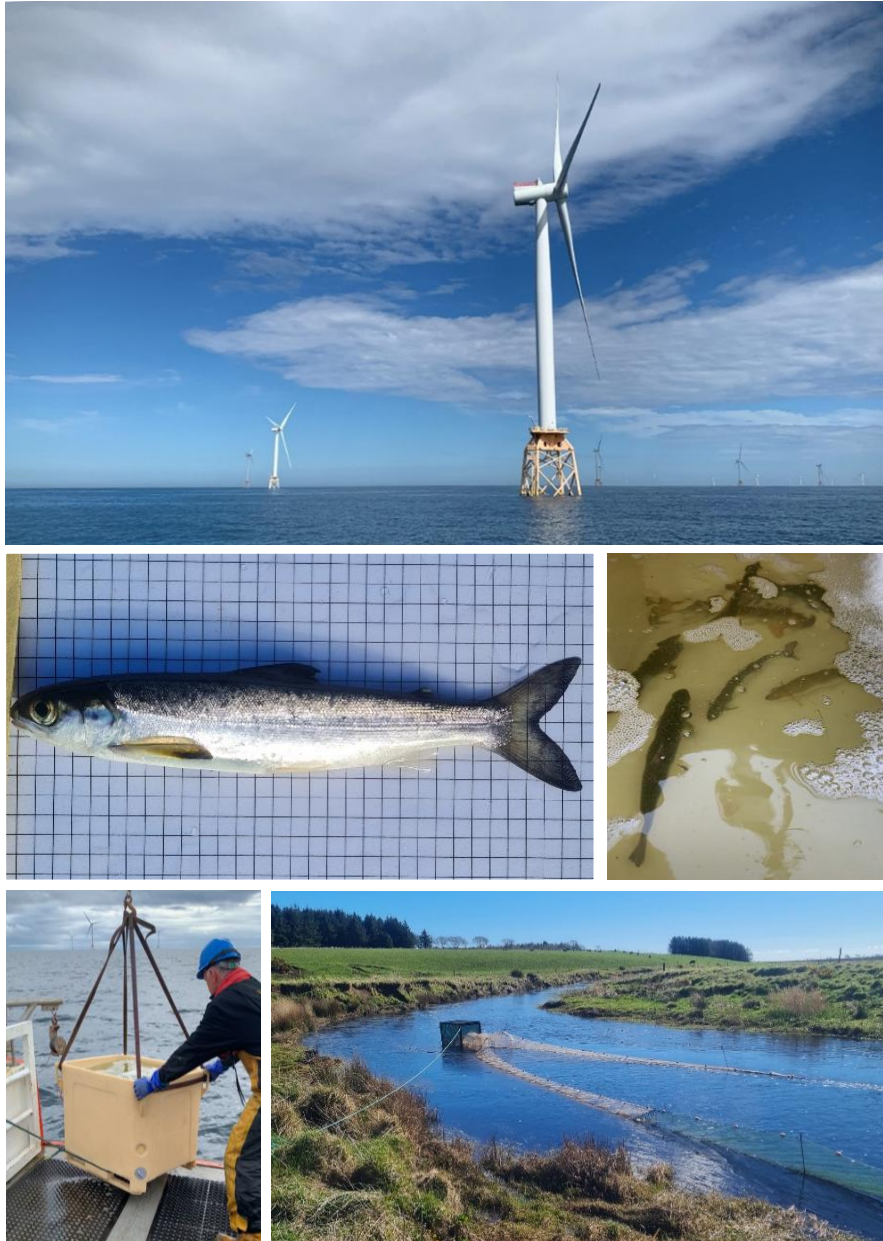


Migration routes and behaviour of Atlantic salmon and sea trout around operational wind turbine arrays in the Moray Firth, Scotland

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Summary

Offshore Wind Developments (OWDs) are set to expand substantially around Scotland over the next decades to meet ambitious carbon reduction targets and meet Net Zero by 2045. A robust evidence base is needed to inform the spatial planning of OWDs to ensure minimal negative impacts on marine biota, including anadromous salmonids for which there are substantial knowledge gaps (Diadromous Fish ScotMER Receptor Group, 2024).

Possible impacts of OWDs on salmon and sea trout migrating through the marine environment may be acute, derived from construction and decommissioning activities (e.g. underwater noise and vibration, sediment disturbance and habitat changes), or chronic, i.e. persisting while the wind farm is operational. The latter may result from exposure to electromagnetic fields (EMFs), flicker and shadow effects from rotating turbine blades, along with on-going habitat changes and elevated predation risk around pile foundations and scour protection structures.

A fish tracking study was conducted in 2023 (Y1) and 2024 (Y2) which aimed to: 1) Determine the overlap between emigrating salmon post-smolt migration routes and OWDs in the North-West Moray Firth, 2) Quantify the duration and characteristics of post-smolt swim paths within two operational OWDs, and 3) Investigate patterns of residency and behaviour of adult sea trout within an operational OWD.

Salmon smolts ($n = 208$) captured in the River Wick were fitted with acoustic transmitters and tracked through an array of receivers within the lower river, harbour, marine bay and two adjoining OWD sites: Beatrice and Moray East. Additional receiver lines projecting from the north and south edges of the Beatrice OWD intercepted migration pathways.

Adult sea trout ($n = 69$) captured from tidal pools and the coast (near River Wester outlet) were fitted with acoustic transmitters, translocated and released either into the Beatrice OWD or a nearby 'control area' outside of the development. Over the following months, sea trout movements and behaviour were tracked throughout the Beatrice and Moray East OWDs and compared with the control area.

On average, 44% of salmon post-smolts did not head directly north after leaving Wick Bay to take the most likely shortest straight-line route to their northerly feeding grounds, but instead swam east, south-east, and to a lesser extent, directly south.

A total of 33 salmon post-smolts (19% of those that entered the Moray Firth) entered the wind turbine zone. Known residency was typically of short duration, with post-smolts spending a median of 36 minutes (maximum 5 h) among the turbines and most swim paths indicated direct transit, generally in an easterly to south-easterly direction.

A small number of salmon post-smolts were in the vicinity of, and potentially in, the turbine zones for extended periods: up to 22 h in Y1 and 51 h in Y2. Three individuals exhibited convoluted swim paths with multi-direction movements.

Translocated sea trout predominantly dispersed outside of the receiver array within a few days, although a substantial proportion of individuals in both Y1 (35%) and Y2 (42%) persisted in the area for over a week, moving extensively with swim tracks of up to 385 km, and re-entered the detection zones multiple times and up to 4 months after first detection.

Sea trout exhibited frequent diving behaviour and extensive use of deep waters (40–76 m). No differences were detected in sea trout behaviour and residency while in Beatrice OWD compared to the control area, suggesting that fish were unlikely to have adopted this deep diving behaviour in response to the turbine structures.

While acknowledging inherent limitations of the detection array and tracking technology, there was no evidence to indicate that either salmon post-smolts or adult sea trout were subject to high levels of marine predation within the OWDs or the wider study area.

The spatial and temporal patterns of salmon and sea trout movement observed in this study aid the prediction of encounter rates and understanding of the potential effects of wind turbines on salmonids as they undertake their juvenile and adult migrations. The findings should be used to inform Environmental Impact Assessments and contribute to the conservation of these imperilled species.

Recommended Citation

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1. Introduction

Increasing global energy demands coupled with recognition of the urgent need to reduce greenhouse gas emissions to counter anthropogenically driven climate change have led to widespread commitments to produce more “clean energy”. Marine renewable energy sources are an important component in this transition, with offshore wind energy production leading the rapid growth in this industry; global installed capacity reached approximately 83 GW in 2025 and is forecasted to grow to 285 GW by 2030 (GWEC, 2025).

The UK aims to achieve 50 GW of wind generation capacity by 2030 to help meet the Government’s emission reduction targets and provide greater energy security (International Energy Agency, 2023). Scotland, with its exposed coastline leading to plentiful and consistent wind generation potential, will play a fundamental role in meeting these goals, with the number of offshore wind developments (OWDs) set to expand significantly around Scotland over the next decade (Scottish Offshore Wind Energy Council, 2024). The Scottish Government aims to achieve net zero by 2045 and to generate 50% of Scotland’s overall energy consumption from renewable sources by 2030 (Scottish Government, 2023)

There exists substantial knowledge about the impacts of long-established onshore wind energy developments on terrestrial organisms, with a particular focus on birds and bats (Arnett & May, 2016; Katzner et al., 2025; Laranjeiro et al., 2018). In comparison, research into the possible impacts of offshore wind developments on marine biota and particularly diadromous fish is in its infancy (Honkanen et al., 2024; Svendsen et al., 2022). While ecological studies of offshore oil and gas installations provide useful indication of the habitat changes and likely responses of biota to the construction of marine engineered infrastructure (Iorio-Merlo et al., 2023), the potential impacts of OWDs are wide-ranging and may include physical, acoustic, and electromagnetic effects across a range of taxa including marine mammals, birds, and fish (Gill et al., 2012; Harding et al., 2016; Malcolm et al., 2015).

Fish are key taxa of concern in the context of OWDs. Within this group, diadromous fishes are associated with the greatest knowledge gaps because of their relative scarcity and transient movements in marine environments (Bicknell, Gierhart, Newton, et al., 2025; Diadromous Fish ScotMER Receptor Group, 2024; Honkanen et al., 2024). The life history strategy of anadromous salmonids such as Atlantic salmon (*Salmo salar*) (salmon hereafter) and the migratory form of brown trout (*Salmo trutta*) (sea trout hereafter) which necessitates spawning in freshwater and migration to marine environments to optimise growth, renders them vulnerable to encountering OWD sites, potentially with multiple exposures (i.e. during both in and out-migrations).

The possible impacts of OWDs on salmon and sea trout fall into two categories: acute and chronic. Acute impacts derive from short-term construction and decommissioning activities and include heightened underwater noise, particle motion and vibration, sediment disturbance and rapid changes to localised habitats (Honkanen et al., 2024; Svendsen et al., 2022). Chronic impacts persist in the medium to long-term while the wind farm is operational and, based on our current understanding, may derive principally from: 1) exposure to electromagnetic fields (EMFs) in the vicinity of cables; 2) flicker and shadow

effects from rotating turbine blades, and 3) on-going effects of habitat modification associated with the turbine and control centre structures. The latter may change within the site's operational life as the ecosystem that colonises infrastructure matures (McLean et al., 2018).

Rotating turbine blades and the dynamic shadowing that results from interruption of direct sunlight potentially influence fish behaviour, reducing their ability to detect prey and predators (Williamson et al., 2024). A recent review by Williamson et al. (2024) concluded that aquatic organisms in proximity of the turbines and those uppermost in the water column would be most susceptible to flicker effects, which is highly relevant to juvenile Atlantic salmon which migrate predominantly near the surface (Davidsen et al., 2008; Newton et al., 2021).

There is high uncertainty about the effects of EMFs on fish. While there is theoretically potential for EMF to disrupt some fishes' ability to migrate (Verhelst et al., 2025), studies looking at the impact of EMF emanating from subsea power cables on free swimming salmonids are lacking. In notable exceptions, acoustic telemetry was used to track Chinook salmon (*Oncorhynchus tshawytscha*) post-smolt movements within San Francisco Bay (Klimley et al., 2017; Wyman et al., 2018). Results were mixed with indications of both avoidance and attraction to energised cables, but overall it was concluded there was no strong barrier effect to migration. Current research suggests close field (<20 m) effects, if any, have the most potential to impact salmonids (Verhelst et al., 2025). Offshore wind energy export cables from fixed foundation turbine arrays are predominantly located in waters deeper than 20 m, and typically buried, so the relevance of EMF effects to surface-oriented salmon and sea trout post-smolts are likely to be limited to shallow areas i.e. particularly near the coast or in estuaries. However, greater focus on floating turbine installations may increase the prevalence of EMF effects on fish generally, and requires better understanding (Honkanen et al., 2024; Verhelst et al., 2025). Salmon transit relatively quickly through coastal waters during both their juvenile feeding emigration (Gilbey et al., 2021; Lilly et al., 2024; Rodger et al., 2025) and adult return spawning migration (Hansen et al., 1993). Conversely, sea trout predominantly remain in coastal waters and often make multiple movements between freshwaters and the marine environment (Thorstad et al., 2016). Further, adult sea trout make greater use of deep water than previously thought (Artero et al., 2025). These behaviours mean sea trout are likely to be more temporally exposed than salmon to the export cable corridors for OWDs (Honkanen et al., 2024).

The potential consequences of habitat modification caused by the presence of turbines and other marine infrastructure likely represent the most far-reaching and multi-faceted effects of OWDs on fish. The localised increases in biodiversity and abundance of marine biota resulting from the artificial reefs potentially created by wind farm piles and scour protection has been well documented (Bicknell, Gierhart, & Witt, 2025; Svendsen et al., 2022). The potential cumulative effect of introducing multiple widely distributed engineered hard structures to the seascape may also help some species spread beyond their natural range by creating a "stepping stone effect" (Coolen et al., 2020, 2022; Dannheim et al., 2020;

Langhamer, 2012). This aggregation of biomass and prey species elicits a response among higher trophic levels, including piscivorous fish species, marine mammals, and seabirds, with the potential to create predation ‘hotspots’ that impose an artificially elevated loss rate on prey species (Bicknell, Gierhart, Newton, et al., 2025). Seals and porpoises have been shown to alter foraging behaviour in response to large offshore structures, with seal even adopting a grid-like hunting strategy (Russell et al., 2014). Salmon and sea trout are prey items for sea mammals such as seals and porpoises (Middlemas et al., 2007), so the aggregation of such predators within OWDs could increase marine loss rates. Conversely, heightened predation of piscivorous fish, which are in turn predators of juvenile salmon, may, along with the potential shelter provided by OWD structures, actually enhance salmonid survival rates during their migration.

Salmon populations are declining globally and in 2023 the International Union for the Conservation of Nature (IUCN) classification for Atlantic salmon (*Salmo salar*) moved from Least Concern to Near Threatened globally, and to Endangered in Great Britain (Nunn et al. 2023). Declines are likely driven by the complex interplay of multiple pressures, particularly habitat degradation and fragmentation in freshwaters and overexploitation, aquaculture, and broadscale changes in oceanographic conditions and productivity in the marine environment (Dadswell et al., 2022; Gillson et al., 2022). Similarly, these pressures have contributed to local collapses of the sea trout populations (Butler & Walker, 2007; Gargan et al., 2007; Skaala et al., 2014). When juvenile salmon and sea trout emigrate from freshwater to undertake their marine feeding migration, and when the adult component of the population returns to freshwater to spawn, there is the potential for migration routes to intersect with marine development sites. Understanding the spatial and temporal distribution of anadromous salmonids in the marine environment in general, and their overlap with OWDs in particular, has been highlighted as a ScotMER priority evidence gap (Diadromous Fish ScotMER Receptor Group, 2024) and is crucial for robust Environmental Impact Assessment of proposed developments. Around the Scottish coast, the paradigm of juvenile Atlantic salmon, on leaving their natal river (during a life phase generally termed ‘post-smolts’), making rapid directed migrations to feeding grounds is being increasingly challenged through detailed study of their migration routes. Acoustic tracking can generate spatially and temporally detailed information on the migration of individual fish. It has provided evidence of indirect migration paths and delay (e.g. Main, 2021; Newton et al., 2021; Rodger et al., 2025) that would appear, at a coarse scale at least, to be inefficient if assuming a strategy to minimise delay and energy expenditure to reach optimal feeding grounds in the Norwegian sea and West Greenland (Holm et al., 2000; Thorstad et al., 2012).

This study had 3 principal aims to:

- 1) Determine the overlap between emigrating salmon post-smolt migration routes and OWDs in the North-West Moray Firth
- 2) Quantify the duration and characteristics of salmon post-smolt swim paths within two operational OWDs in the Moray Firth (Beatrice and Moray East); and

- 3) Investigate patterns of residency and behaviour of adult sea trout within an operational OWD in the Moray Firth (Beatrice)

2. Methods

Study area and telemetry array

The Moray Firth, North East Scotland, contains several OWD sites at various stages of planning including consented, in construction, and operational. Beatrice and Moray East OWDs located 13 and 22 km offshore, respectively, within the Moray Firth were the focus of the current study. Beatrice, completed in 2019, has a generation capacity of 588 MW from 84 fixed turbines while Moray East, completed in 2022, has a generation capacity of 950 MW from 100 fixed turbines. The turbines of both wind farms are located in water of 35–60 m depth.

Acoustic telemetry (69 kHz) was used to track: 1) the outmigration of Atlantic salmon smolts from the River Wick into the Moray Firth and through the Beatrice and Moray East wind farms, and 2) the movements of adult sea trout translocated from the River Wester into the vicinity of the Beatrice and Moray East wind farms. The study utilised an acoustic receiver array (Innovasea, model VR2AR) deployed as part of the collaborative 'Predators and Prey Around Renewable Energy Development' (PrePARED) project, along with additional study-specific receivers (Innovasea, models VR2AR, VR2W and VR2Tx) deployed in the Rivers Wick and Wester, and in the Moray Firth (Figure 1). The PrePARED receivers ($n = 84$) were deployed close to turbine base structures within the Beatrice and Moray East wind farms, with a nearest neighbour spacing of approximately 1150 m, and maintained for the duration of the current study (14th April 2023 – 30th March 2025). Additionally, 60 study-specific receivers were deployed in two lines (30 receivers on the North Line and 30 receivers on the South Line) extending out from the Beatrice OWD with a spacing of 500 m between adjacent receivers for (Figure 1). The lines were in situ from 9th March 2023 to 10th July 2023 (Y1) and from 29th February 2024 to 15th September 2024 (Y2). This configuration was designed to determine if salmon post-smolts travelled east after leaving Wick Bay or south-east towards the wind farms, with passage through the latter confirmed by the extensive receiver array there. Due to high fishing pressure directly north of Wick Bay, it was not feasible to deploy receivers in this region to detect the northward movements of smolts. During the period from 27th February 2024 to 18th September 2024 (Y2), 14 receivers were deployed 11 km north of Beatrice OWD to provide the "Control Area" in which to release and track translocated adult sea trout. The hexagonal grid configuration and spacing of these receivers were identical to the hexagons within the North and South areas of the Beatrice OWD, thus enabling direct comparison of detection patterns within these 3 areas (Figure 1).

