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Revealing potential Atlantic salmon bycatch hotspots from pelagic fisheries landings across the Northeast Atlantic

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Abstract

Atlantic salmon (*Salmo salar*) marine survival has declined markedly over the past five decades, leading to concerns about future population viability. While many studies have explored the impacts of stressors such as climate change and predation, less is known about bycatch from pelagic fisheries targeting finfish species. This study, focused on the first few months of the salmon marine migration period, narrows down the space–time domains where pelagic fisheries bycatch is most likely to occur. Landings from an International Council for the Exploration of the Sea-led data call were used to assess bycatch exposure. Temporal patterns of monthly landings of six commercially important pelagic finfish species (mackerel *Scomber scombrus*, herring *Clupea harengus*, horse mackerel *Trachurus trachurus*, sardine *Sardina pilchardus*, capelin *Mallotus villosus*, and chub mackerel *Scomber colias*) within the Northeast Atlantic region from 2000 to 2022 were considered alongside reconstructed salmon migration regions. This study indicated that bycatch exposure from herring and mackerel fisheries was higher than that of other pelagic fisheries along the shared salmon migration corridor between April and August, with cumulative exposure highest over time for the herring fishery. Southern salmon populations were also exposed to the horse mackerel and sardine fisheries in April. Temporal patterns of monthly pelagic landings were compared with patterns of marine return rates in salmon index populations, but

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no consistent relationships were present. Quantifying salmon bycatch rates at sea remains challenging due to highly variable and sparse data but, given the severity of declines across their range, conservation measures that address factors affecting marine survival of salmon are urgently needed. Future investigations using emerging technology in the pelagic fisheries identified in this study could provide opportunities to develop more robust information on bycatch risk to Atlantic salmon stocks and to direct appropriate mitigation measures.

KEYWORDS
Atlantic salmon, bycatch, fisheries management, marine survival, pelagic fisheries

1 | INTRODUCTION

Declines in Atlantic salmon (*Salmo salar*, hereafter salmon) populations have been observed in many areas across the North Atlantic over the last 50 years (Lehnert et al., 2019; Limburg & Waldman, 2009; Olmos et al., 2019; Parrish et al., 1998). Reduced marine survival is thought to be a major contributory factor to the observed population declines in recent decades (Chaput, 2012; Olmos et al., 2019; Pardo et al., 2021; Thorstad et al., 2012), even while increased controls on salmon fisheries exploitation have substantially reduced targeted fishing pressure (ICES, 2024; Jacobsen et al., 2012). As such, a better understanding of the drivers underlying the observed changes in marine survival is needed to inform management strategies aimed at protecting salmon populations (Bull et al., 2022; Vollset et al., 2022).

Salmon is an anadromous fish species that begins its life cycle in rivers, migrating towards the sea in spring or early summer (Hanson & Quinn, 1998; Klemetsen et al., 2003). They then spend 1–4 years at sea before returning as adults to reproduce in rivers (Aas et al., 2010). After first entering the sea as juveniles, and until the end of the first winter at sea, salmon are known as 'post-smolts' (Allan & Ritter, 1977), and variable mortality rates of this life-stage are believed to drive overall trends in the species' marine survival (Olmos et al., 2020; Thorstad et al., 2012). A typical post-smolt will enter the sea at a body length of 10–20 cm (Thorstad et al., 2010) and may reach 30 cm by late August (Mork et al., 2012). The whole migration paths of post-smolts during their first months at sea are not yet fully known, but post-smolts from southern European rivers enter the sea from April to June and migrate north towards the Norwegian Sea (Gilbey et al., 2021; Otero et al., 2014). Scientific surface trawling has identified relatively high numbers of post-smolts along the continental shelf-edge west of the British Isles (Gilbey et al., 2021; Holm et al., 2000). Contrastingly, there is very little data on the migration routes of post-smolts through the North Sea (ICES, 2023a; Newton et al., 2026). During their marine migration, post-smolts generally remain within the top five metres of the water column, with occasional deeper dives recorded down to a depth of 37 m (Davidsen et al., 2008; Guðjónsson et al., 2015; Renkawitz et al., 2012). Post-smolts occupy the same environments as many commercially important pelagic finfish species, such as herring (*Clupea harengus*), mackerel (*Scomber scombrus*), and sardine (*Sardina pilchardus*) (ICES, 2023a, 2024).

Concern has been expressed about the potential bycatch of salmon in pelagic fisheries that target finfish in the Northeast Atlantic (Elliott et al., 2023; Gillson et al., 2022; ICES, 2023a, 2023b, 2023c). Since 2004, several International Council for the Exploration of the Sea (ICES) Working Groups have aimed to identify bycatch risks of post-smolts, but their attempts have been hampered by data limitations (ICES, 2004, 2023b). There is certainly cause for concern, however, with several million tonnes of pelagic fish landed annually in this region (ICES, 2024), potentially in areas and periods with a risk of bycatch of salmon. Salmon are classified as 'near threatened' globally, and 'vulnerable' in Europe, by the International Union for the Conservation of Nature (IUCN) Red List Assessment (Darwall, 2023; Sayer, 2024) and are listed as threatened under national and international legislation (Elliott et al., 2023; Nieto et al., 2015; OSPAR, 2008). Despite their status, salmon were only included on the list of species considered by the ICES Working Group on Bycatch of Protected Species (WGBYC) for the first time in 2025 (ICES, 2025), and the first assessment produced by this group concluded that existing monitoring coverage is insufficient and data submissions are too sparse to generate robust salmon bycatch estimates. This illustrates that the mobilisation of data on salmon bycatch is in its infancy, and more research is required to better understand the bycatch risks posed by pelagic fisheries on this species.

Insufficient monitoring has thus far limited the availability of salmon bycatch data, with the majority of bycatch observer effort allocated to demersal fisheries (ICES, 2023a). When fishery monitoring is undertaken, logistical challenges may arise due to the difficulty of detecting the relatively small numbers of salmon in large (hundreds of tonnes) pelagic trawl and purse seine catches (ICES, 2004). In the cases where landed pelagic target fish are sorted, no routine monitoring for bycatch takes place (Roberson et al., 2020). However, despite the limitations in data, there have been numerous records of salmon bycatch occurring in pelagic fisheries (Elliott et al., 2023; ICES, 2004, 2013, 2021a, 2025; Olafsson et al., 2016), with several gear types being reported. The Netherlands Institute for Fisheries Research (RIVO) and French fisheries observer data reported the bycatch of salmon in gillnets, trammel nets, otter trawls, and pelagic trawls (Elliott

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et al., 2023; ICES, 2004). Monitoring of mackerel and herring landings in the Icelandic pelagic trawl fisheries between 2010 and 2013 found a bycatch rate of 0.0054 salmon per tonne of mackerel and herring, with approximately 13% of these being post-smolts (i.e., 0.0007 post-smolts per tonne; Gudbergsson et al., 2014). These values depend on the spatiotemporal distribution of salmon as well as on fishing effort, gear type and reporting procedure (Urban et al., 2024). ICES (2004) reported a much higher value of 57 post-smolts per tonne of mackerel in the Norwegian Sea, though there were differences in the gear type and operating depth of that study in comparison with the commercial fishery. The likelihood of capturing salmon as bycatch with different gear types is not currently known, nor is it clear if there are interactions between gear selectivity and increasing post-smolt body size along migration corridors.

In the North Pacific Ocean, bycatch of Chinook salmon (*Oncorhynchus tshawytscha*) and Chum salmon (*O. keta*) in trawl fisheries is well documented and sampled using at-sea observers, cameras and electronic monitoring, allowing for estimation of the impacts of bycatch on populations (Ianelli & Stram, 2015; Sabal et al., 2023; Witherell et al., 2002). Following declines in Pacific salmon (*Oncorhynchus* spp.), measures have also been implemented to reduce bycatch in pelagic trawls (Yochum et al., 2021). For other fish, marine mammals, and seabirds, detailed information on bycatch is not always available, in which case, analysis of bycatch risk might be undertaken by comparing satellite-tracked movements with fishing effort from expected at-risk fisheries (Clay et al., 2019; Queiroz et al., 2019), or by developing species distribution models and comparing these with fishing activity (Frantz et al., 2024; Hatch et al., 2023; Hines et al., 2020; Stock et al., 2019).

For Atlantic salmon, understanding bycatch risk is complicated by our present incomplete knowledge of post-smolt migration paths (Gilbey et al., 2021). Acoustic telemetry studies (e.g., Artero et al., 2023; Lilly et al., 2024) are unable to reveal the full migration paths of post-smolts due to limitations on the placement of acoustic receivers, while modelling studies (e.g., Borland et al., 2025; Mork et al., 2012) have not been undertaken for all relevant migration regions (ICES, 2023a). Stable isotope analysis can also provide large-scale insights into migration pathways, but the coarser resolution of this approach has not yet enabled precise inference of migration paths (Hanson et al., 2022). Environmental DNA (eDNA) analysis is increasingly being used to analyse bycatch risk (Albonetti et al., 2023; Maiello et al., 2024; Urban et al., 2024), and recent technological advances in eDNA analysis have allowed estimates of species abundance, as well as composition, to be made (Baetscher et al., 2025; Guri et al., 2024). However, this approach has not yet been implemented for salmon bycatch, and access to eDNA data requires a legislative shift to enable its collection onboard fishing vessels.

Risk, applicable but not exclusive to bycatch, is a function of exposure and sensitivity to pressures (Samhouri & Levin, 2012). Exposure to pelagic fisheries is defined by the spatial and temporal extent and intensity of pelagic fishing within salmon migration corridors (ICES, 2023a), where higher fishing intensity in these areas during the active migration window infers a higher exposure (Greenstreet et al., 2009). Sensitivity would then be defined by salmon mortality (i.e., bycatch) rates per unit of fishing but, to date, this information is not available. The lack of quantitative and standardised information on salmon bycatch across their range prevents the quantification of bycatch risk. It is therefore logical to suggest that a higher overall exposure to pelagic fisheries activity is likely to cause a greater probability of bycatch risk.

This study narrows down the space–time domains within the Northeast Atlantic Ocean where there is a high potential risk of post-smolt salmon bycatch, directing future research efforts on quantifying and mitigating bycatch risk. Bycatch exposure was assessed using a recently mobilised dataset on the total monthly pelagic landings of six commercially important finfish species identified by ICES as potentially problematic in terms of salmon bycatch risk (mackerel *Scomber scombrus*, herring *Clupea harengus*, horse mackerel *Trachurus trachurus*, sardine *Sardina pilchardus*, capelin *Mallotus villosus*, and chub mackerel *Scomber colias*), and relationships between salmon marine return rates and landings were tested. The relationship between pelagic landings and fishing intensity varies by species and biomass, spatial regions, vessels, gear types, and time of year (Arnason, 1996; Batista et al., 2015; ICES, 2023a, 2023b, 2023c, 2024). Fishing effort data (e.g., hours fished) from these targeted pelagic fisheries would provide a better measure of exposure than landings. Unfortunately, consistent effort data for pelagic fisheries targeting different species across the spatial and temporal extents of this study were not available (some effort data exist in specific regions, e.g. ICES, 2022, but using this would have greatly narrowed the scope of our study). Using landings data as the most widely available measure of fishing intensity (Greenstreet et al., 2007) represents a practical step forward in the challenge of understanding the factors affecting salmon survival at sea.