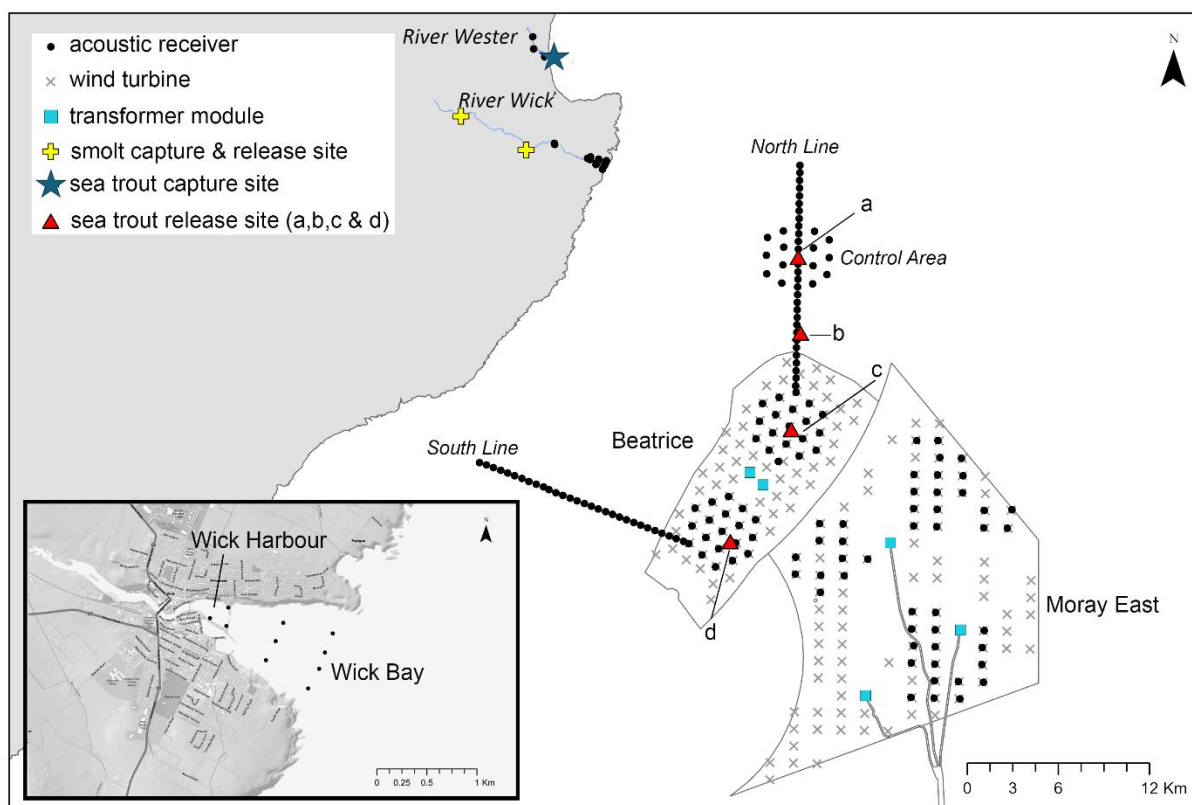


Figure 1 The study area showing the Beatrice and Moray East offshore wind developments (OWDs) within the Moray Firth, 2 smolt capture and release sites (yellow crosses), 1 sea trout capture site (blue star), 4 sea trout release sites (red triangles) and the marine acoustic receiver array. The latter comprised receivers within the OWDs (PrePARED array – 38 receivers in Beatrice and 46 receivers in Moray East), the North Line (30 receivers), the South Line (30 receivers), the “Control Area” (Y2 only, comprising 14 receivers arranged within an hexagon on the North Line to mimic the hexagons in Beatrice), 3 receivers on the River Wester, 2 receivers in the River Wick and 10 receivers in Wick Harbour and Wick Bay (inset).

All marine moorings comprised a 70 kg weight attached to an acoustic release canister system via a 2 m rope stop. This configuration enables remote retrieval of all items from the seabed using a surface vessel. Receivers in freshwater were deployed on the riverbed, attached to a weighted stand. Data download and battery replacement were conducted annually.

Fish capture and tagging

Atlantic salmon smolts

Salmon smolts were captured during the period from 13th to 22nd April 2023 (Y1) and from 11th April to 2nd May 2024 (Y2) using an upstream-facing box funnel trap deployed at Bilbster (58.464363°, -3.230271°) located 11.1 km upstream of Wick Harbour on the River Wick (Y1 & Y2), and at Haster (58.445416°, -3.154892°) on Haster Burn, a tributary of the River Wick, 6.4 km upstream of Wick Harbour (Y2).

Captured fish were visually assessed and selected for tagging (n= 108 in Y1; n = 100 in Y2) if they were clearly smolting, of sufficient size (≥ 120 mm fork length) and exhibited no notable external indicators of damage or disease. Selected individuals were anaesthetised (0.1 g/L MS222 1:1 buffered with NaHCO_3), measured (fork length, mm) and placed on a V-shaped sponge saturated with river water. An incision (approximately 10 mm length) was made in the ventral abdominal wall, anterior to the pelvic girdle, and a uniquely coded acoustic transmitter (Innovasea) with a transmission rate of 15–45 s inserted into the peritoneal cavity (Table 1). The TP transmitter model incorporated tag depth and temperature sensors from which data were transmitted on alternate transmissions (nominally each minute). The incision was closed using two interrupted surgeon knots with 4/0 Ethilon nylon sutures. The gills were continuously irrigated with river water throughout tag implantation. The fish was subsequently transferred to an aerated tank, then after full recovery placed into a perforated in-river containment box (0.7 m length x 0.45 m width x 0.60 m depth) that had throughflow of freshwater, close to the point of capture and held until release, which occurred after sunset (minimum 8 h, maximum 11 h).

Table 1 Number of acoustically tagged Atlantic salmon smolts from the River Wick and Haster Burn in two study years (Y1 & Y2), including tag specifications and fork length (mm) of tagged individuals.

Study Year	No. fish	Tag model	Tag diameter x length (mass in air)	Expected tag life (days)	Fork length (mm)min–max (mean $\pm$ SD)
Y1	68	V6-2x	6.3 x 13 mm 0.5 g	52	120–149 (134 $\pm$ 6)
Y1	40	V7-2x	7 x 19.5 1.5 g	69	134–164 (143 $\pm$ 6)
Y2	70	V6-2x	6.3 x 13 mm 0.5 g	52	120–140 (132 $\pm$ 5)
Y2	30	V7TP-2x	7 x 21 mm 1.7 g	57	131–156 (144 $\pm$ 5)

Total Number of Fish: 208

Adult sea trout

Adult sea trout were captured on 12th and 13th July 2023 (Y1) and 30th June and 18th July 2024 (Y2) by seine netting in the sea pools of the lower River Wester (58.500314°, -3.135941°) (Figure 1). Captured individuals which exhibited one or more visual indicators of a migratory lifestyle (i.e. silver body colouration and altered spot colour and configuration) (Pratten & Shearer, 1983), were of sufficient size (≥ 190 mm fork length) and apparently healthy were retained for tagging. One of three models of acoustic transmitter was implanted, dependent on fish size, using the methods described above but with a larger incision for the V9 models (approximately 14 mm) (Table 2). The tag transmission rate of all IDs was 15–45 s. Tag depth and temperature data were transmitted from the V9TP-2x tags on alternate transmissions (nominally each minute).

Table 2 Number of acoustically tagged sea trout from the River Wester which were translocated offshore into the Moray Firth in two study years (Y1 & Y2), including tag specifications and fork length (mm) of tagged individuals.

Study Year	No. fish	Tag model	Tag diameter x length (mass in air)	Expected tag life (days)	Fork length (mm) min-max (mean $\pm$ SD)	Release location - Control Area (a)	Release location - South of Control Area (b)	Release location - Beatrice North (c)	Release location - Beatrice South (d)
Y1	17	V9TP-2x	9 x 31 mm 4.9 g	231	255–509 (322 $\pm$ 72)	-	-	7	10
Y2	11	V7-2x	7 x 19.5 mm 1.5 g	196	195–220, (204 $\pm$ 9)	0	3	4	4
Y2	6	V9-2x	9 x 27.5 mm 4.5 g	232	200–219, (210 $\pm$ 8)	2	0	2	2
Y2	35	V9TP-2x	9 x 31 mm 4.9 g	231	225–440, (279 $\pm$ 53)	7	5	12	11
TOTAL	69	N/A	N/A	N/A	N/A	9	8	25	27

After recovery, fish were held within a rigid mesh in-river cage (1.5 m length x 0.7 m width x 1 m depth) that had throughflow of freshwater close to the capture location. Prior to release, fish were transported by road in an aerated tank (600 L) of river water to Wick Harbour and transferred in water-filled containers to a larger aerated tank (800 L) on the deck of a vessel. This tank was filled with a mixture of seawater and freshwater to achieve comparable salinity as that at the capture site. Fish were transported offshore and released at one of four sites: Beatrice North (Y1 & Y2); Beatrice South (Y1 & Y2); the “Control Area” (Y2) or “South of the Control Area” (Y2) (Figure 1) (Table 2). The latter was not a planned release site but was used due to deteriorating weather conditions on the release day. On arrival at each release site, ambient seawater was slowly pumped into the holding tank at a rate which replaced the entire volume over a period of 15 minutes to facilitate fish acclimation. The tank was subsequently slowly lowered by crane into the sea to sink approximately 1 m below the surface, whereupon the fish left volitionally.

Detection range

Tags had a power output of 137 - 146db dB re 1 μ Pa @ 1m which results in a typical optimal deep open water transmission range of 300–500 m. Numerous physical and environmental factors may reduce or increase detection range and efficiency including water depth, bed substrate type, the presence of suspended particles, and localised varied effects of factors such as wind (Brownscombe et al., 2019). Based on the typical optimal scenario, all tagged fish should have been detected while passing through Wick Bay and the North and South lines, but could potentially have passed through the OWD and control area grids without detection.

Environmental data

Data on tidal current direction and speed along with bathymetry were generated for the study area in the Moray Firth using the Scottish Shelf Model developed by the Scottish Government Marine Directorate (Barton et al., 2022). Depth-averaged 2D data were extracted at 30 minute time intervals over the entire study period at 662 nodes within a polygon of approximately 30 km x 40 km.

Data analysis

Atlantic salmon smolts

Time-stamped detection data were filtered to remove spurious records linked to false IDs, and the remaining 123,481 detections relating to salmon were analysed to generate metrics on the following: 1) the timing and duration of salmon post-smolt river emigration; 2) the residency of salmon post-smolts within Wick Bay; 3) the direction of movement of salmon post-smolts after leaving Wick Bay, and 4) the duration and distance travelled by salmon post-smolts within the OWDs.

The last detection of a salmon post-smolt on the outer receiver line in Wick Bay was used to denote the time of successful emigration of into the Moray Firth.

To explore the potential influence of tidal currents on the movement direction of fish leaving Wick Bay, the last detection times of post-smolts on the outer line of receivers in Wick Bay were rounded to the nearest 30 minutes and joined to tidal current data. Multinomial logistic regression was used to test the effect of current speed (m s^{-1}), current bearing and year on the first detection location after leaving Wick Bay (North Line, South Line, “Control Area”, turbine array, or not detected). Model fitting and simplification was performed in R (R Core Team, 2024) using package “nnet” (Venables & Ripley, 2002). Z-scores were used to calculate p-values for coefficients.

The time difference between the first and last detections in the marine array was used to infer the duration that post-smolts spent within the marine array. Durations were compared across years using a Wilcoxon rank sum test.

Detections on the 84 PrePARED receivers along with 3 additional receivers from the North Line and 2 receivers on the South Line which were within 500 m of a turbine were used to indicate when fish were within the OWDs. For salmon post-smolts, time spent in the OWDs was quantified using residence events. Each residence event was defined as a period of detection at the same receiver, during which consecutive detections were separated by time intervals of less than 390 seconds. The detection of the fish at a different receiver marked the start of a new residence event, irrespective of the detection interval. The temporal cut-off was informed by interval analysis which identified that 95% of detection intervals were at the cut off value or lower.

The movement patterns of individual fish within the OWDs were determined from consecutive residence events. The swim bearing (°) and minimum track distance (m) were calculated for each swim path 'step'. In cases where consecutive residence events were separated by 24 h or more (i.e. one day passed without detection), the fish could not reasonably be presumed to have remained in the OWDs. Therefore, track metrics were only calculated within discrete periods where consecutive residence events were temporally separated by less than 24 h. These periods ranged in duration from <1 s to 22.04 h (median 2.54 h) in Y1 and from <1 s to 50.62 h (median 10.53 minutes) in Y2.

Adult sea trout

Detections of sea trout on all receivers in the North and South lines, except those receivers in the North Line that formed part of the "Control Area" hexagon comprising 19 receivers (Y2 only, see above) were excluded from the dataset (9564 from a total of 103706 detections). To exclude atypical movements associated with post-release dispersal behaviours, detections within 30 minutes of release were omitted, leaving 93,780 detections for analysis.

All detection records, along with the depth and temperature profiles from those fish equipped with sensors, were examined for evidence of mortality or predation. Specifically, relevant records were removed from the database if: 1) a continuous detection pattern was observed at the same receiver for >24 h without subsequent movement (i.e. stationary tag, presumed dead); 2) temperature exceeded 30°C, indicating mammalian predation; or 3) depth use was far outside the expected behavioural limits of sea trout (e.g. continuous detections on the sea floor for >24 h), suggesting predation or the scavenging of a dead sea trout by an ectothermic demersal fish. A total of 1308 records from 1 individual in Y2 were omitted.

Durations within the OWDs and control area were quantified using residence events (as above), using 790 seconds as a temporal cut off derived by interval analysis of all marine detections whereby 95% of detection intervals were 790 seconds or less.

A Roaming Index was calculated to quantify exploratory behaviour in the three receiver hexagons (test areas) comprising Beatrice North, Beatrice South and the Control Area. The number of unique receivers visited by each fish in each area per day was divided by the daily

total duration of residence in that area (h), yielding a Roaming Index value for each fish per area per day. Generalised Linear Mixed Models (GLMMs) were used to investigate the effect of potential descriptors ('test area' and 'year') on the response variables 1) Roaming Index, and 2) Total residency in a test area per fish per day. Negative binomial error distributions were used for both response variables, with Fish ID included as a random effect. Stepwise deletions were performed using chi-square tests to identify non-significant terms and to reach the model with lowest Akaike Information Criterion value (Akaike, 1973).

To account for varying seafloor depths across the study area, pressure sensor data along with bathymetric data from the model node (see above) nearest to the detecting receiver were used to calculate swimming depths as a percentage of total water depth.

Detection areas

For clarity, the term 'marine detection area' is used throughout to denote all receivers deployed offshore, while 'within OWDs' refers only to those receivers within the boundaries of the wind farms Beatrice and Moray East.

3. Results

Atlantic salmon smolts

Timing and duration of river emigration

The proportion of tagged smolts that out-migrated from the River Wick was similar in Y1 and Y2 with 88% and 90% reaching Wick harbour, equating to a freshwater loss rate of 1.1% km⁻¹ and 0.9% in Y1 and Y2, respectively. Individuals took a median of 5 days 23h 24 minutes (range 11 h 17 minutes – 15 days 11 h 46 minutes) (Y1) and 4 days 20 h 24 minutes (range 6 h 29 minutes – 25 days 23 h 17 minutes) (Y2) after release to reach Wick harbour.

Temperature and depth (pressure) data (available for Y2 only) suggested that two salmon were preyed on by mammals within Wick harbour. Recorded temperatures rose rapidly from approximately 10°C to in excess of 30°C, concurrent with depth profiles suggesting rapid diving movements (Figure 2).

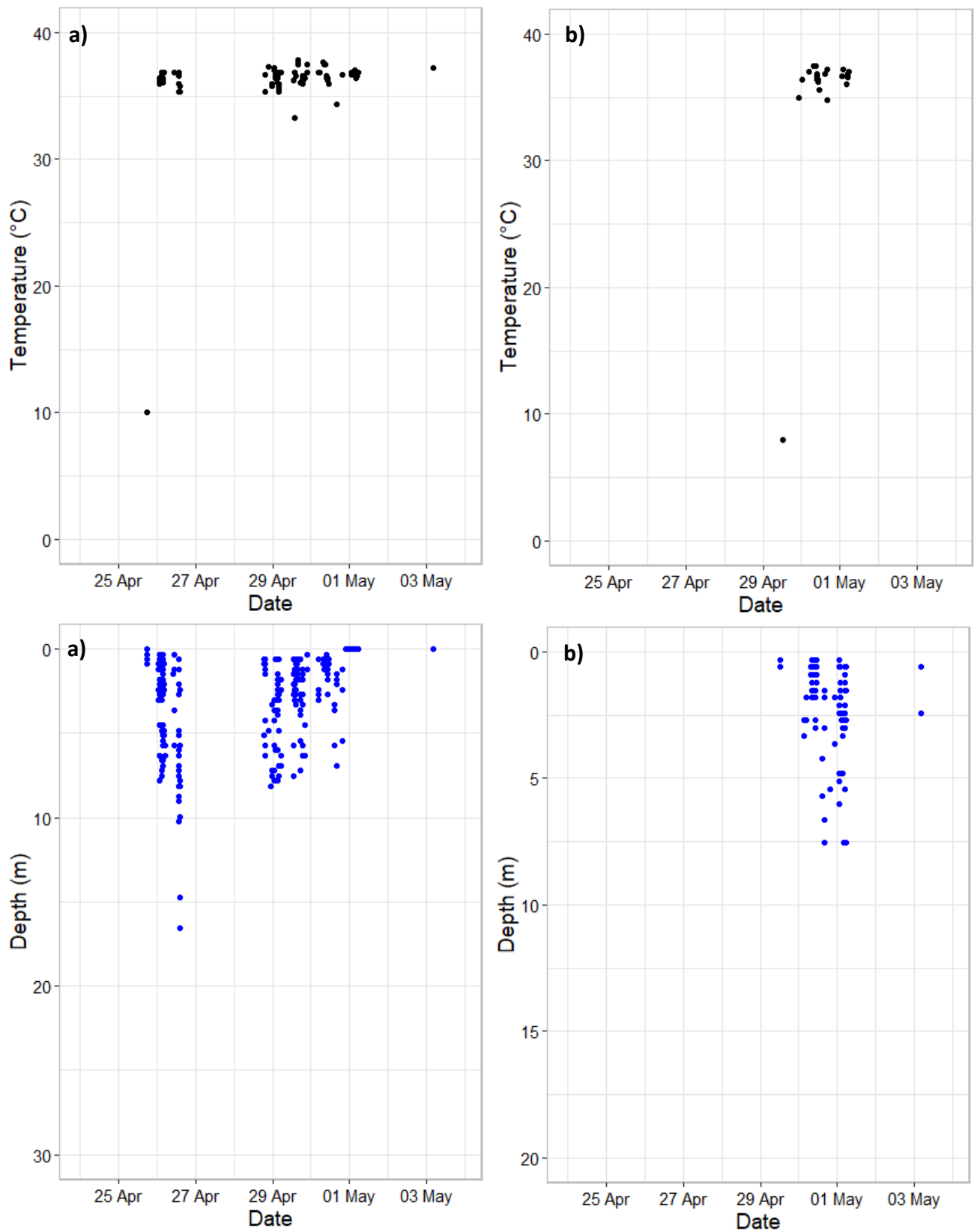


Figure 2 Temperature and depth time series graphs from two salmon post-smolts (a & b) presumed to have been preyed on by a mammalian predator within Wick Harbour in 2024.

A total of 94 post-smolts in Y1 (87%) and 80 post-smolts in Y2 (80%) were assumed to have successfully entered the Moray Firth, having either been detected on the outer line of receivers in Wick Bay (173 individuals) or detected in the marine array after passing through the outer line without detection (1 individual). Most post-smolts passed through Wick Bay without delay, with 95% residing for 24 h or less (Figure 3). Outmigration occurred almost exclusively during darkness with movements predominantly associated with the period from 2100 to 0100 (Figure 4). In Y1, 39 individuals exited on an ebb tide and 55 on a flood tide compared to 37 exiting on an ebb and 42 exiting on a flood tide in Y2 (excluding the one individual for which we do not know the precise time of departure).