2 | METHODS

2.1 | Study area and post-smolt migration regions

For post-smolts originating from European rivers (Figure 1), monthly regions of occupation were defined using survey data on the capture of post-smolts at sea between April and August from 1995 to 2018 (Gilbey et al., 2021). Data were binned into ICES statistical rectangles (0.5° latitude by 1° longitude resolution) and used to define regions covering the likely shared post-smolt migration corridor of multiple populations. The migration corridor was further subdivided into regions relevant to salmon populations entering the sea in the southwest, west, and east regions of the modelled domain, as well as a 'common-north' region where all populations are assumed to aggregate (Olmos et al., 2020) (Figure 2a), with the divisions between these areas informed by the genetic assignment of trawled post-smolts at sea to regions/countries (Gilbey et al., 2021). The latitudes of post-smolts observed in the surveys ranged from 52.2° to 76.3°. However, given that salmon from rivers further south than this observed capture latitude also migrate through the study domain (Gilbey et al., 2021), the

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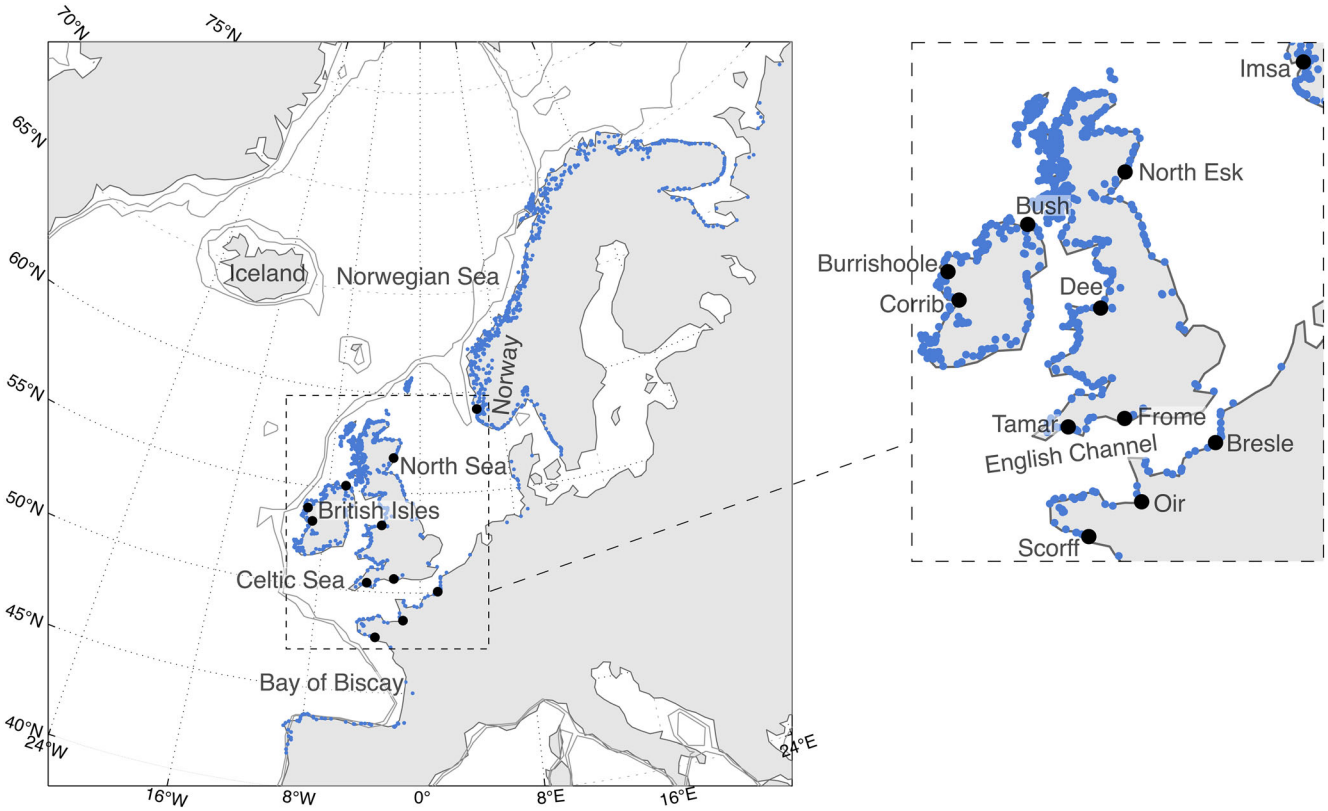

FIGURE 1 Salmon rivers in the Northeast Atlantic (blue) and monitored rivers with time series of marine return rates available for analysis (black). Isobaths at 200 and 400 m indicate the location of the continental shelf-edge.

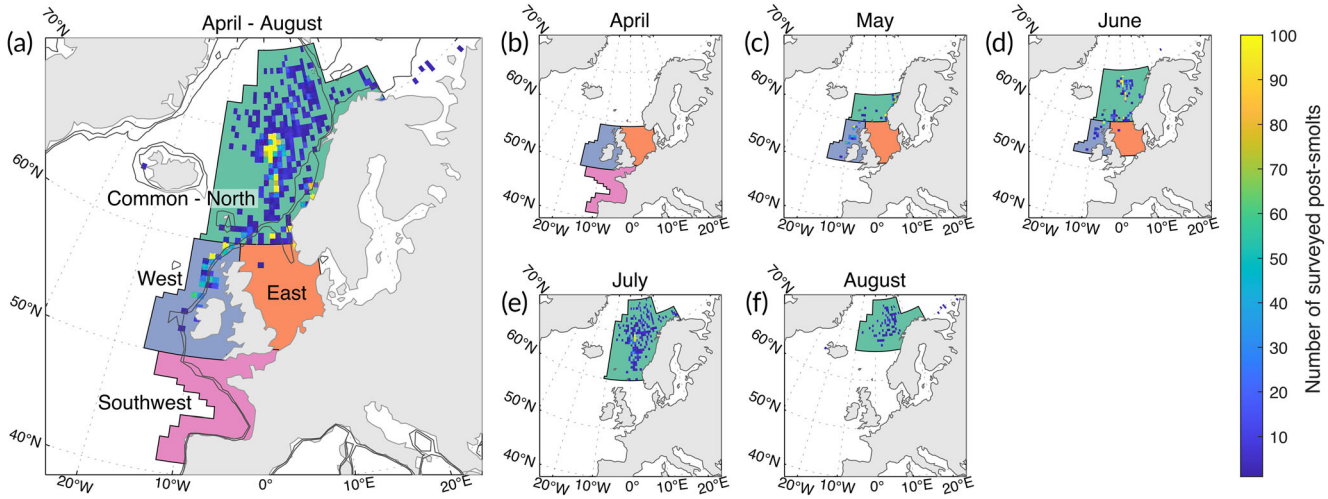

FIGURE 2 ICES rectangle scale (0.5° latitude × 1° longitude) locations and concentrations of surveyed post-smolts (Gilbey et al., 2021) for: (a) April to August; (b) April; (c) May; (d) June; (e) July; and (f) August. Defined post-smolt migration regions are displayed (southwest, west, east, and common-north). Isobaths at 200 and 400 m in (a) indicate the location of the continental shelf-edge.

regions were extended south to 41° latitude, the location of the river Ulla in Spain (the southernmost known river where smolt emigration timing data was available; Otero et al., 2014). The continental shelf edge was used as the western boundary, in line with the post-smolt observations and the main areas of high occupancy of simulated migrating smolts by Mork et al. (2012). The North Sea was included (east region) despite there being only one surveyed post-smolt location there, as there are several large salmon rivers in this region, and other studies have partially revealed the migration routes of post-smolts within the North Sea (Main, 2021; Newton et al., 2026; Turrell, 1997).

Using the monthly observed capture locations of post-smolts, these general regions (Figure 2a) were split latitudinally by month

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from April to August (Figure 2b–f), the period when post-smolts are known to migrate northwards. Smolts from rivers between 41° and 57° latitude generally migrate during April (Otero et al., 2014). Due to the nature of the post-smolt migration, not all the regions are occupied each month (e.g., the 'common-north region' is not occupied in April, because post-smolts are not expected to reach this latitude until May).

The locations of captured post-smolts used here are not comprehensive because surveys were not conducted over our entire study region, and locations where no post-smolts were found were not recorded in the dataset (i.e., presence-only data). Further, the locations where higher densities of post-smolts were observed (Figure 2) do not necessarily represent the actual locations with higher densities of post-smolts; they may represent the areas with more samples. While these data (along with known emigration timing from several rivers) allow us to determine the general regions likely to be occupied by post-smolts each month, we cannot infer their exact locations or concentrations. As such, we did not consider exposure within the individual ICES rectangles of these observations. Instead, we assume that post-smolts were evenly distributed within the defined post-smolt migration regions per month. Then, the quantity of pelagic landings in each region was considered a proxy for bycatch exposure risk.

2.2 | Pelagic fisheries data

Landings data in tonnes per ICES statistical rectangle for six pelagic finfish species (mackerel, herring, horse mackerel, sardine, capelin, and chub mackerel) were obtained from the ICES Working Group on North Atlantic Salmon (ICES, 2025) after a data call associated with a Workshop on Salmon Mortality at Sea (ICES, 2023b). Blue whiting (*Micromesistius poutassou*) was included in the list of species in this call, but these data were omitted from the analysis as the operational fishing depth of the blue whiting fisheries (300–600 m, ICES, 2023a) exceeds typical post-smolt swimming depths (0 to ~50 m). The six target fisheries of focus here operate, at least partly, at depths of 0–50 m (ICES, 2023a; further information in Table S1). Eleven nations provided landings data with a geographic resolution of 0.5° latitude and 1° longitude (i.e., ICES statistical rectangles) for 2000–2022: Denmark, France, Great Britain, Iceland, Ireland, Lithuania, Netherlands, Norway, Poland, Spain, and Sweden. Spatial maps of monthly landings per ICES rectangle within the post-smolt migration regions (Figure 2) from April to August were developed for total landings of combined and individual species. Within each region, landings were summed per month (April–August) and year (2000–2022) to create time series indexing pelagic fishing activity relevant to post-smolts. The mean landings per region and month were then used to quantify exposure rates for each fishery, month, and region. Pelagic landings datasets were not received from Russia or the Faroe Islands. These are nations that contribute a significant proportion (26% by tonnage in 2023) of herring and mackerel landings in the Northeast Atlantic region (ICES, 2024). Fishing effort from these nations was examined using data from Global Fishing Watch (GFW; https://globalfishingwatch.org/), which uses Automatic Identification Systems (AIS) data to estimate fishing effort. Data were obtained from April to August of 2012–2020 (all of the available years) across the Northeast Atlantic (latitudinal range 40°:70°, longitudinal range −30°:20°). Gear types available and considered were purse seines, seines, and trawls. Unfortunately, the trawl gear type in Global Fishing Watch data does not differentiate between pelagic and demersal trawls but most trawling in this region is pelagic (ICES, 2021a), and hence relevant to the species of focus in this study. Furthermore, these data are not disaggregated by species.