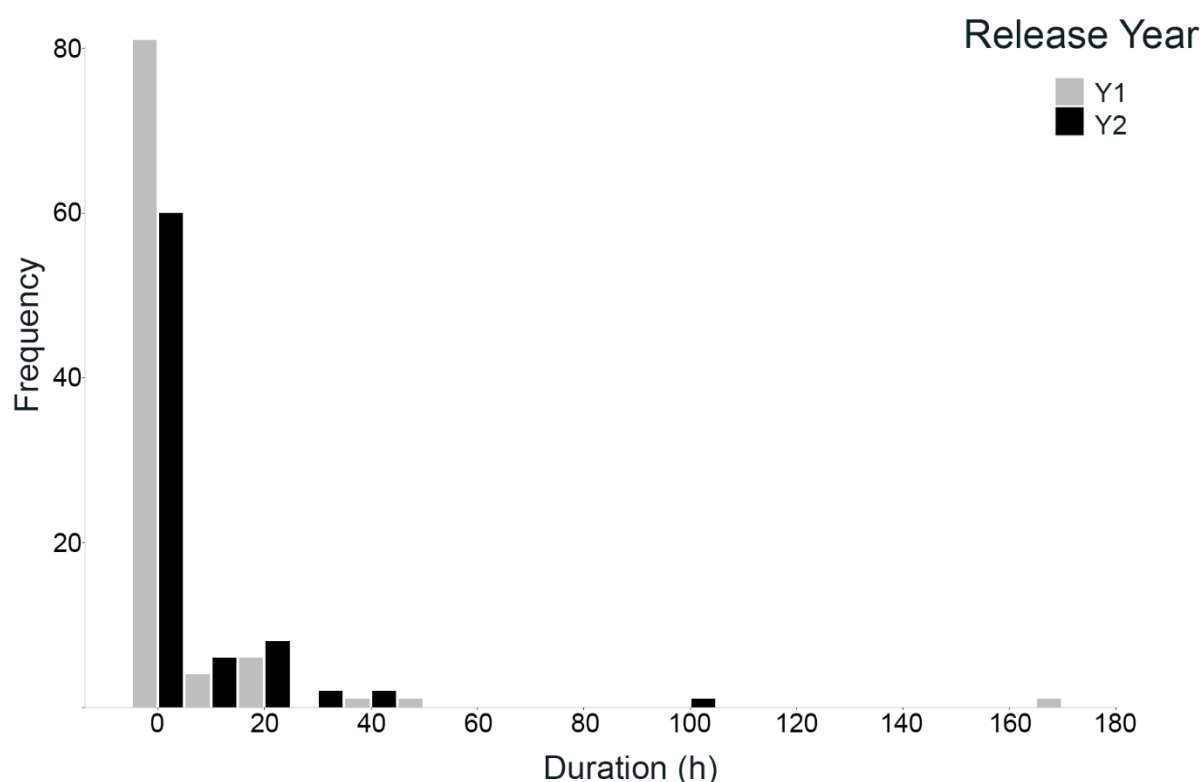


Figure 3 Duration (h) salmon post-smolts spent within Wick harbour and bay before assumed successful emigration to the Moray Firth (denoted by last detection on outer receiver line in Wick Bay) (n = 173)

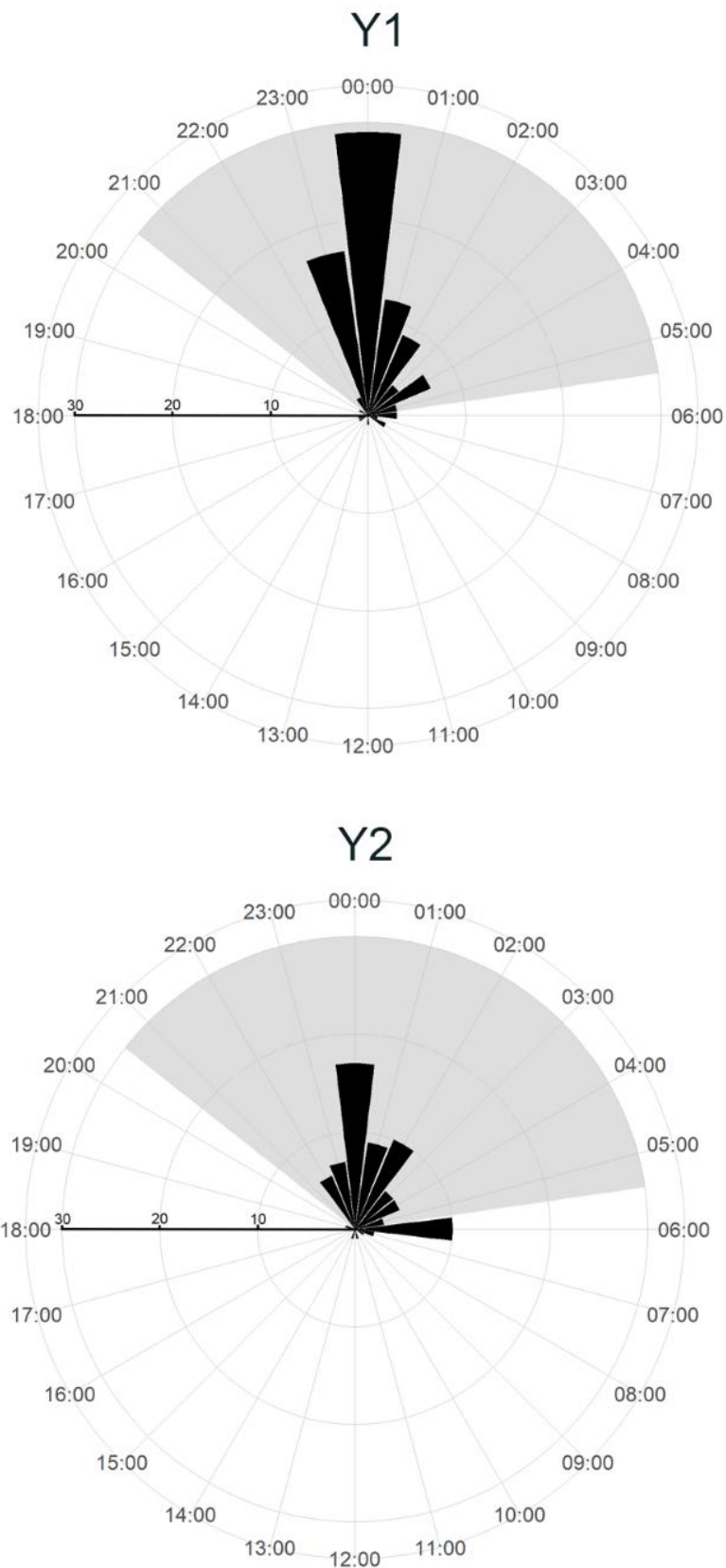


Figure 4 Rose diagrams depicting the time of day at which salmon post-smolts departed Wick Bay and entered the Moray Firth in Y1 (n = 94) and Y2 (n = 79). Grey shading indicates the period between sunset and sunrise.

Marine migration characteristics

A total of 37 emigrating salmon post-smolts in Y1 (39%) and 39 in Y2 (49%) were subsequently detected by the marine receiver array. In both years, most of the first offshore detections were on the North Line of receivers: 51 % in Y1 and 49 % in Y2 compared to 24 % and 10% on the South Line in Y1 and Y2, respectively (Figure 5). The time between emigration into the Moray Firth and first detection in the marine array ranged from 7 h 56 minutes to 5 days 1 h 55 minutes (median 26 h 28 minutes). Neither current speed or bearing at Wick Bay entrance, nor release year, had a significant effect on the location of first detection after leaving Wick Bay.

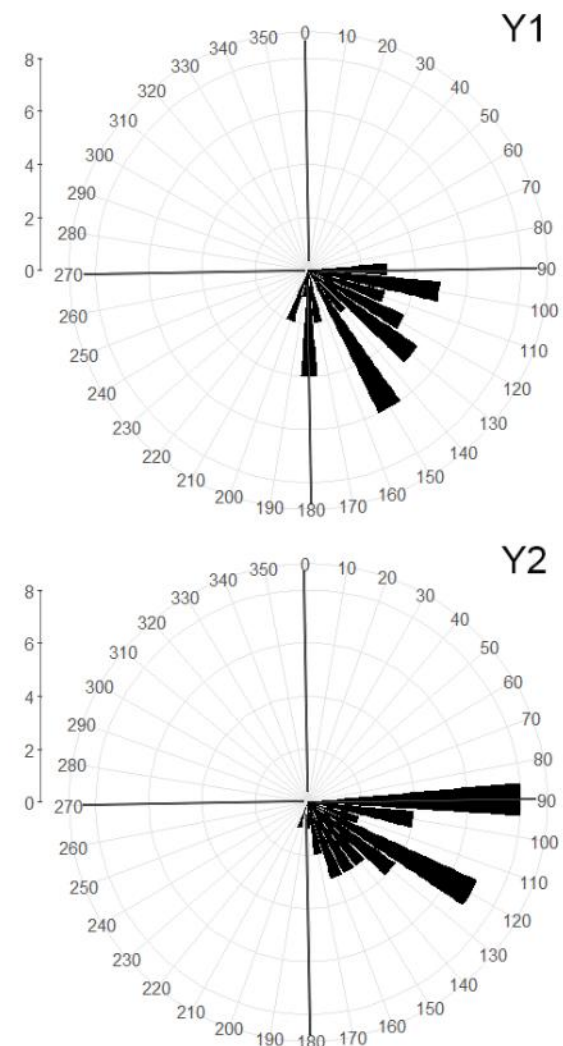
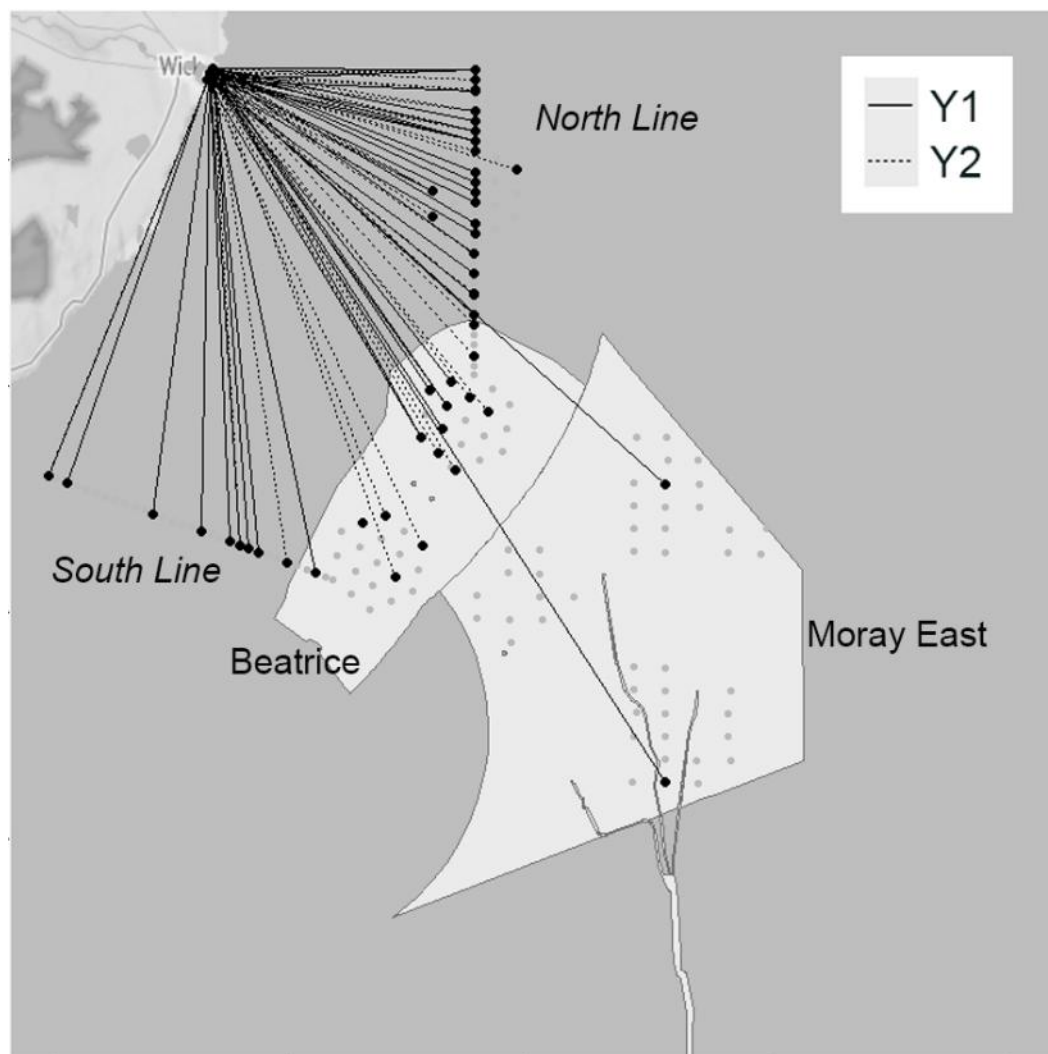


Figure 5 Map (left) and rose diagrams (inset) depicting assumed straight line swim bearings of salmon smolts that departed Wick Bay and were subsequently detected by receivers in the marine array in the Moray Firth in Y1 ($n = 37$) and Y2 ($n = 39$)

The time between the first and last detections in the marine receiver array ranged from 1 s to 7 days 14 h 53 minutes (median 1 h 7 minutes) in Y1 and from 5 minutes 17 s to 6 days 17 h (median 7 h 48 minutes) in Y2. In both years, receivers in the north line detected the highest number of individuals (Figure 6).

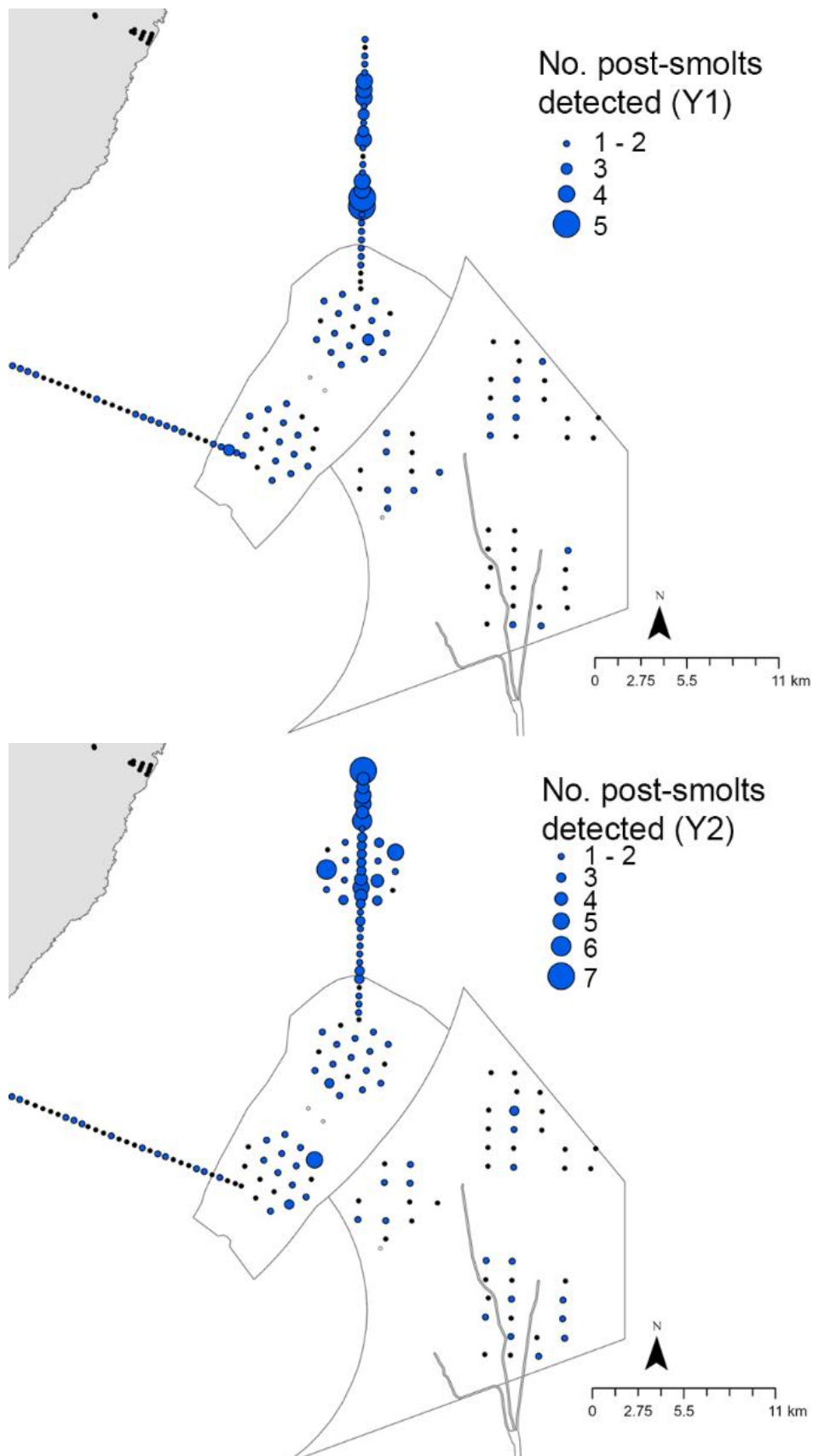


Figure 6 Number of salmon post-smolts detected per receiver within the whole marine array, including the turbine zones of the Beatrice and Moray East offshore wind development sites in Y1 and Y2

Association with offshore wind development sites

Just under half of the post-smolts detected within the marine array were detected within the OWDs; a total of 17 post-smolts in Y1 (46%) and 16 in Y2 (41%), which in both years represented 16% of all smolts tagged. Sixty one percent of those 33 post-smolts were not intercepted by the North Line or South Line, i.e. their first marine detection was within a OWD boundary, mostly within Beatrice. By contrast, most of their last detections were in Moray East (Figure 7).

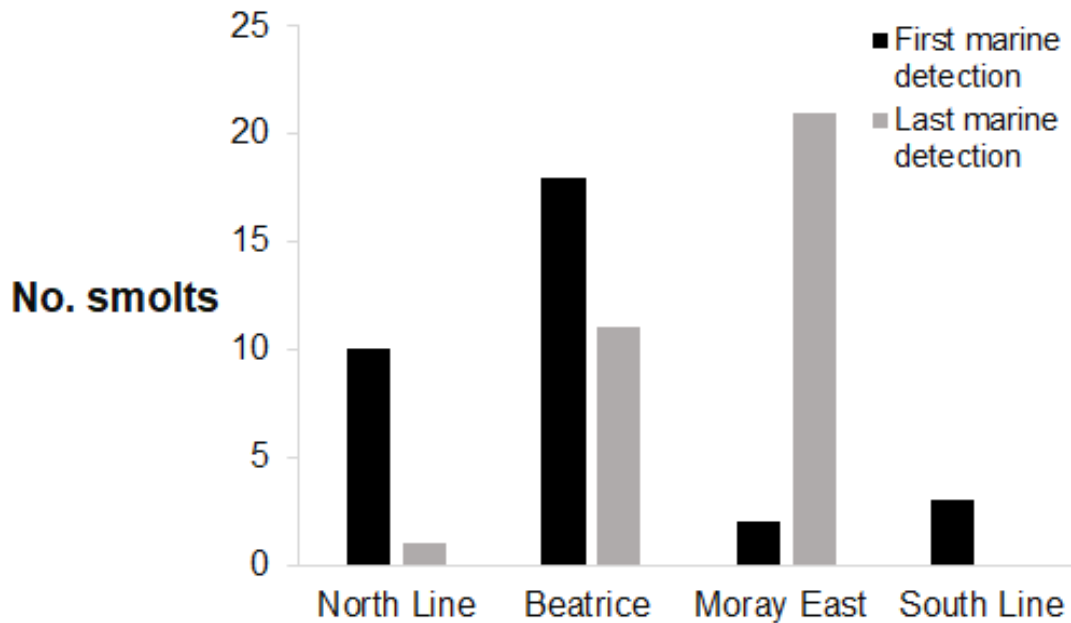


Figure 7 Region of first and last detections within the marine array for the 33 post-smolts which entered the Beatrice and Moray East OWDs (Y1 & Y2 combined)

Post-smolts resided within the OWDs for a *minimum* total duration of between 1 s and 4 h 44 minutes (median 35 minutes 31 s), with no significant difference between years ($W = 128$, $p = 0.79$, $n = 33$). The spatial pattern of residency in the turbine areas indicated longest durations within the Beatrice OWD (Figure 8). Individual residence events lasted from less than 1 s to 2 h 22 minutes, with a median duration of 3 minutes 30 s.