Effort data (fishing hours) from GFW were summed within the post-smolt regions for Russia, the Faroe Islands, and the 11 nations considered in this study (combined). For each region and month, the relative quantity of Russian and Faroese landings was calculated in comparison with the combined 11 nations considered in this study. As such, we calculated the increase in fishing effort that would have been observed if this study included these two nations. Assuming that effort is correlated with landings (as assumed throughout this study), we used this analysis to estimate how much higher the post-smolt fishery exposure rates might have been if the landings dataset had included the Russian and Faroese fleets. The GFW data were only available for nine of the 22 years considered in this study; therefore, annual estimates could not be produced and incorporated into the landings time series. Instead, we estimated total exposure within the post-smolt regions by raising the existing exposure (defined by landings) according to the proportional increases in fishing effort calculated when considering fleets from Russia and the Faroe Islands in combination with the other fishing nations. This assumes that the catch per unit effort (CPUE) is similar between nations.

The GFW effort data may not correlate exactly with the landings data in this study if a proportion of the effort in the 'trawl' gear category is demersal trawls. Additionally, the GFW effort data misses a large proportion (>99%) of small vessels (<12 m) as they do not have AIS fitted (Kroodsma, et al., 2018). Within the defined regions, we assumed that the ratio of pelagic to demersal trawl fishing and the proportion of small vessels (<12 m) was similar between fishing nations. Due to the uncertainties arising from these assumptions, precise landings estimates were not generated. Instead, the exposure rates calculated for each month and region for all fisheries combined were updated on an order of magnitude scale.

While a fishing effort dataset would have been optimal for calculating exposure, as discussed previously, we note that the GFW effort data were unsuitable for our other analyses (above) due to the same uncertainties. Additionally, it would not have allowed us to identify high-exposure-risk fisheries, the key aim of this study, because it is not disaggregated by species.

2.3 | Comparing pelagic landings time series with marine return rates

Marine return rates of salmon can serve as a proxy for marine survival (Chaput, 2012), though they also depend on variable maturation rates.

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Here, they were compared with the pelagic landings time series to consider any potential large-scale relationships between marine survival and pelagic fishing activity. We utilised marine return rate datasets for salmon spending one full winter at sea before returning (1SW) because these are the most numerous life-history type with the most complete time series. As this study focused on vulnerability to bycatch during the early marine phase, it was considered that 1SW survival rates are likely to provide a stronger signal of post-smolt survival, compared to the return rates of fish spending multiple winters at sea (Artero et al., 2023; Elliott et al., 2026). Annual 1SW wild salmon return rates were available from 11 monitored rivers within our study domain (Figure 1; ICES, 2023a). Because there are differences in the methods used to estimate return rates among rivers (ICES, 2023a), which could influence the time series, we used normalised return rates to remove some of the small quantitative differences while retaining the temporal trends.

Monitored rivers were grouped according to the geographical divisions in Figure 2. In each region, the mean of the normalised annual 1SW return rates for the relevant rivers was used as an index of return rates within that region (Figure 3). Return rates for the North Esk were only available for 2000–2002 and 2005–2009, so the East group return rates consist solely of the Imsa for the remaining years. Our grouped return rates for this study differed from those used by Tyldesley et al. (2024), being based on geographical division (Figure 2) rather than clustering analysis.

Each grouped annual marine return rate time series (southwest, west, and east) was compared with landings from each pelagic fishery in the relevant post-smolt regions. The year associated with the 1SW return rate data (Figure 3) was recorded for the year in which smolts entered the sea, so no time lag was required when comparing it with landings during the migration period. Only those combinations of landings and return rates where the salmon populations would migrate through the landings region were considered (e.g., we did not consider possible correlations between east landings and west return rates).

Pearson correlation coefficients (r) were calculated for combinations of annual marine return rates and monthly post-smolt region landings. As the annual marine return rates and landings time series exhibit autocorrelation, the modified Chelton method (Pyper & Peterman, 1998), where the degrees of freedom are adjusted based on the level of autocorrelation, was used to determine p-values. Correlation coefficients (r, p) were also calculated between detrended

FIGURE 3 Normalised marine return rates for one-sea-winter (1SW) salmon for individual populations (thin blue lines) and combined means per region (thick orange lines) from 2000 to 2021 for: (a) the southwest region (including the Scorff, Oir, Bresle, Tamar, and Frome); (b) west region (Corrib, Burrishoole, Bush, and Dee); and (c) east region (North Esk and Imsa).

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annual marine return rates and landings time series to consider whether interannual fluctuations in landings and returns were correlated. Return rates were detrended by fitting a linear trend via least-squares regression and then subtracting it from the time series. Rather than determining the significance of correlations based on a single arbitrary confidence level, the approach proposed by Muff et al. (2022) was applied to categorise correlations by the strength of evidence, whereby $p \leq 0.001$ is considered to be very strong evidence, $0.001 < p \leq 0.01$ to be strong evidence, $0.01 < p \leq 0.05$ as moderate evidence, $0.05 < p \leq 0.1$ as weak evidence, and $p > 0.1$ as little or no evidence.