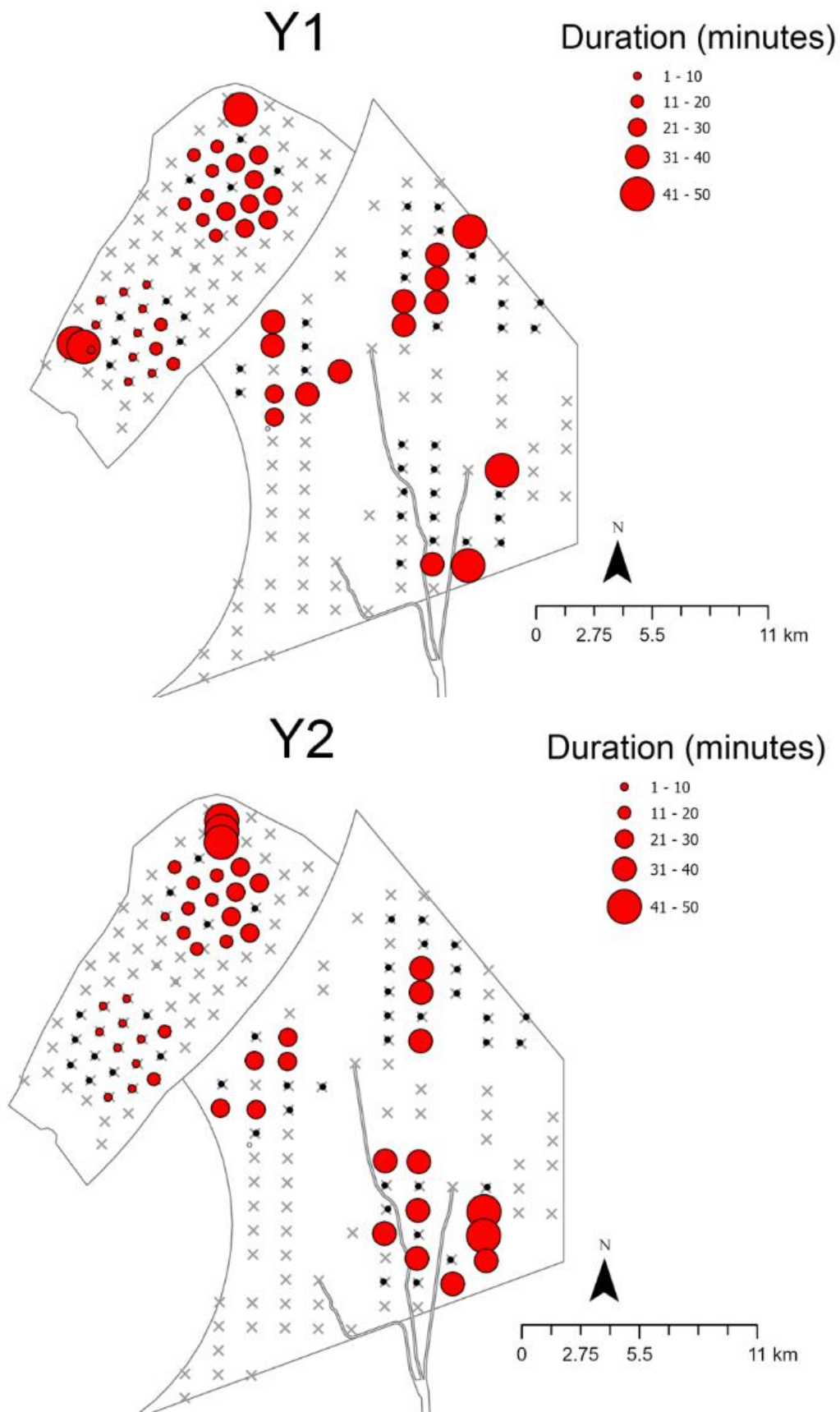


Figure 8 Total duration of residence events of salmon post-smolts within the turbine zones of the Beatrice and Moray East offshore wind developments during Y1 (n = 17) and Y2 (n = 16)

Residency durations determined by summing the duration of individual residence events denotes certain but *minimum* time spent by fish in the OWDs because there was not complete receiver coverage of the turbine arrays, hence fish may have been in the vicinity of the turbines but undetected. The temporal pattern of detections suggests most post-smolts were present within the OWDs for one or two discrete events (Figure 9, Figure 10). The temporal spread of detections was generally longer in Y1 than Y2, spanning a period of 17 days in Y1 and 7 days in Y2.

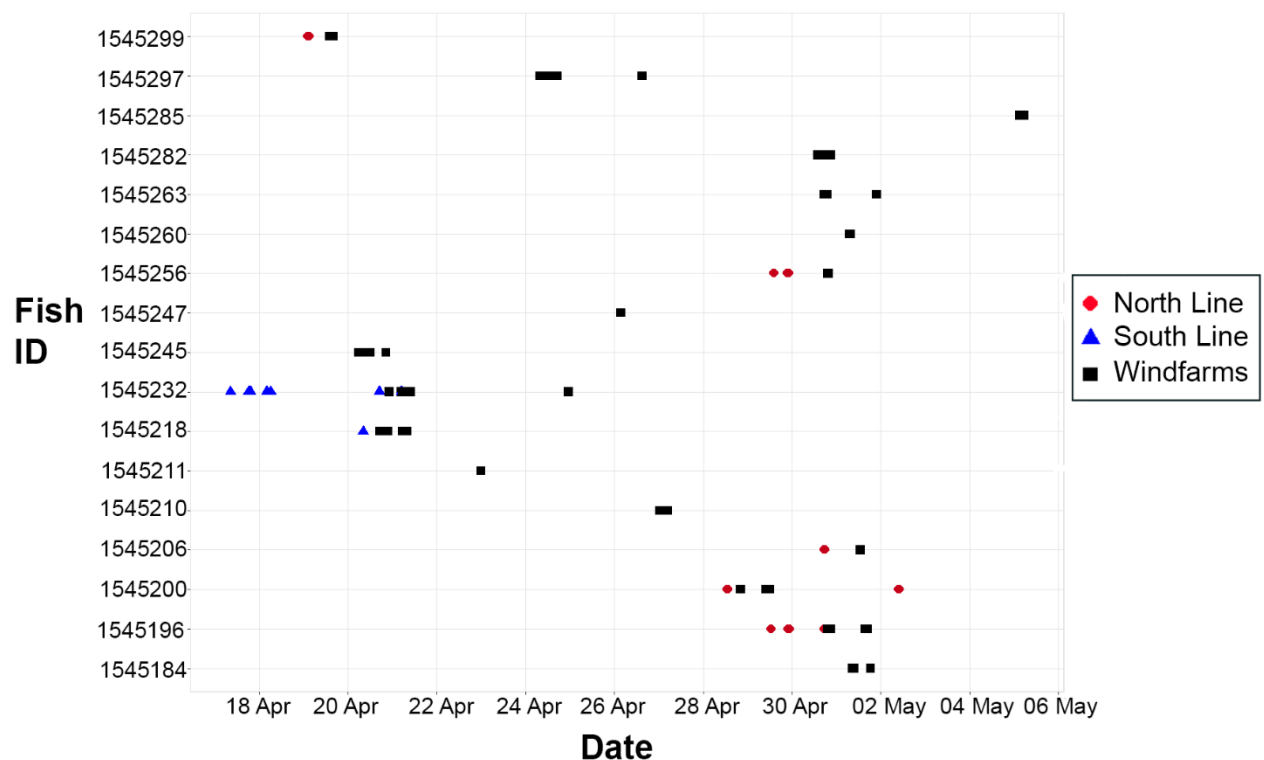


Figure 9 Temporal pattern of detections on the North Line and South Line of receivers and within the Beatrice and Moray East OWDs for post-smolts in Y1 (n = 17) that entered the OWDs during their marine migration.

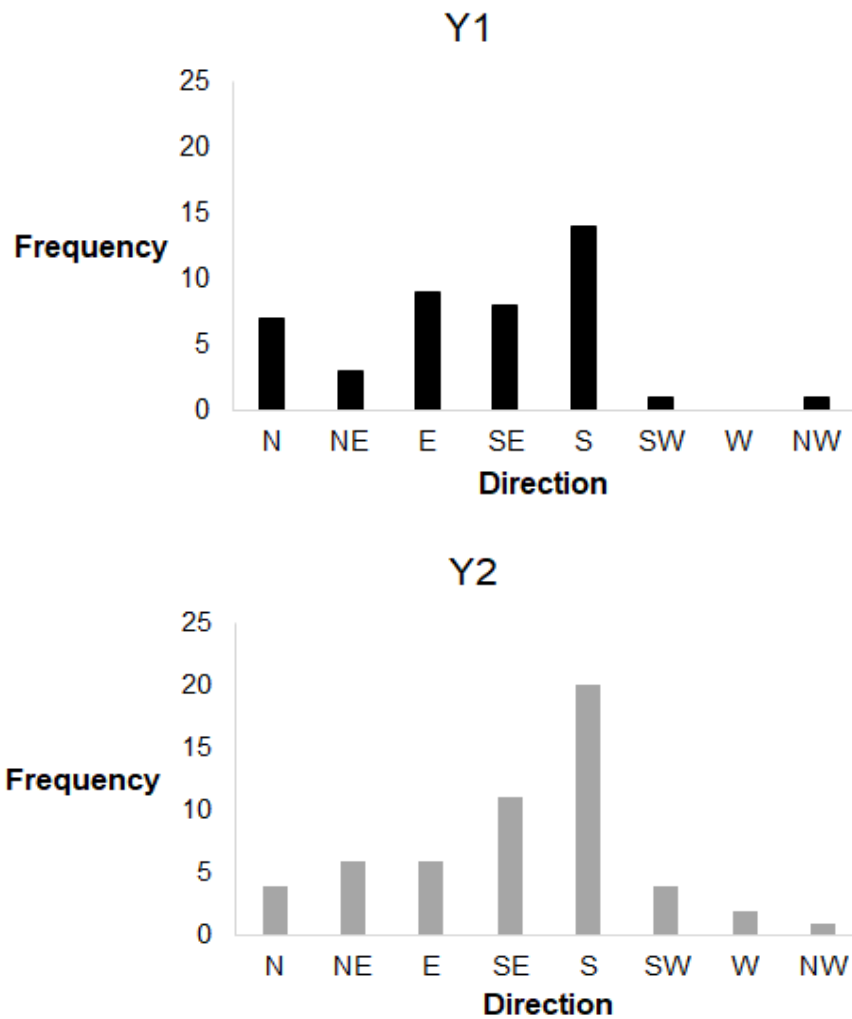


Figure 11 Frequency histograms of compass bearings of swim path steps between consecutive residence events at different receivers in the Beatrice and Moray East OWDs for 14 post-smolts in Y1 (33 steps) and 12 post-smolts in Y2 (57 steps)

The total distance travelled by individual post-smolts within the OWDs ranged from 0.51 to 13.91 km (median 6.82 km) in Y1 and from 1.14 to 45.29 km (median 9.33 km) in Y2 (Figure 12). Individual trajectories were highly variable (Appendix 1).

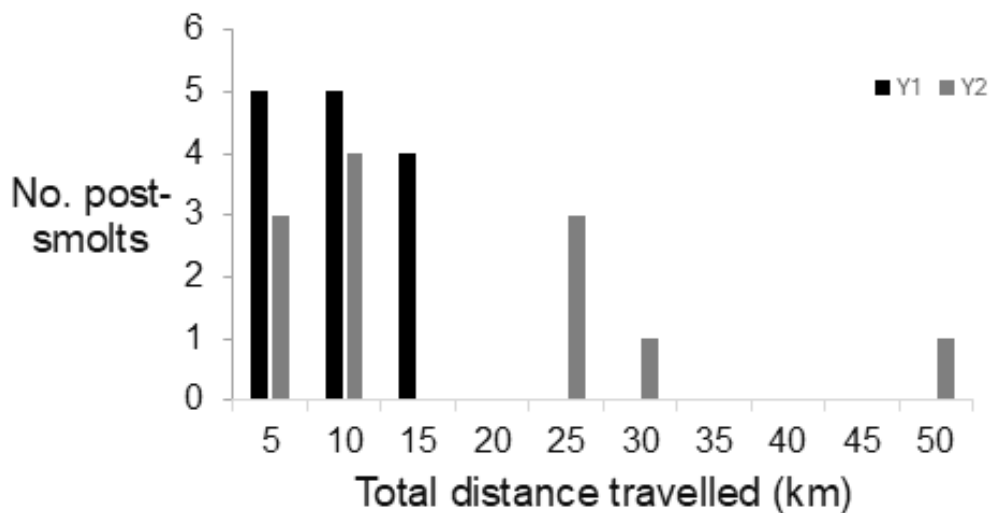


Figure 12 Frequency histogram showing minimum total distance travelled by post-smolts within the Beatrice and Moray East OWDs for 14 post-smolts in Y1 (black bars) and 12 post-smolts in Y2 (grey bars)

Temperature and swimming depth

Of the 30 smolts tagged with transmitters with temperature and pressure sensors (Y2 only), temperature data were recorded from 14 individuals (298 detections) and depth data from 15 individuals (1211 detections) while within the marine receiver array. Recorded temperatures ranged from 7.85 to 10.67°C (mean 8.52 ± 0.43 S.D.) and recorded depths were consistently within the surface layer (range 0–3.31 m) with 98% of values 2.05 m or shallower. The median swimming depth recorded during the day (sunrise to sunset) was 0.30 m (range from 0.0001 to 3.31 m) (681 values from 15 individuals). The median swimming depth recorded during the night (sunset to sunrise) was 0.0001 m (range from 0.0001 to 0.31 m). These data provide no evidence of predation on post-smolts by mammalian predators while within the marine array. Predation by ectothermic predators such as piscivorous fish cannot be ruled out, but depth profiles did not show any sudden rapid changes in depth or use of deeper waters which can be indicative of such predation.

Adult sea trout

Detections from all of the 17 adult sea trout released in Y1, and from 45 of the 52 sea trout released in Y2 were retained within analyses. The overall time difference between the first and last marine detections of individuals ranged from 25 minutes to 17 days 6 h (median 31 h 19 minutes 48 s) in Y1 and from 37 minutes 10 s to 129 days 1 h 12 s (median 2 days 21 h 22 minutes) in Y2. Fish dispersed from their release points and were frequently detected within other parts of the array; 18% and 20% of the last marine detections were in the Moray East OWD in Y1 and Y2, respectively (Figure 13 and Figure 14).

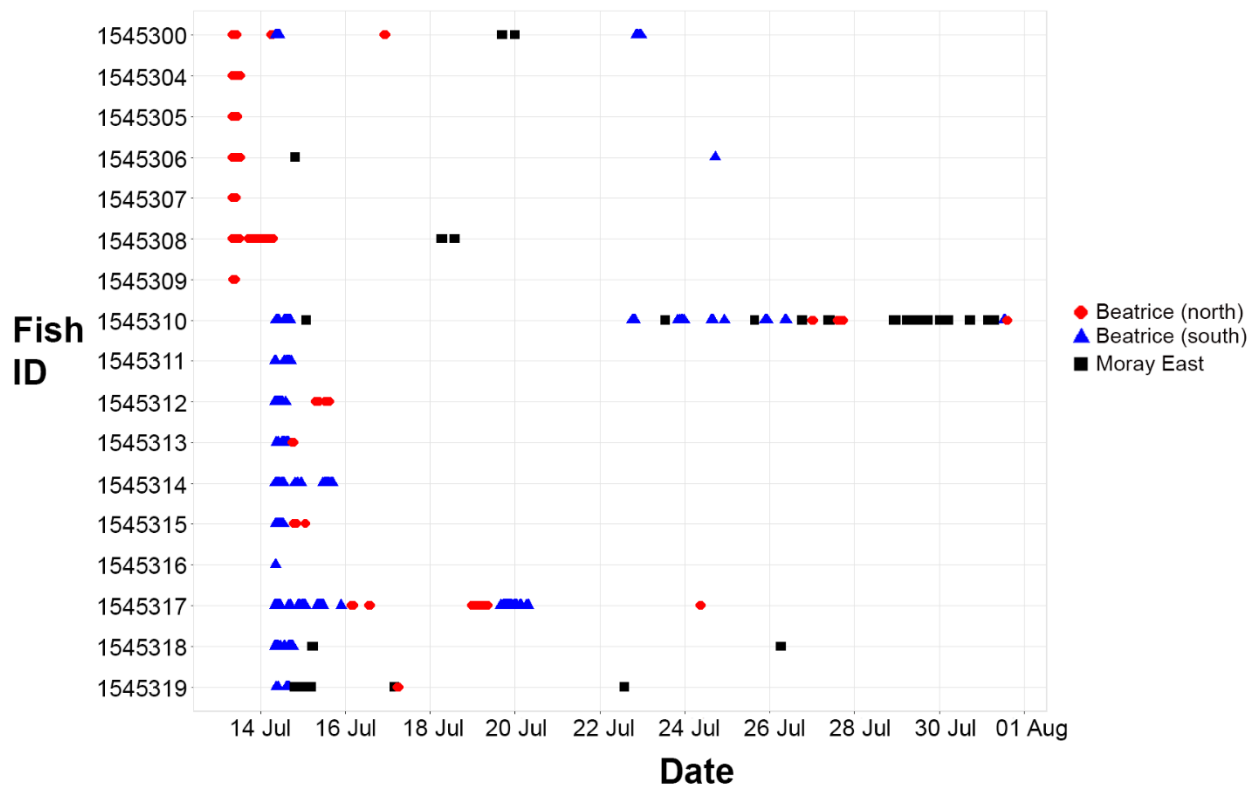


Figure 13 Temporal pattern of marine detections of adult sea trout released in Y1 (n = 17)

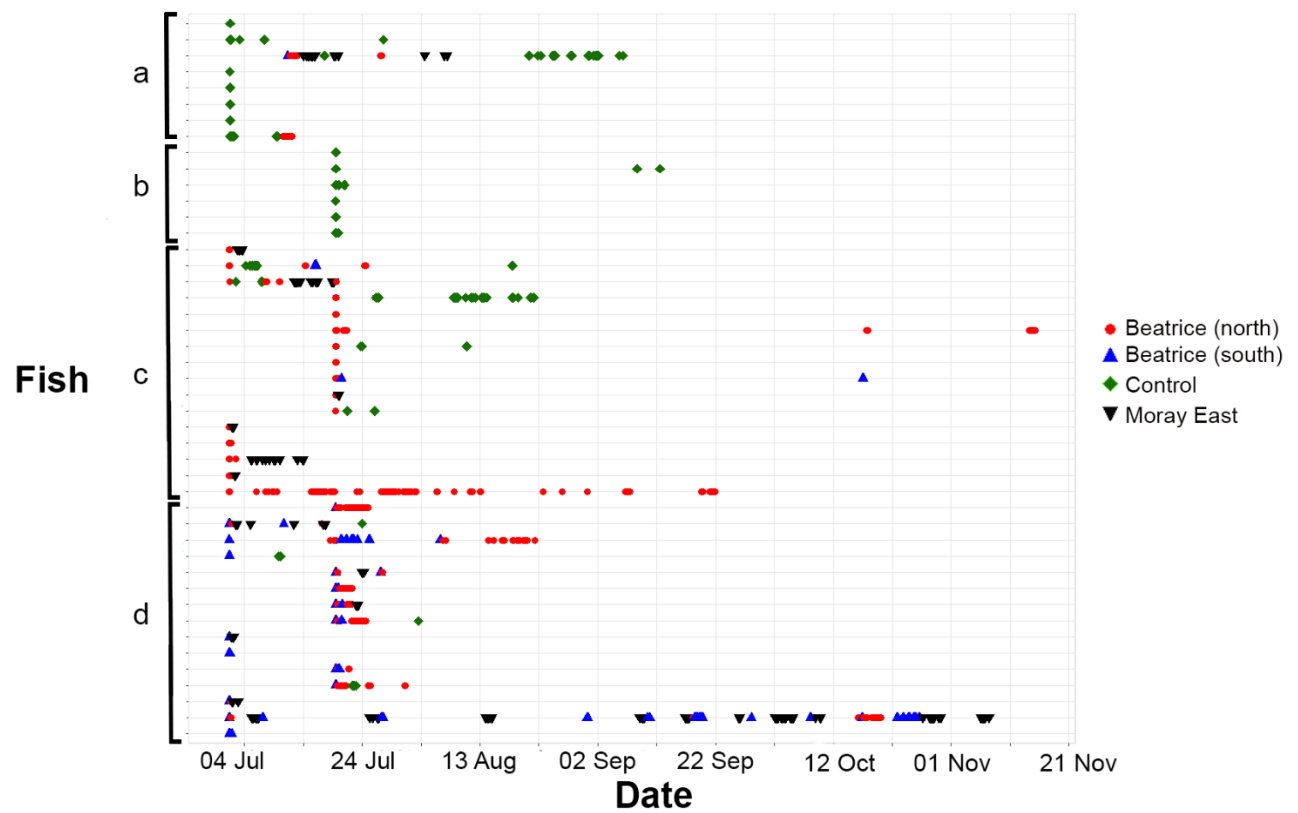


Figure 14 Temporal pattern of marine detections of adult sea trout released in Y2 (n = 45). Each horizontal line denotes an individual fish. Letters indicate the release

location: a – “South of Control Area”; b – “Control Area”; c – Beatrice (North); d – Beatrice (South).