3 | RESULTS

3.1 | Pelagic landings within monthly post-smolt migration regions

For each month from April to August, consistent and high pelagic fishery activity was found within the post-smolt migration regions (Figure 4). The fishery also exhibited variation across months, years and regions (Figure 5). In the common-north salmon migration region, pelagic landings were predominantly comprised of herring and mackerel, with an increase in landings observed between May and June. There were very few landings of chub mackerel and capelin recorded within the post-smolt migration regions. In the southwest region, pelagic landings predominantly consisted of three species, namely mackerel, horse mackerel, and sardine (Figure 5). There were fewer landings in the west region, comprised of mackerel and horse mackerel in April–May and herring in June. While landings in the western region were relatively low across all months, they also decreased from April to June. Contrastingly, landings in the eastern region (mainly herring) increased from April to June, becoming much higher than in other regions. Landings maps of individual species within the post-smolt regions are provided in Figures S1–S6.

Landings from the Russian and Faroese pelagic fishing fleets were not included in our dataset, but effort data from GFW for Russia and the Faroe Islands was generally concentrated in the Norwegian Sea within the common-north salmon migration region (Figures S7 and S8). Summed fishing effort in the common-north region was greatly increased (by a factor of two from May to July and a factor of five in August) when Russian and Faroese fishing effort was added to the effort from the 11 nations included in this study (Figure 6).

The mean landings per region and month from Figure 5 are summarised in Table 1. Exposure values are categorised according to the comparative quantities of landings: lower exposure values being less than 0.002 tonnes/km^2; moderate values defined as between 0.002 and 0.02 tonnes/km^2; and higher values being greater than 0.02 tonnes/km^2. The herring fishery had the highest cumulative landings, followed by the mackerel fishery. In April, horse mackerel and sardine fisheries presented medium exposure values for southern salmon populations. Capelin and chub mackerel were omitted from the table

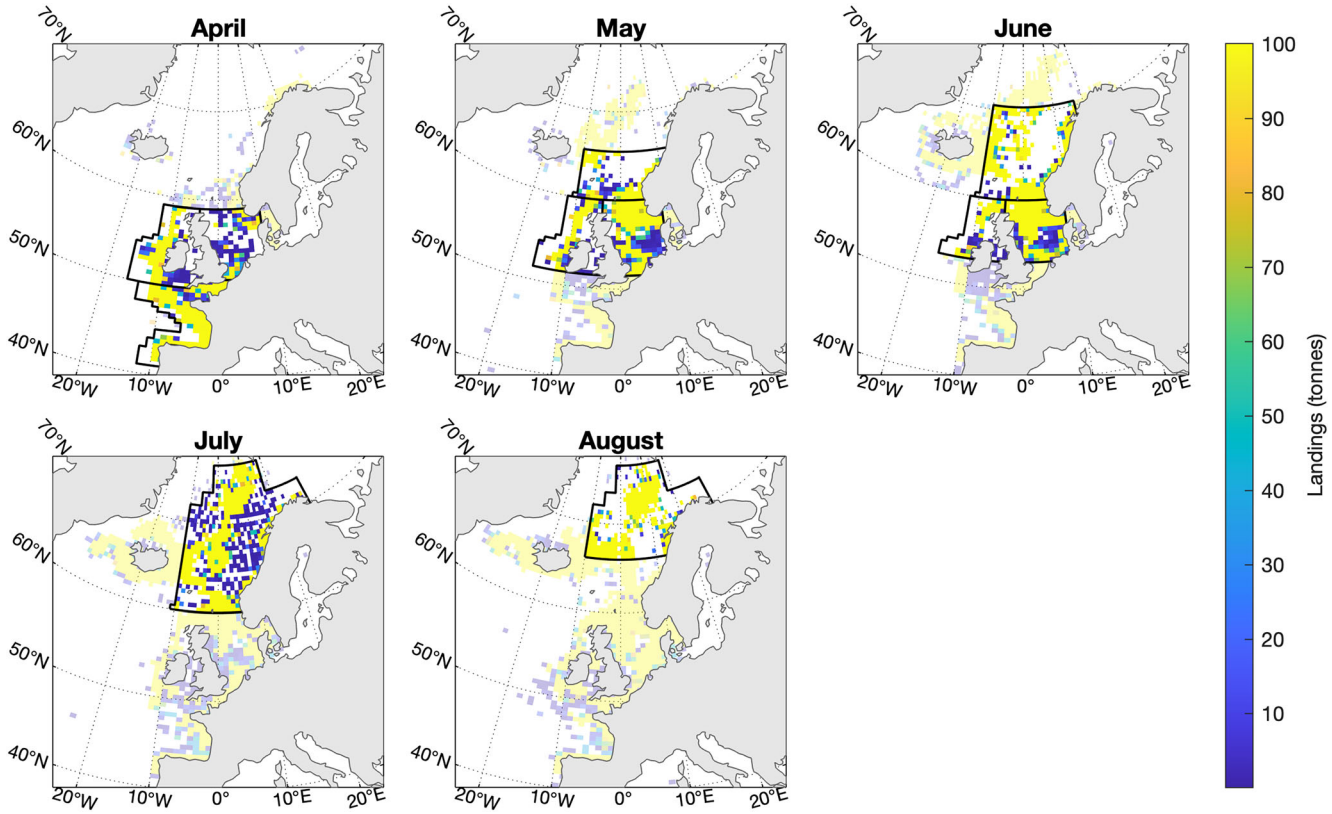

FIGURE 4 Total landings of all species (mackerel, herring, horse mackerel, capelin, chub mackerel, sardine) from 11 fishing nations by ICES rectangle within the post-smolt regions (outlined in black) per month across 2000–2022.