Residency within the offshore wind developments

The total duration of residency events per fish within the OWDs ranged from 25 minutes 8 s to 16 h 36 minutes 36 s (median 3 h 6 minutes) in Y1 and from 10 minutes 41 s to 5 days 14 minutes 24 s (median 5 h) in Y2. The minimum total distance covered during these residencies (track length) ranged from 3.50 km to 201.32 km (median 27.47 km) and from 1.20 km to 384.60 km (median 21.76 km) in Y1 and Y2, respectively.

The longest total durations (all fish combined) were associated with receivers near the release sites in the Beatrice OWD, although there were total durations up to 2h (Y1) and 18 h (Y2) spread throughout the Moray East OWD (Figure 15). The maximum total duration per receiver was 7 h 13 minutes 12 s in Y1 and 49 h 13 minutes 48 s in Y2.

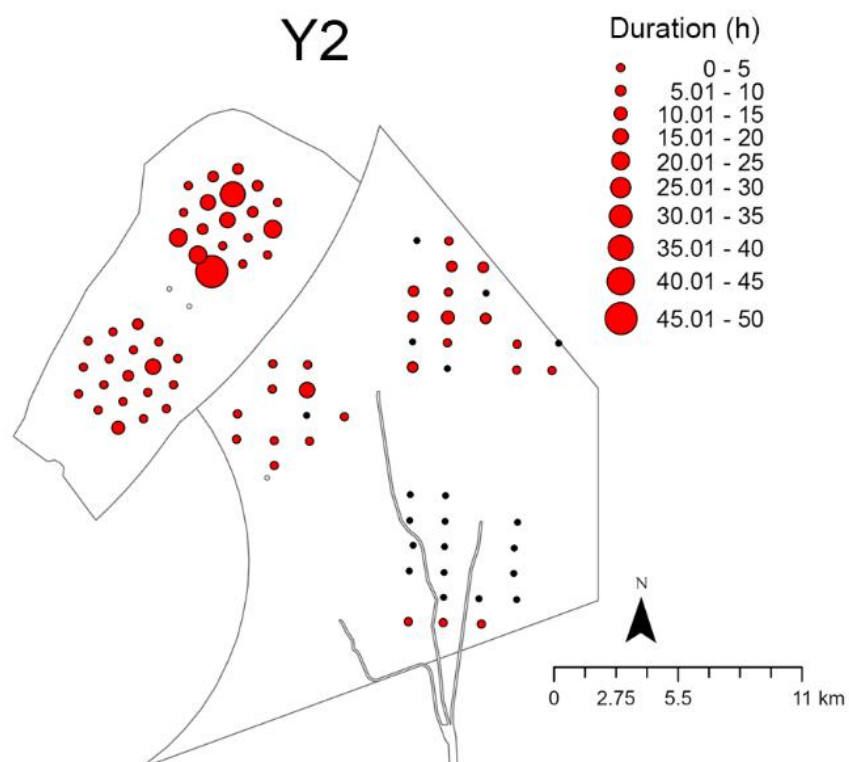
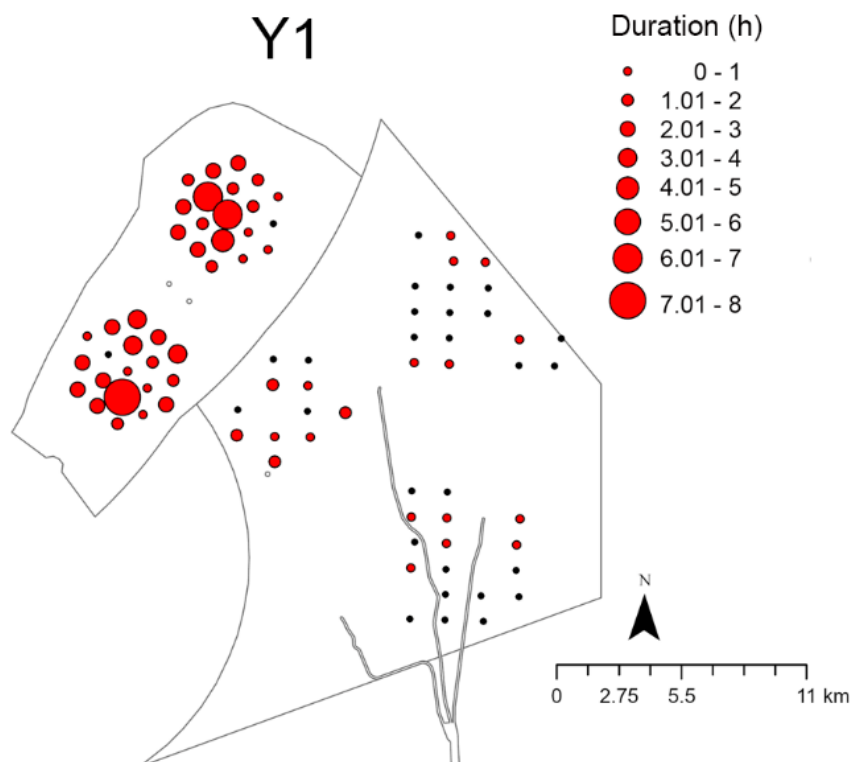


Figure 15 Total duration of residence events of adult sea trout within the turbine zones of the Beatrice and Moray East offshore wind developments during Y1 and Y2

Comparing residency and behaviour in Beatrice OWD and control area

A minimum of 12 sea trout individuals were detected, beyond the 30 minute acclimation cut-off, in each of the three comparable 'test areas' (i.e. identical hexagons of receivers in Beatrice North, Beatrice South and "Control Area", see Figure 2) per year (Table 3).

Table 3 Number of adult sea trout detected in the three test areas (receiver hexagons) per year, irrespective of release location, along with minimum and maximum number of detections and average total residence duration per fish.

Year	Test area	No. ST detected	Minimum no. detections/fish	Maximum no. detections/fish
Y1	Beatrice North	13	21	826
Y1	Beatrice South	12	10	786
Y1	Control Area	NA	-	-
Y2	Beatrice North	29	6	1920
Y2	Beatrice South	18	4	2197
Y2	Control Area	23	3	782

Residence duration in each area per fish per day ranged from less than one second to 8 h 10 minutes 48 s in Y1 and from less than one second to 14 h 40 minutes 48 s in Y2, with no difference between areas (test area explained 0.36% of residual deviance in GLMMs).

A Roaming Index, the average number of stations within an area visited by a fish per hour, used to infer exploratory behaviour, did not vary between test areas for either year. Sea trout in Y2 visited a median of 2.24 and 2.40 stations h^{-1} in Beatrice North and Beatrice South, respectively, compared to a median of 2.90 stations h^{-1} in the control area. Test area was not a significant predictor of Roaming Index, explaining just 0.2% of residual deviance in GLMMs.

Depth use

Swimming depth data which were available for all 17 of the sea trout released in Y1 and 34 of the sea trout released in Y2 showed greatest use of the top 10% and bottom 20% of the

water column with fish tending not to dwell in the central zones (Figure 16, Figure 17). In Y2, sea trout were most frequently detected at in water depths of 40-55 m (Figure 17).

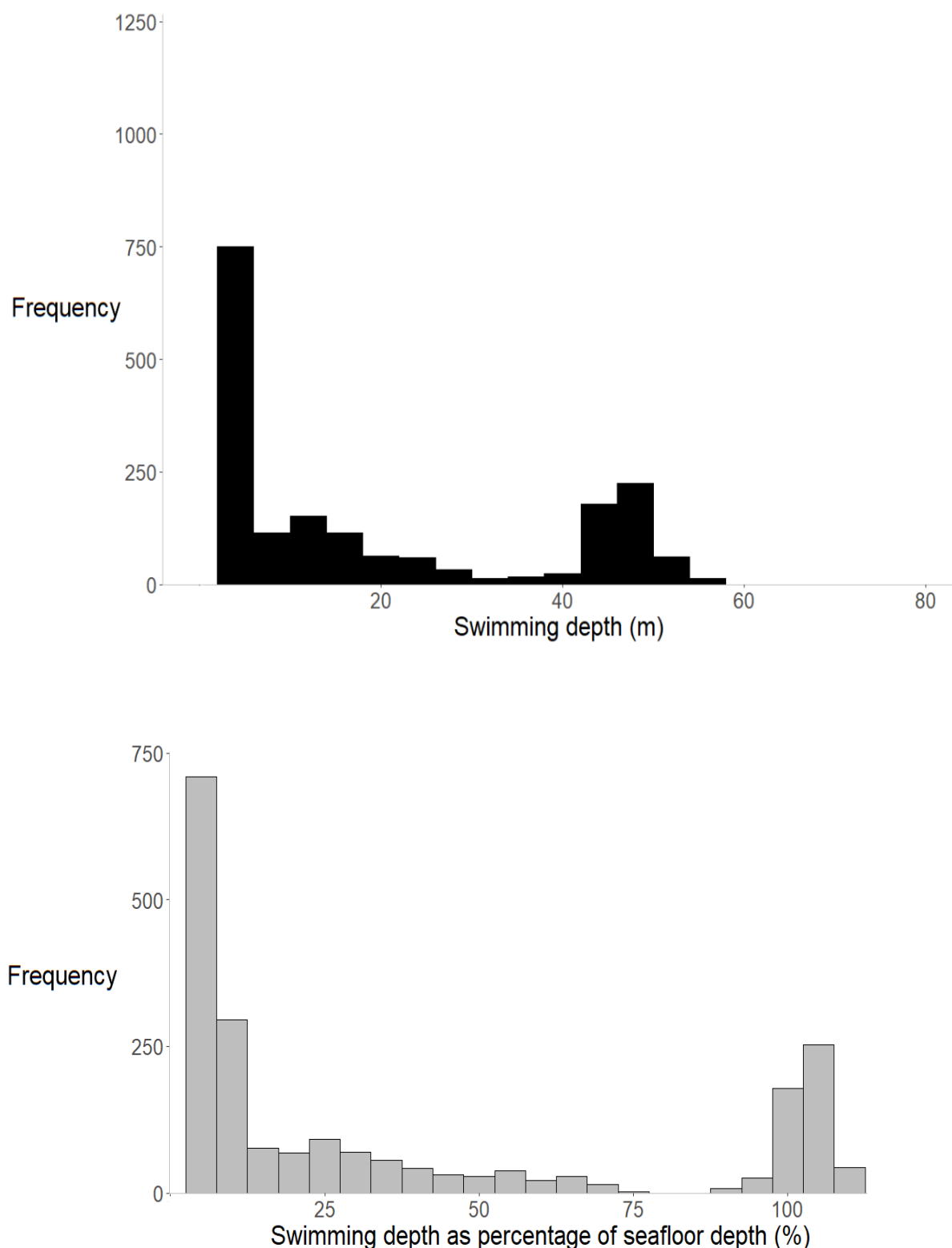


Figure 16 Frequency histograms of swimming depths expressed in m (a) and % of total seafloor depth (b) recorded from 17 adult sea trout released into Beatrice offshore wind development in Y1. Note: some % values exceed 100 due to limitations in the resolution of bathymetric data

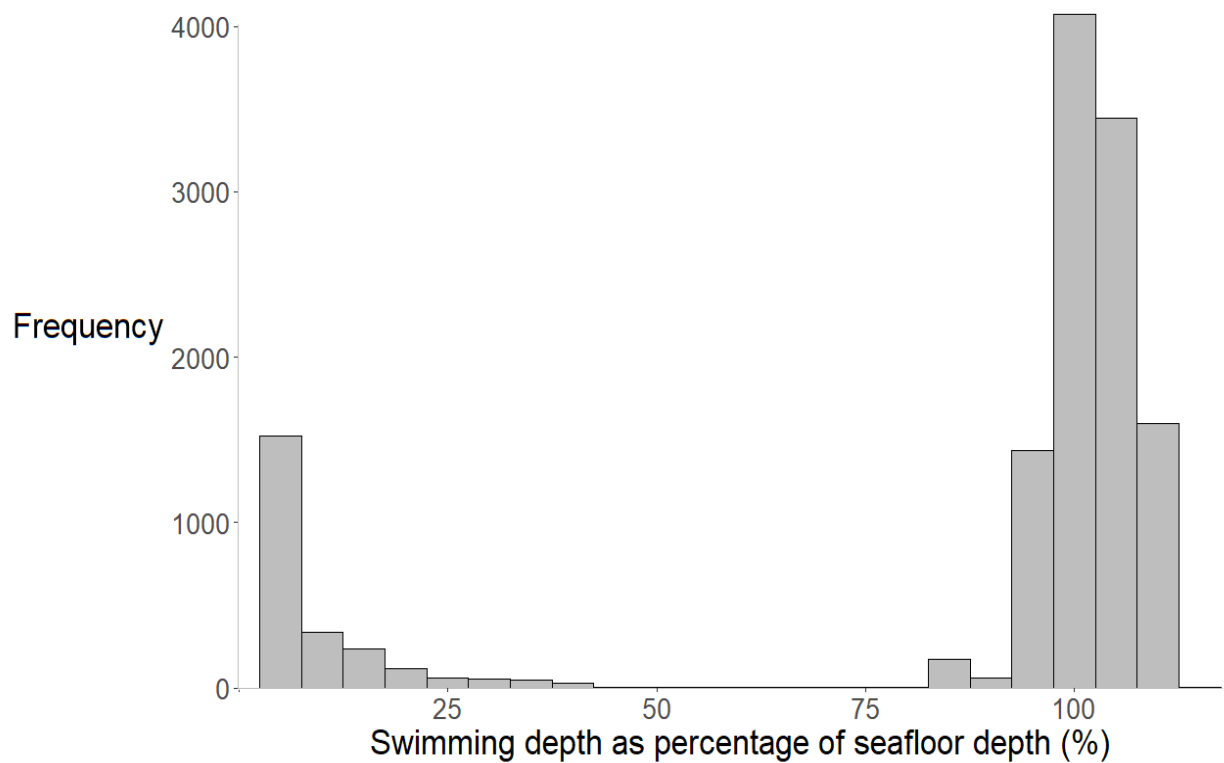
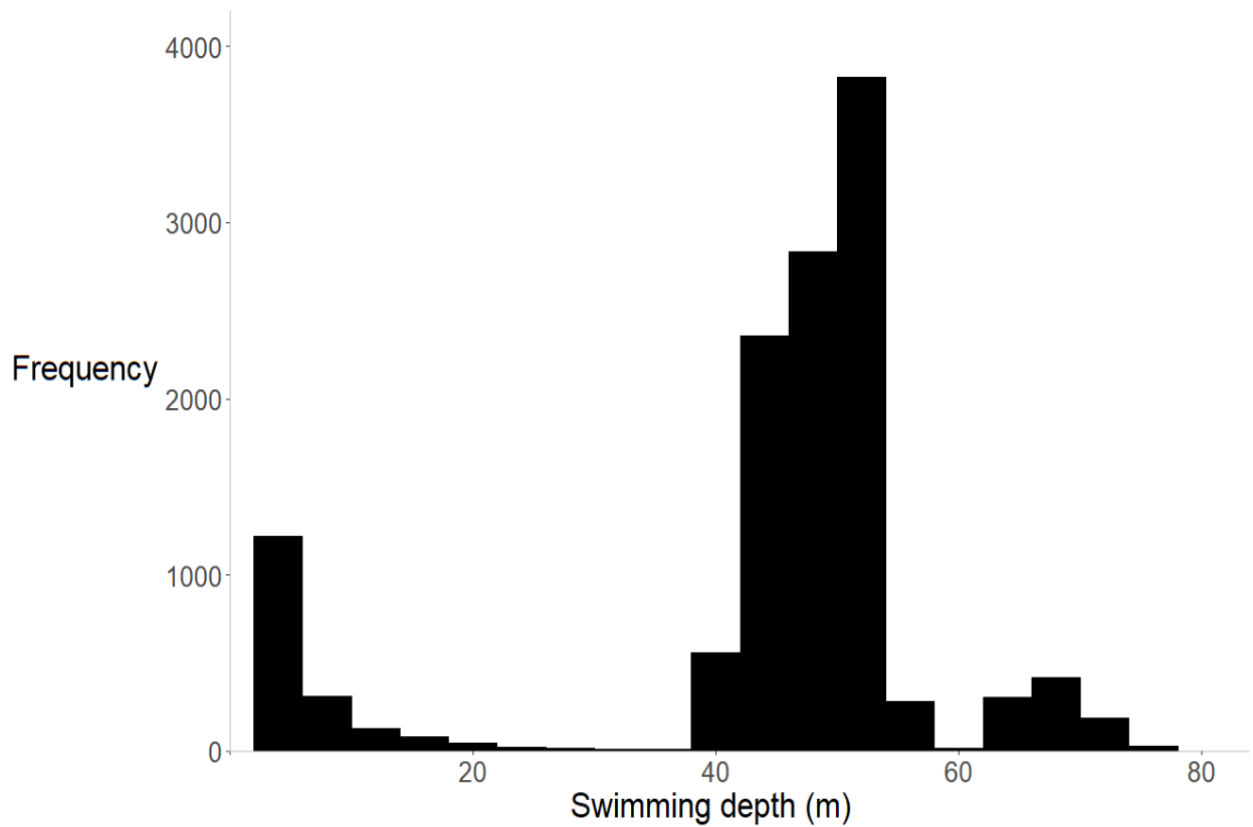


Figure 17 Frequency histograms of swimming depths expressed in m (a) and % of total seafloor depth (b) recorded from 34 adult sea trout released into the Control Area and Beatrice offshore wind development in Y2. Note: some % values exceed 100 due to limitations in the resolution of bathymetric data

Comparison of swimming depth values recorded in both the OWDs (Beatrice and Moray East) with those from the Control Area revealed a similar bimodal distribution (Figure 18). In the OWDs, 75% of recorded depths were at 75% of seafloor depth or deeper compared to 54% of values in the Control Area, suggesting slightly less use of the deepest water depths in the Control Area.