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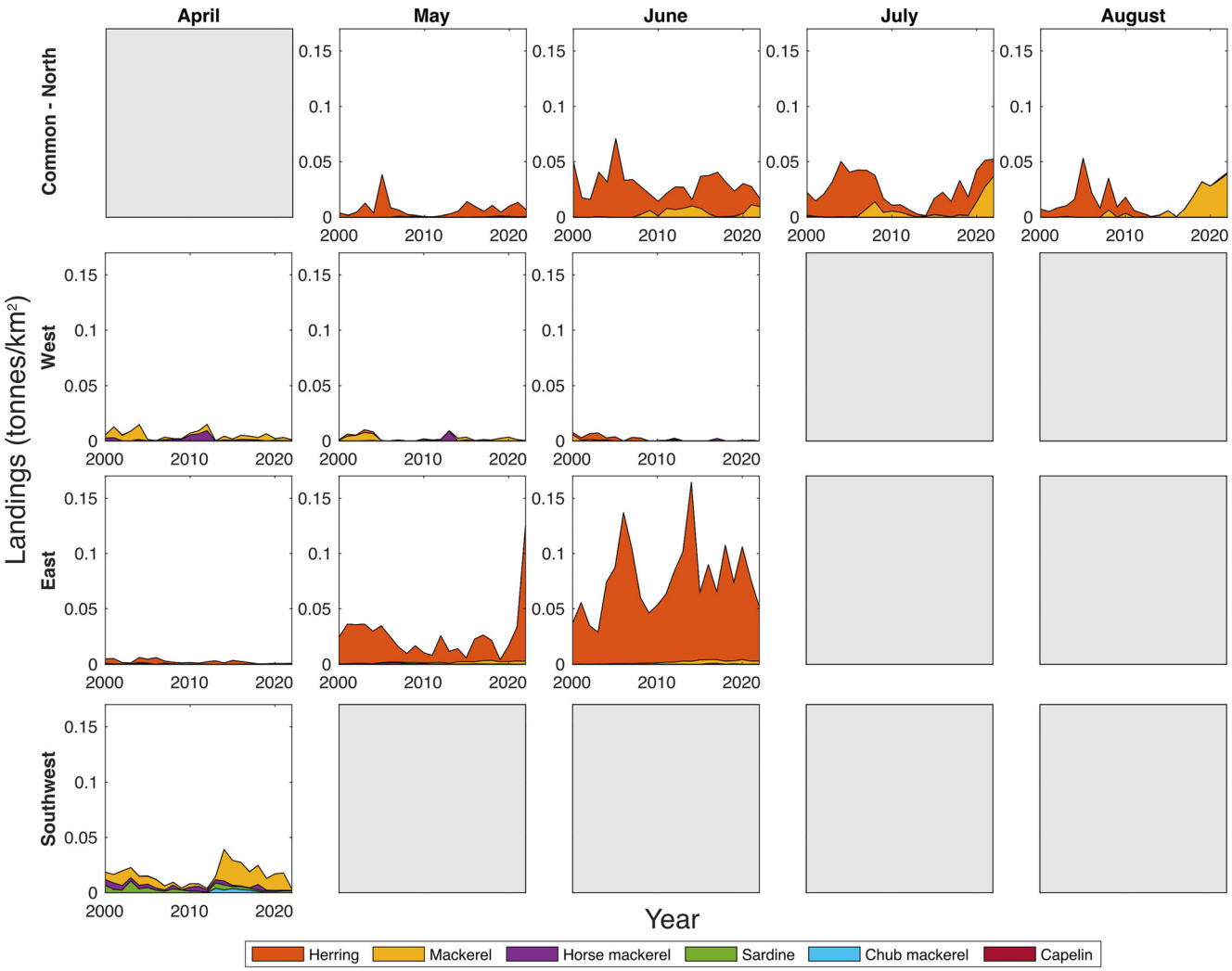

FIGURE 5 Absolute landings (in tonnes per square kilometre) time series from 11 fishing nations per region and per month between 2000 and 2022, coloured by the proportional contribution of each species. Grey plots indicate region-month combinations for which post-smolts are not expected to be present.

because their landings were very low across regions and periods. Based on the analysis of GFW fishing effort, the regions and months in which exposure values are likely to be notably underestimated are highlighted. Furthermore, updated exposure categories (lower, medium, or higher) are provided using the estimated increase in pelagic landings when including the Russian and Faroese fishing fleets (where exposure values were raised by the multiplicative factors from the final column of the fishing effort matrix in Figure 6).

3.2 | Comparing time series of pelagic landings and salmon 1SW return rates

No consistent patterns of association between pelagic fishery landings and annual return rates of 1SW salmon across the study period were found. Most correlations revealed weak or no evidence of relationships, and the correlations with moderate to strong evidence were both positive and negative (Table S2). Comparisons in the Norwegian Sea (the common-north post-smolt region) were not made because of incomplete Russian and Faroese landings data. This also prevented comparisons being made for various patterns of 1SW salmon return rates and 'along-migration' fishery activity where, for example, southwest salmon populations might be subject to exposure to southwest pelagic fishery activity in April, west in May and the common-north region in June to August.