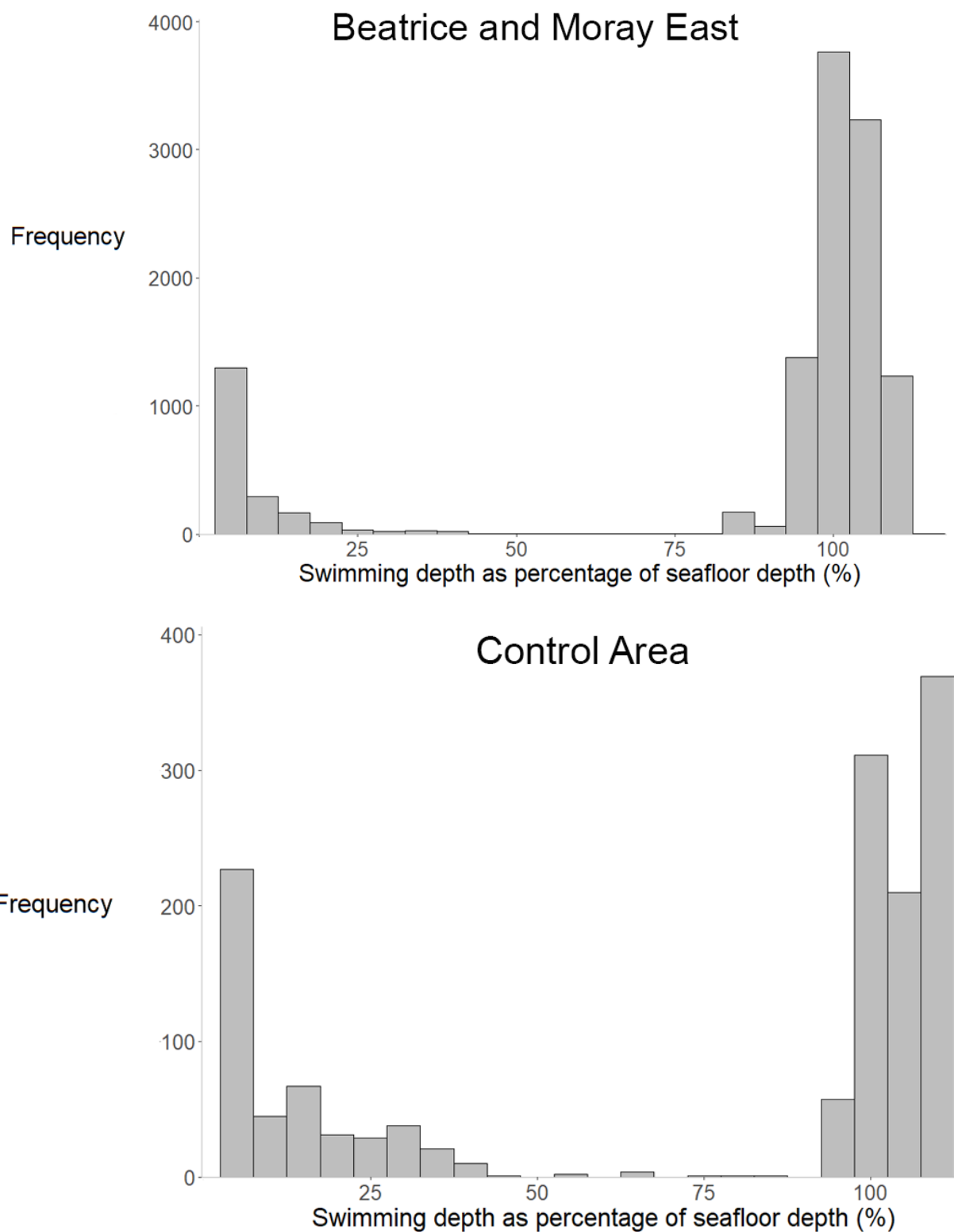


Figure 18 Frequency histograms of swimming depths expressed as % of total seafloor depth recorded from 24 sea trout detected in the Beatrice and Moray East offshore wind developments, and 15 sea trout detected in the Control Area. Note: some % values exceed 100 due to limitations in the resolution of bathymetric data

Due to depth data being collected only at the timestamps when fish were in the detection zone of a receiver, robust reconstruction of individual depth profiles was limited by temporal gaps in the detection record. However, data from a small number of fish with extended periods of near continuous detections provided more detailed insight into the range of behaviours exhibited by sea trout in the current study. These included, for example, repeated dives from the surface to depths of 25 to 30 m, which occurred exclusively during the daytime, with the fish dwelling near the surface overnight (Figure 19). Among several other fish, there was a pattern of fish spending time near the surface (hours or days) before diving to great depth (> 40 m) and remaining there for extended periods i.e. multiple days (Figure 20, Figure 21). Some fish were only detected in surface waters, with the majority of their recorded swim depths within the top 10 m of the water column (Figure 22).

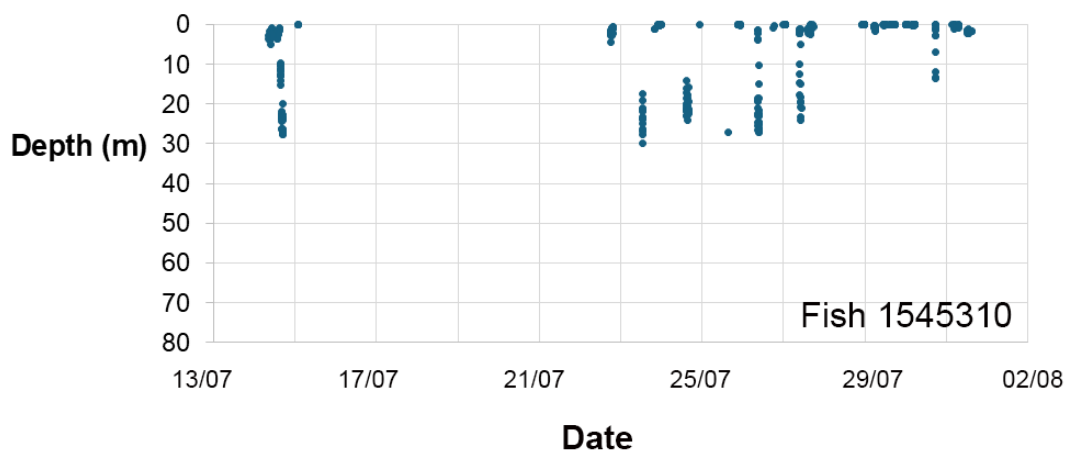


Figure 19 Swimming depth profile of an adult sea trout (Fish 1545310) detected within the marine acoustic receiver array during a period of 18 days in Y1

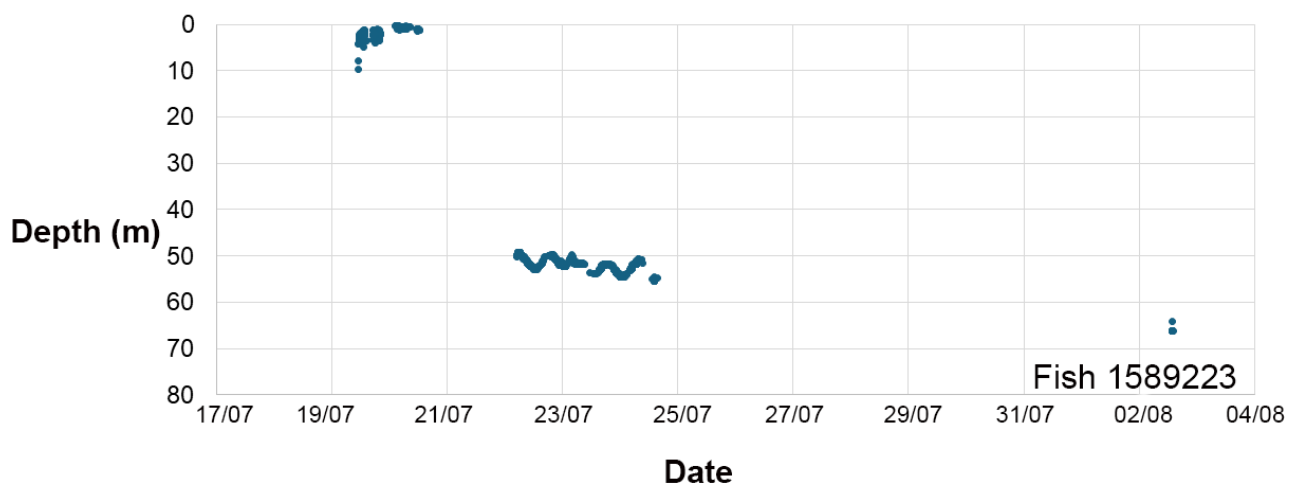


Figure 20 Swimming depth profile of an adult sea trout (Fish 1589223) detected within the marine acoustic receiver array during a period of 15 days in Y2

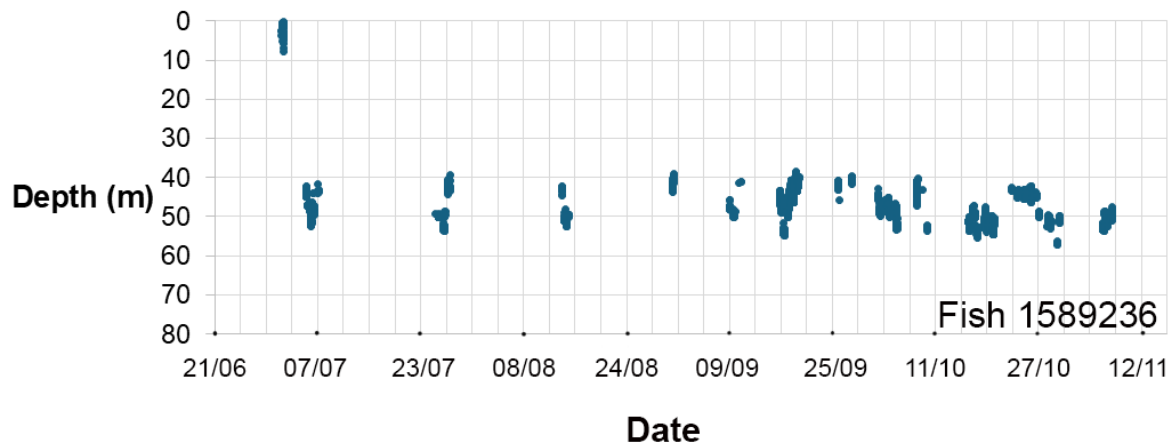


Figure 21 Swimming depth profile of an adult sea trout (Fish 1589236) detected within the marine acoustic receiver array during a period of 4 months and 7 days in Y2

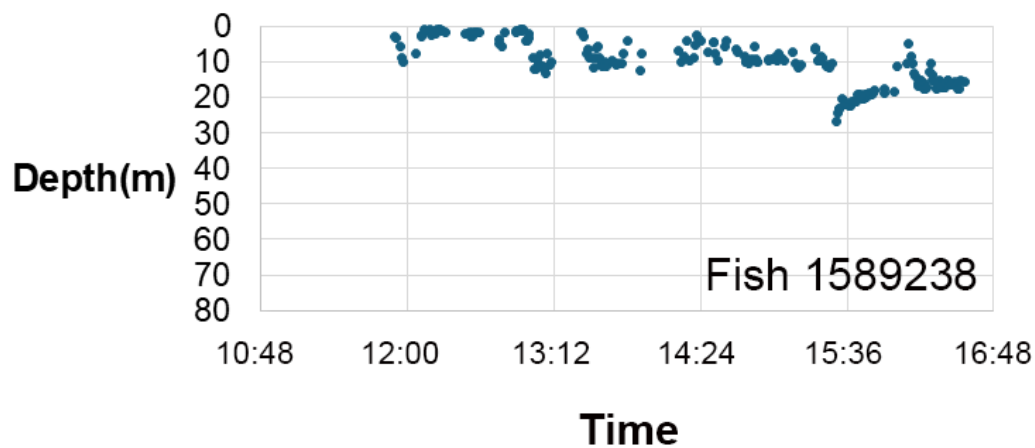


Figure 22 Swimming depth profile of an adult sea trout (Fish 1589238) detected within the marine acoustic receiver array during a period of 4 h on 1st July in Y2

Temperature data

Temperature data recorded by the marine receiver array fell within a narrow range in both Y1 (11.30 – 15.38°C) and Y2 (10.67 – 13.96°C) (Figure 23) and therefore provided no evidence of predation of sea trout by mammals in either year.

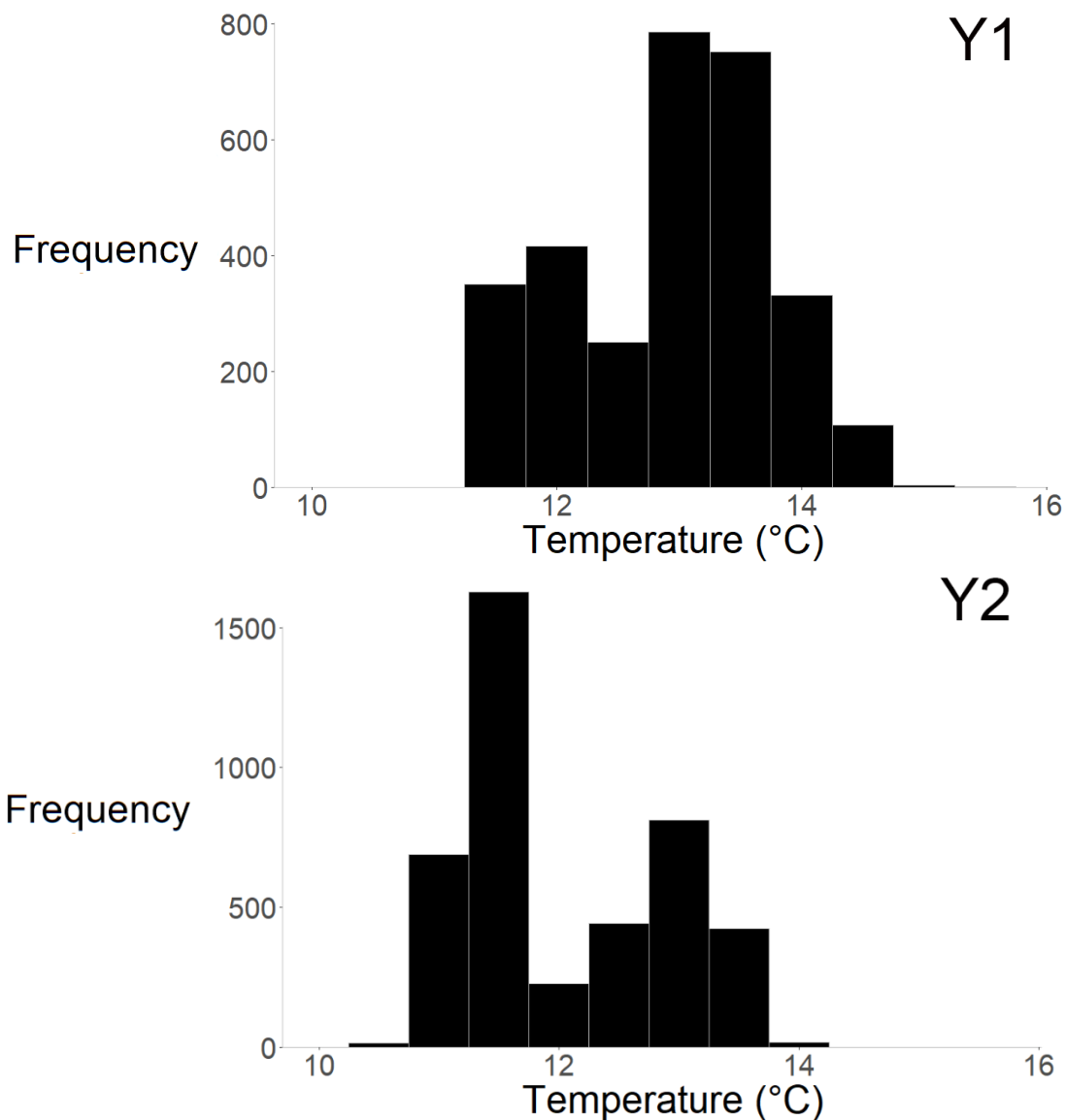


Figure 23 Frequency histograms of temperature data recorded from sea trout detected within the marine receiver array during Y1 (n = 17) and Y2 (n = 34)

4. Discussion

Salmon smolt migration to the marine environment

Successful emigration of salmon post-smolts into the Moray Firth was generally rapid (median ~5 days after release) and showed little inter-annual variation. Given that loss rates during the riverine stage can be high, between 0.3 and 7.0% per km migration distance in river systems (Jepsen et al., 1998; Thorstad et al., 2012), the annual average freshwater loss rate of 1% km⁻¹ in the current study was minimal, and slightly lower than that reported for

the nearby river Conon ($2.2\% \text{ km}^{-1}$) (Newton et al., 2021). However, after leaving freshwater, losses of salmon post-smolts in Y2 increased dramatically. The detection records of 10 individuals ended in Wick Bay, with two clearly preyed on by mammals. The remaining individuals generally moved quickly through this area, entering the Moray Firth during darkness. Previous studies highlighted the role of tidal currents in estuarine transit (Lacroix et al., 2004; Lothian et al., 2018), but the timing of movements through Wick Bay was apparently unrelated to tide, perhaps due to the comparatively small size of this 1.5 km long inlet, beyond which fish access open coastal waters.

Migration path/ bearing

On average, 44% of salmon post-smolts did not head directly north after leaving Wick Bay to take the shortest straight-line route to feeding grounds, but instead swam east, south-east, and to a lesser extent, directly south. While post-smolts that travelled through this first part of the Moray Firth on bearings of 88° through to 204° were intercepted by the marine receiver array with high probability, they may have passed through without detection due to the ≥ 500 m spacing of receivers. Therefore, 44% represents the minimum proportion of smolts taking these easterly to southerly trajectories. It has been suggested that such individuals at some point make a course adjustment and turn north on a trajectory to the Norwegian Sea/Greenland (Main et al., 2022; Ounsley et al., 2020). Directly crossing the North Sea and following the Norwegian Coastal Current north is potentially more energetically efficient than the alternate proposed route whereby smolts follow the coast north then head north-west to enter the Slope Current (Newton et al., 2021). The current findings support the growing evidence that the former is the preferred migration route for a significant proportion of salmon smolts leaving the east coast of Scotland. While smolts migrating along this route may gain an energetic advantage, it brings a greater likelihood of fish passing through one or multiple OWDs.

Post-smolt association with the offshore wind developments

The two operational OWDs investigated within the current study lie to the south-east of the River Wick, with the closest turbines located 19 km south-east from the estuary mouth. The minimum encounter rate of emigrating smolts with these OWDs was highly consistent between study years, with 18 and 20% of smolts that entered the Moray Firth migrated through the turbine zones.

Known residency in the OWDs was of short duration, with post-smolts spending a median of 36 minutes (maximum 5 h) among the turbines. This is what would be expected with transitory movement through the area, and the majority of reconstructed swim paths indeed showed relatively unidirectional movements, predominantly in easterly, southerly and south-easterly directions, resulting in 64% of last detections within Moray East. However, some individuals were in the vicinity of, and potentially in, the OWDs for extended periods: up to 22 h in Y1 and 51 h in Y2. Most acoustic telemetry studies on Atlantic salmon post-smolts in the marine environment have employed receivers configured in lines across

potential migration routes (e.g. Lilly et al., 2024; Rodger et al., 2025). While effective for quantifying migration success and the proportion of individuals using each route, such arrays do not capture more complex movements. Use of the PrePARED grid array in the current study therefore provided a valuable opportunity to detect multi-directional movements and recurrent behaviour among migrating post-smolts, and these were apparent in the reconstructed swim paths of three individual fish. It was not possible to determine whether such movements were in response to factors associated with the OWDs in particular or simply reflected natural migration behaviour. Either way, these convoluted swim paths inevitably increased the exposure time of the post-smolts to the OWDs and resulted in long trajectories within the turbine zones; over 45 km in one case.

One area of concern about OWD impact pathways on diadromous fish is the potential for enhanced predation rate due to the aggregation of predators around scour protection, fixed pile and foundation tower structures (Bicknell, Gierhart, Newton, et al., 2025). Deducing possible predation events, and indeed any mortality, from acoustic telemetry data is an often overlooked yet important consideration due to the risk of introducing bias into data interpretation, particularly when inferring behaviours (Klinard & Matley, 2020). The use of depth and temperature sensors in Y2 of the current study provided valuable insight in this regard, with no evidence of predation events among the component of salmon post-smolts with sensors that were tracked in the marine array. There are, however, limitations to these data. Predation may have occurred undetected, for example, by avian predators targeting the shallow swimming post-smolts during which the tag would likely be ingested and subsequently undetectable as the bird flies away, or by other ectothermic fish with swim speeds and depths not atypical of the smolts themselves. Where depth and temperature data were not available, the deduction of possible predation events relied solely on the examination of reconstructed swim paths, looking for erratic behaviours and unusually fast swimming speed, which is inherently less reliable, particularly when using an array in which receiver spacings greatly exceed detection distance. Therefore, while the current study provided no indication of heightened predation on post-smolts within the OWDs, this topic warrants further investigation, ideally employing the emerging technologies such as prey-to-predator switching tags specifically designed to address questions about predation (Jacoby & Piper, 2025; Lennox et al., 2023).

Sea trout association with the offshore wind developments

Translocation of tagged adult sea trout into the centre of the two turbine zones in Beatrice and into the “Control Area” provided an opportunity to study the movements and behaviour of a statistically robust number of individuals within the marine environment. Although on average fish appeared to disperse outside of the receiver array within a few days and did not return, a substantial proportion of individuals in both Y1 (35%) and Y2 (42%) persisted in the area for over a week and re-entered the detection zones multiple times; one individual revisited this zone over 4 months after its first detection. While these often complex detection records provided valuable behavioural insights and demonstrated the value of this

novel approach, it is important to acknowledge the inherent compromises associated with the translocation approach i.e. additional fish handling, transportation and acclimation between capture and release locations. Capture in a nearby marine aggregation site (Wester sea pools and bay), where fish were in saline water and had been using marine habitats (evidenced by the presence of sea lice on most individuals), followed by the slow acclimation between capture site water and release site water during the boat transportation were seen as biologically reasonable and pragmatic approaches to obtaining large amounts of behavioural data from a greater number of individuals than could have reasonably been expected if relying on in-site capture of study animals around the open water marine study site (OWDs).

Sea trout have been shown to exhibit high variation in their use of marine waters (Eldøy et al., 2015; Nevoux et al., 2019; Thorstad et al., 2016). Although they predominantly remain in coastal areas rather than travelling to distant feeding grounds offshore, long-distance migrations in the order of 100s of kilometres are not uncommon (Bekkevold, et al 2020; Birnie-Gauvin et al., 2019). Recent studies employing Data Storage Tags (DSTs) also suggest that sea trout make much greater use of deep water while in the marine environment than previously thought; a behaviour that the authors postulated was likely exploiting food resources (Artero et al., 2025; Kristensen et al., 2019). Depth data from the current study strongly support this, with over half of recorded depths at 40 m or greater. The deep diving behaviour of sea trout kelts has also been linked to using deeper water as a thermal refuge during warmer periods (Eldøy et al., 2017; Kristensen et al., 2018). Sea trout dwelling predominantly at the surface and making regular dives to around 20 m is commonly described in the literature and considered to be the result of fish foraging activity and the avoidance of the surface layers during the brightest daylight hours to reduce predation risk (Artero et al., 2025; Kristensen et al., 2018; Rikardsen et al., 2007). This behaviour was observed in the current study, but more prevalent was a tendency to dive to 40-60 m depth, often close to the sea floor, and remain there for extended periods, sometimes several days. Importantly, depth use characteristics in the OWDs were not demonstrably different from those in the “Control Area”, suggesting that fish were unlikely to be adopting this deep diving behaviour in response to the turbine structures and the potential increase of predation events associated with wind farm infrastructure.

Reduced marine survival is implicated as one cause of the decline in sea trout populations observed worldwide (Butler & Walker, 2007; ICES, 2013). As for salmon post-smolts, there is concern that sea trout could be the subject of heightened predation within the OWDs due to potential predator ‘hotspots’ among the structures. Conversely, sea trout are themselves predators of smaller fish and crustaceans (Knutsen et al., 2001; Rikardsen et al., 2006), which can be abundant in the artificial reefs created by OWDs (Svendsen et al., 2022 and references therein). The avoidance of predators in the first instance, or the attraction to rich foraging in the second, may be expected to have influenced the residency patterns and activities of the tagged sea trout. The results showed no difference in residency duration between Beatrice OWD and the Control Area, nor any difference in exploratory activity. Of

the 62 adult sea trout with sufficient detection records to analyse, there was one presumed predation event, which was due to an ectothermic predator; no predation by mammals was detected. In the absence of consistent depth and temperature recording, such as that provided by DSTs, there is an inherent risk of predation bias, and it cannot be ruled out that some detections denote the movements of predators rather than sea trout. Ingested tags are usually expelled after a few days (Kristensen et al., 2019), but this can be substantially longer, up to 34 days for shark species for example (Brunnschweiler, 2009). Thorough examination of depth and temperature data in the context of reconstructed spatial movements rendered the risk of predation bias low for fish with relatively numerous detections; for fish with relatively few detections or detections with large temporal spread, the risk was increased. Accepting these limitations, data were of sufficient quantity and resolution to conclude that while predation of sea trout was observed, it was not widespread among study animals.

5. Conclusions

Given the current and projected rapid growth of offshore wind developments around the coast of Scotland, predicting possible encounter rates and understanding the potential effects of wind turbines on salmonids as they undertake their post-smolt and adult migrations is imperative to inform Environmental Impact Assessments and contribute to the conservation of these imperilled species.

By employing acoustic telemetry to track the movements and behaviours of Atlantic salmon post-smolts and adult sea trout in the Moray Firth, this study showed that almost half (44%) of salmon post-smolts emigrating from Wick Bay did not follow a northerly direction that would represent the logical 'shortest route' route to their northerly feeding grounds but instead initially travelled east, south-east or south. A total of 19% of salmon post-smolts undertook routes that passed within 500 m of turbines. This represents a minimum passage rate through the OWDs studied because only 48% of turbines were associated with a receiver station. Most salmon post-smolts exhibited fairly direct movement paths through the OWDs, on average residing for less than 1 h. However, a component of study group showed migration paths contrary to the hypothesis of rapid transit through the Moray Firth during emigration, thus increasing potential exposure to turbine areas.

Adult sea trout translocated into an operational OWD and nearby "Control Area" outside of the OWD remained close to the turbines for a *minimum* average duration of 4.2 h, with 40% making multiple re-entries to the area over a period of one week or more. Fish exhibited frequent diving behaviour and extensive use of deep waters, with over 50% of detections recorded at 40 m depth or greater. No differences were detected in adult sea trout behaviour and residency while in the OWD compared to the "Control Area".

While it is acknowledged that inherent limitations of the detection array and tracking technology reduce certainty about the fate of a small number of individuals, there was no evidence to indicate that either salmon post-smolts or adult sea trout were subject to high levels of marine predation within the OWDs or the wider study area.

Given the extended and complex association with turbine areas observed for the first time in salmon post-smolts and adult sea trout, greater consideration needs to be given to the possible postulated negative effects that may arise in wind energy generation sites, including predation hotspots, sound and vibration, visual cues, and electromagnetic zones. The findings of this study highlight the potential for multiple and extended exposure periods. This needs to be considered in future research in the context of possible cumulative effects from exposure among fish populations encountering multiple OWDs; as may result from the realisation of consented and in construction wind farm developments, in addition to those already in operation. Further, dense grid arrays of acoustic receivers that permit continuous tracking of individuals within OWDs would provide the opportunity to expand on the possible drivers of complex migration paths, such as those observed both in salmon post-smolts and adult sea trout in the current study.

Acknowledgments

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Compliance with Ethical Standards

Fish capture was conducted under licence from the Marine Directorate. Fish tagging and translocation were carried out in compliance with UK Home Office regulations and were subject to approval by the Zoological Society of London Ethics Committee.

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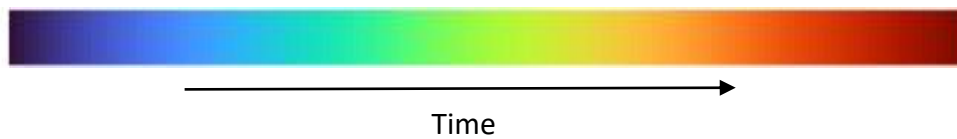
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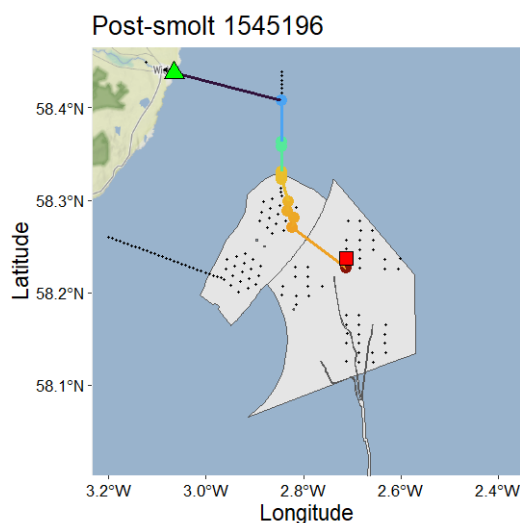
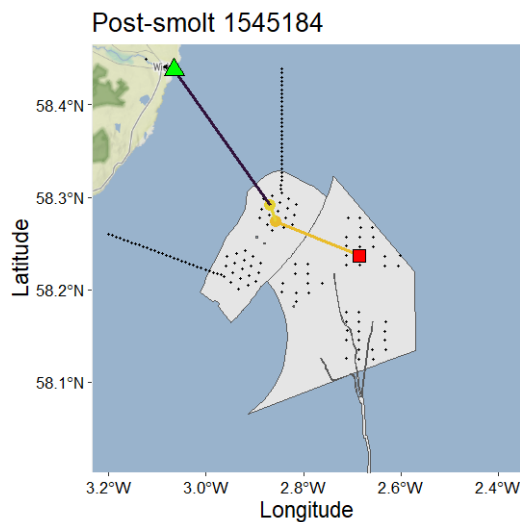
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Appendix 1 Individual reconstructed swim path trajectories (assumed straight lines between consecutive detection locations) of post-smolts that interacted with the Beatrice and Moray East offshore wind developments

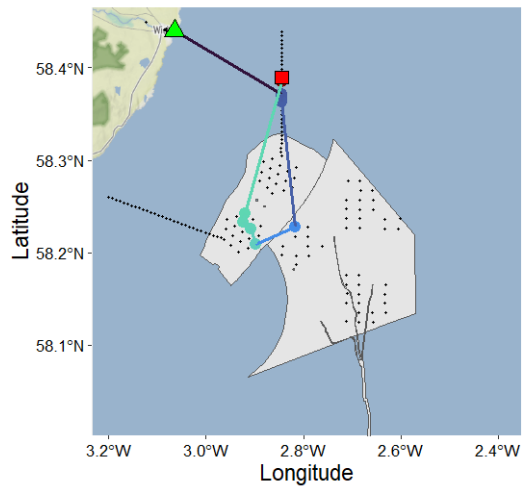
The green triangle and red square depict the start and end, respectively, of the marine swim path. Coloured lines depict swim path steps between the coloured circles which depict locations of detection. Colours reflect passing time, along the following colour gradient:



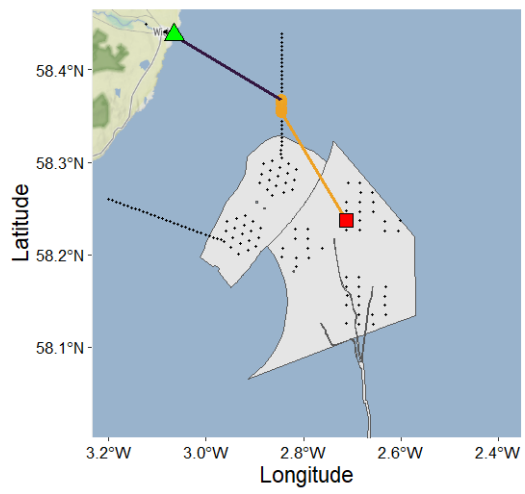
Year 1 (n = 17)



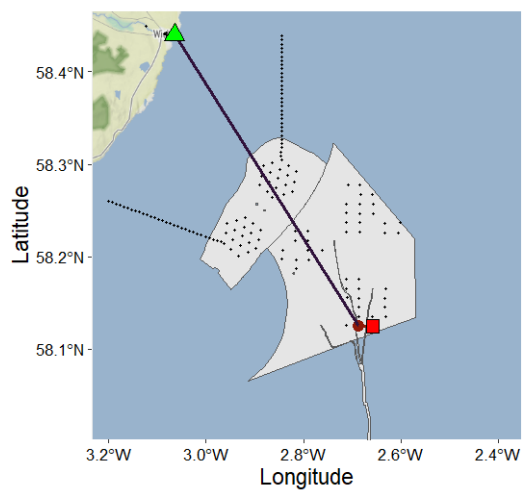
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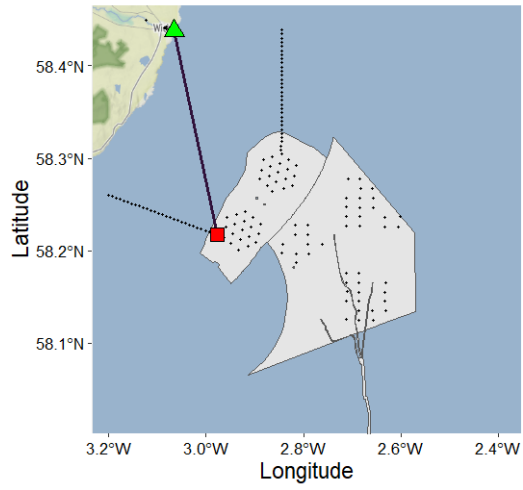
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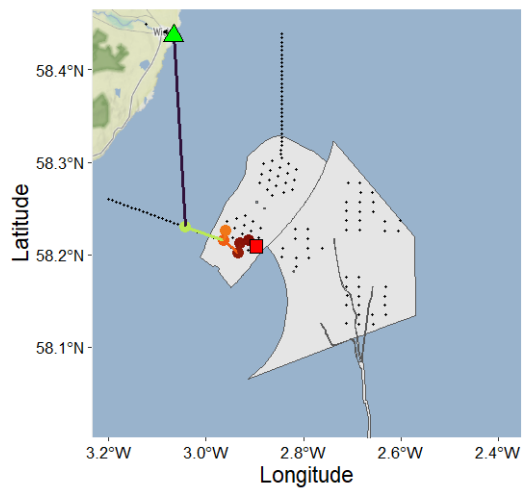
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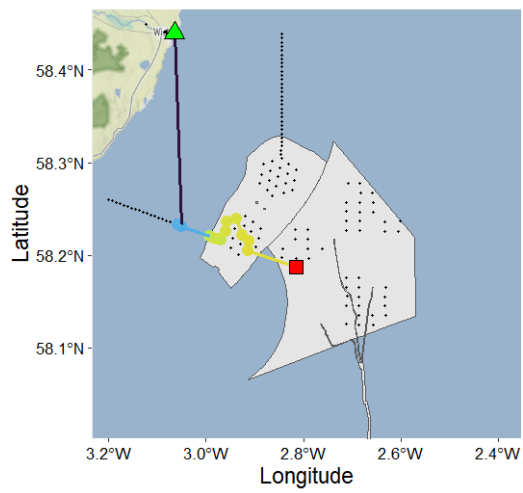
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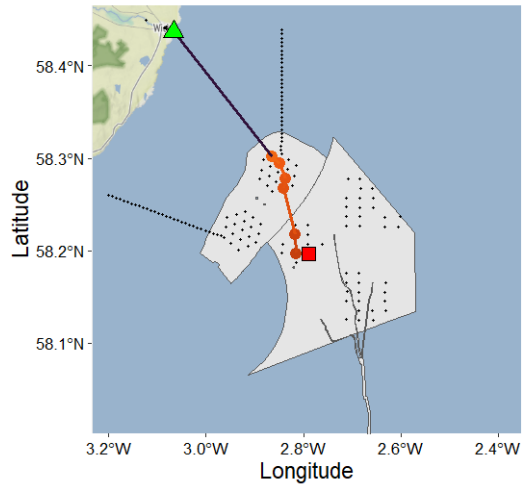
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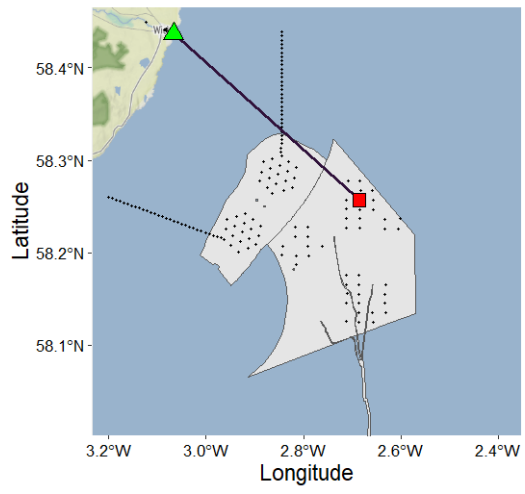
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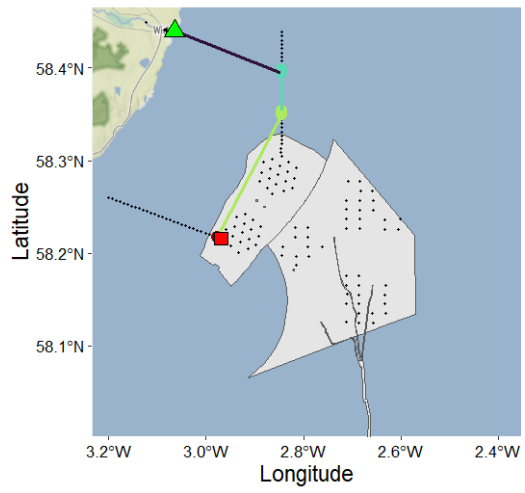
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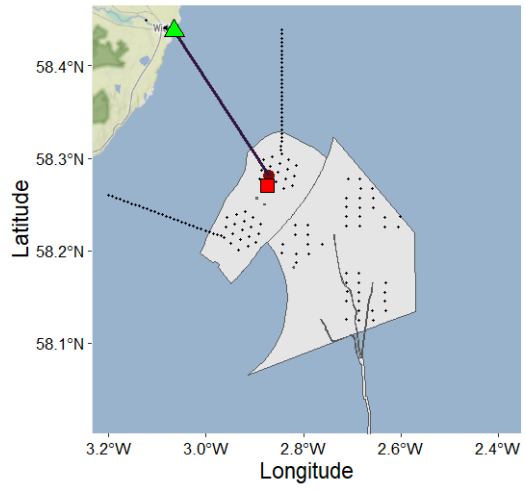
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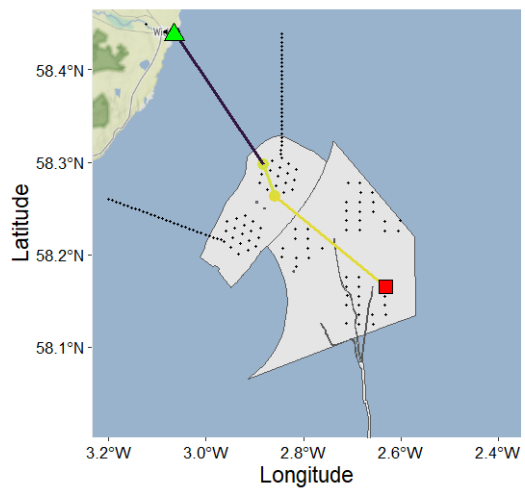
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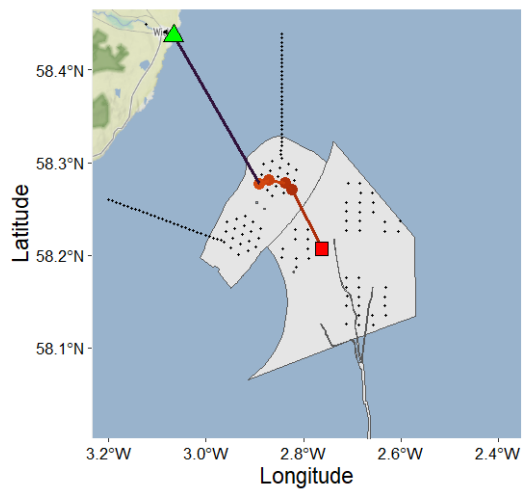
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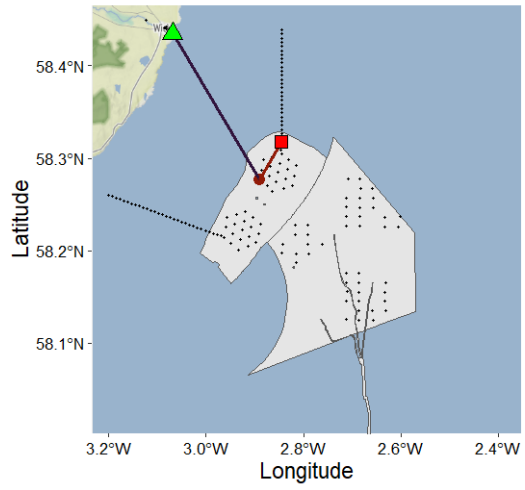
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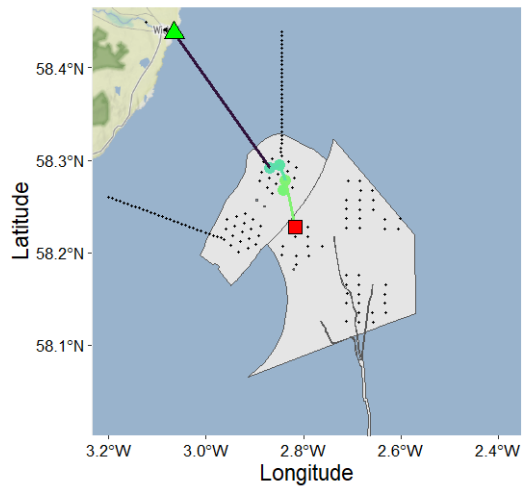
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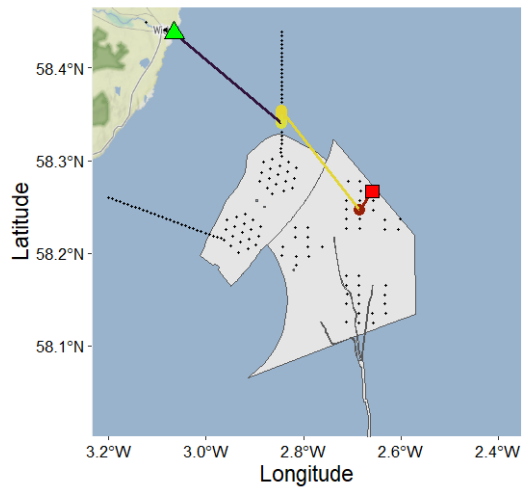
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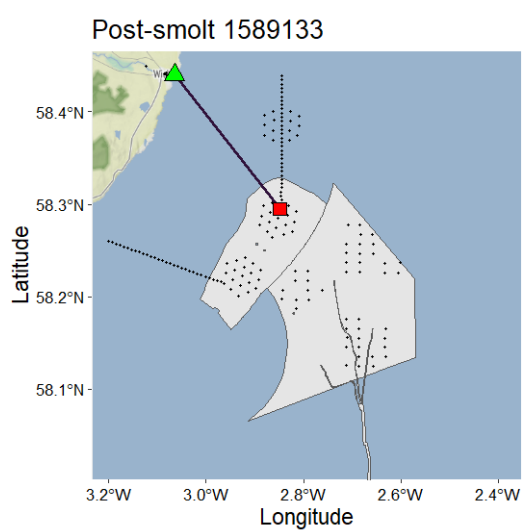
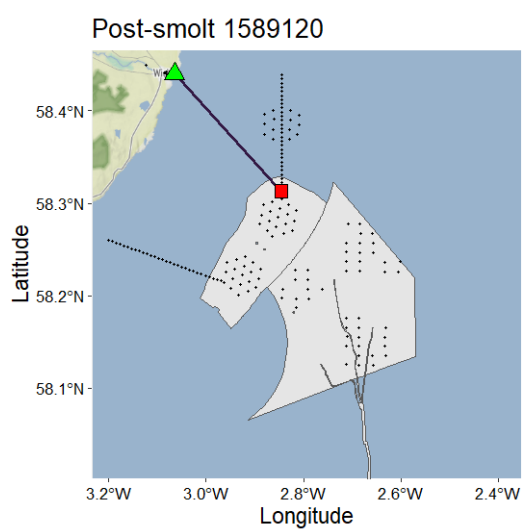
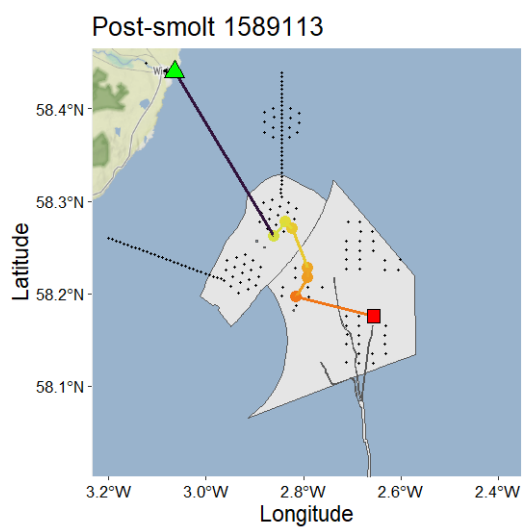
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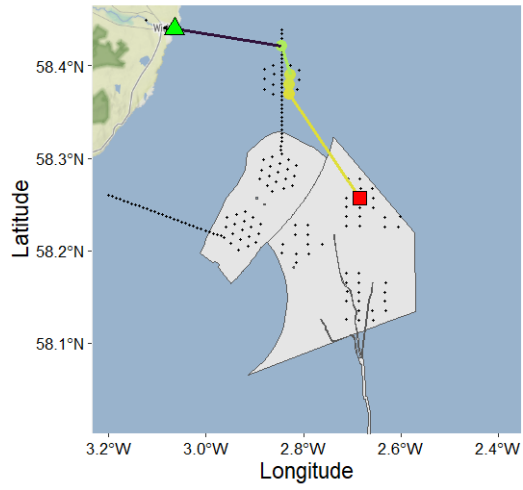
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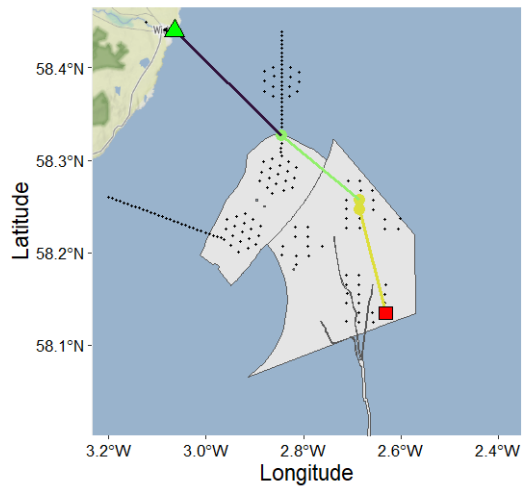
Year 2 (n = 16)



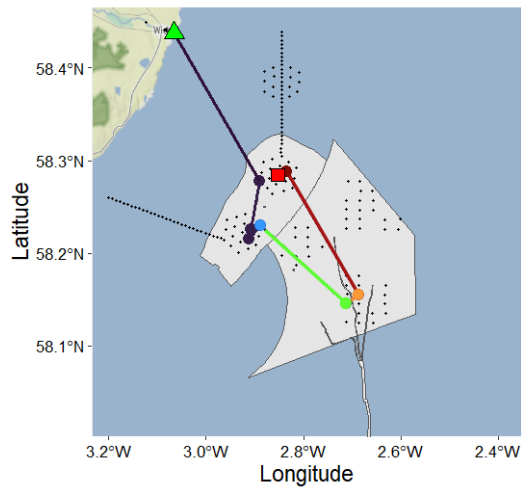
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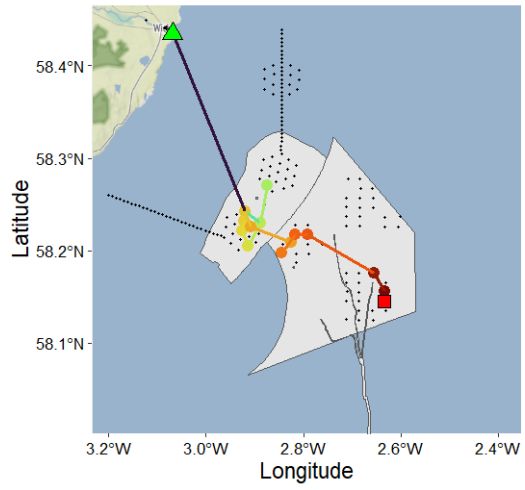
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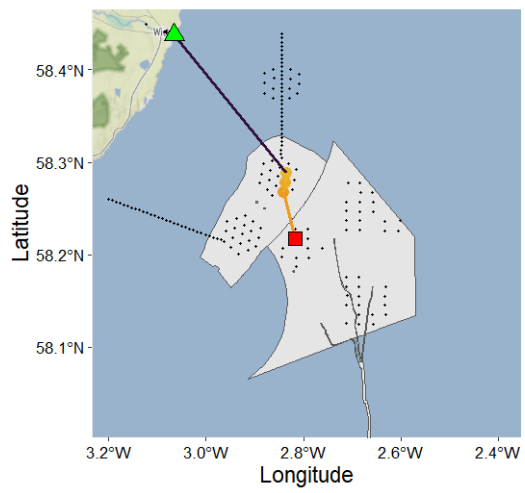
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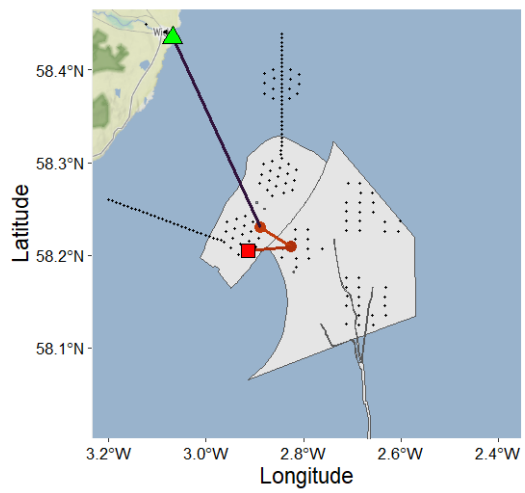
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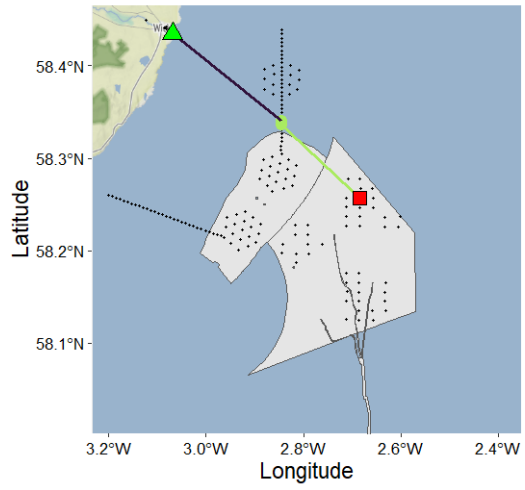
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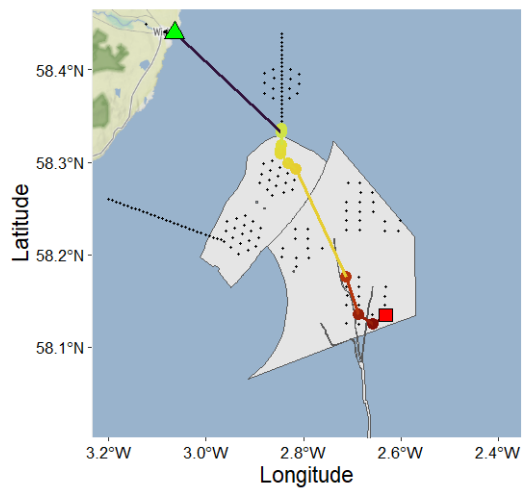
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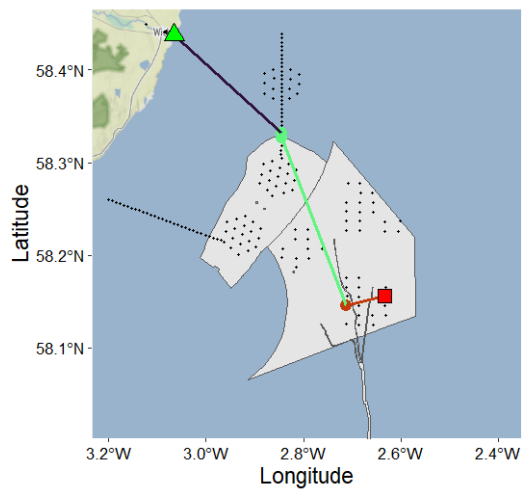
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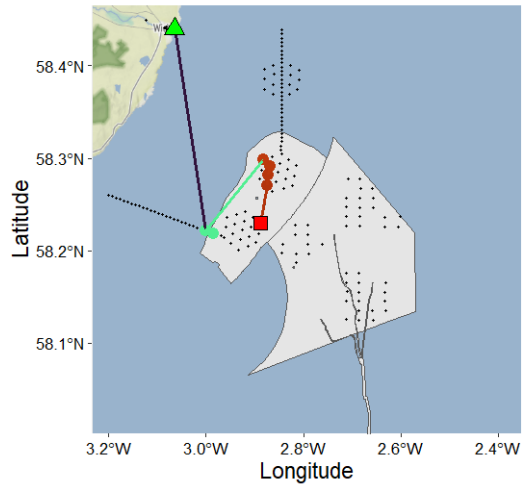
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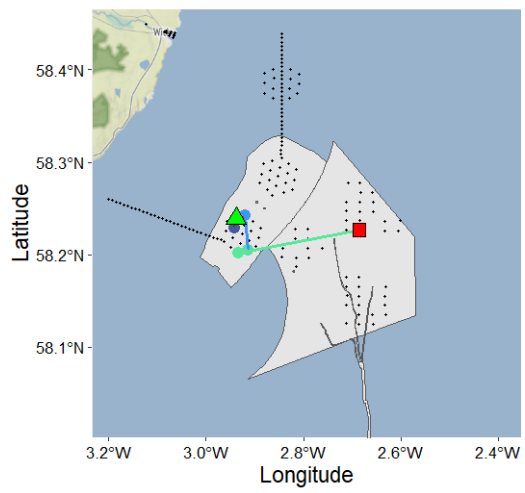
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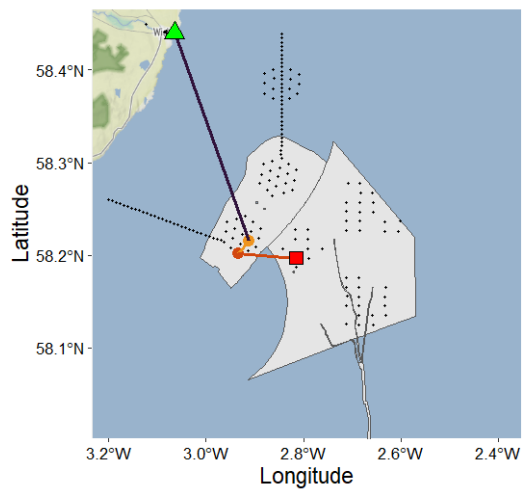
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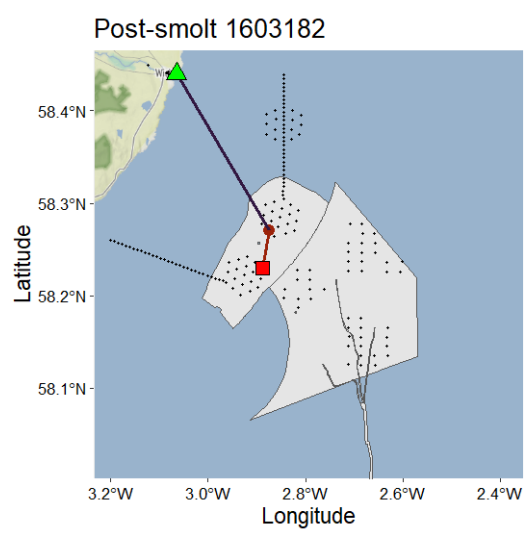


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Post-smolt 1603169







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