4 | DISCUSSION

This study has refined our understanding of the exposure risks of migrating salmon to pelagic fisheries during the first few months of their marine migration in the Northeast Atlantic. The available data revealed spatial–temporal overlap between post-smolt migratory regions and pelagic fishing activity in the Northeast Atlantic, indicating potential bycatch risks. The results provide evidence of salmon bycatch exposure from pelagic fisheries (ICES, 2004, 2023b), with

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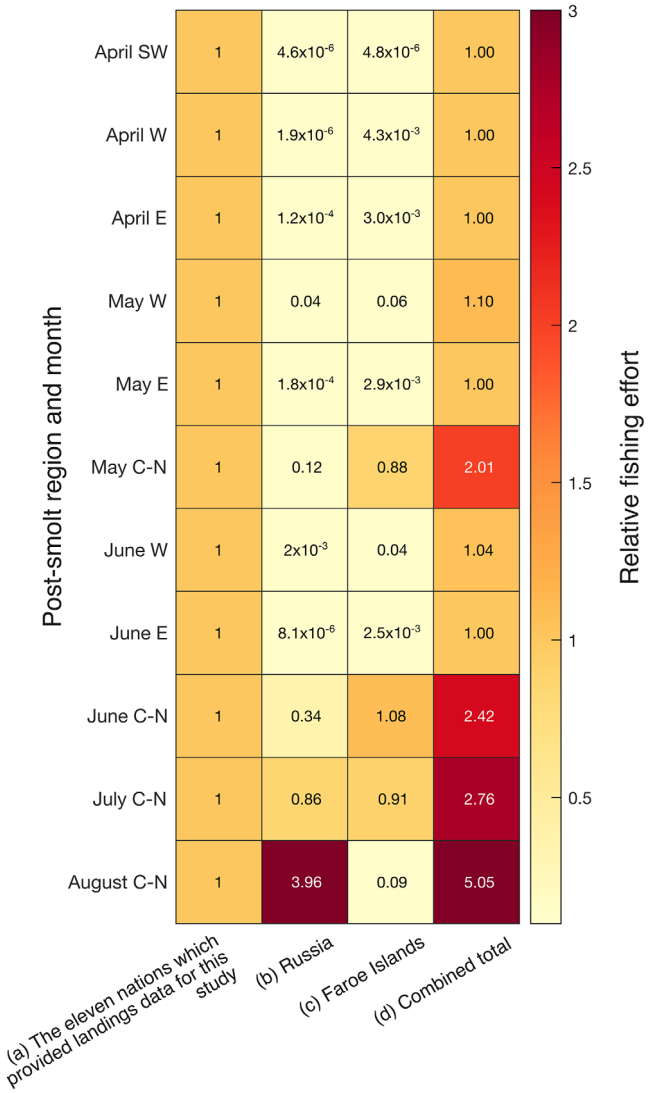

FIGURE 6 Relative fishing effort within the post-smolt migration regions (SW = southwest, W = west, E = east, C-N = common-north) from: (a) the 11 nations which provided landings data for this study (Denmark, France, Great Britain, Iceland, Ireland, Lithuania, Netherlands, Norway, Poland, Spain, and Sweden); (b) Russia; (c) the Faroe Islands; and (d) the sum of columns (a–c), i.e. the combined effort relative to the effort from only the 11 nations with available landings data. Rows were normalised by dividing by the effort in column (a).

relatively high pelagic landings taken within each of the post-smolt migration regions from April to August between 2000 and 2022. This supports the view that post-smolts from all populations face a risk of bycatch throughout their migration up to and within the Norwegian Sea, varying through space and time with pelagic fishing activity.

4.1 | Pelagic fisheries exposure analysis

Along the whole migration corridor, post-smolts have the greatest total exposure to the mackerel and herring fisheries, out of all the pelagic fisheries considered. Mackerel fisheries operate predominantly in the west, while the herring fisheries operate more in the east, and herring landings were higher in total. Post-smolts have a lower total exposure to the horse mackerel and sardine fisheries as these fisheries operate only in the southern part of salmon's migration corridor (ICES, 2024). There were very few landings of capelin and chub mackerel in the post-smolt migration regions, so we expect that these fisheries pose a negligible bycatch risk to post-smolts within the geographic region of focus. It should, however, be noted that a northward expansion has been observed in the distribution of chub mackerel (Domínguez-Petit et al., 2022; ICES, 2021b), and if this trend continues, then the chub mackerel fishery might have greater overlap with post-smolts in the future. Climate-driven northward expansions in the spatial distribution of herring and mackerel have also been observed (dos Santos Schmidt et al., 2024; ICES, 2025; Pacariz et al., 2016; Rose, 2005), which could indicate a future change in the exposure of post-smolts to these fisheries.

Other changes to the fisheries are possible, and perhaps likely, in future. The total declared catch of mackerel exceeded the ICES advised catch every year from 2015 to 2024, and declines in spawning stock biomass (SSB) were concurrently observed over this period (ICES, 2025). Consequently, ICES has recommended significantly reduced limits on mackerel fishing, with the 2026 catch advice being 47% lower than the 2025 recommendation (ICES, 2025). If these limits are met, the future exposure risks of post-smolts to mackerel fisheries may be halved. Contrastingly, the recommended catch limits for herring have been stable over recent years (ICES, 2025), so it is likely that the herring fishery exposure risks estimated in this study, which were higher than those identified for the mackerel fisheries, will remain relevant.

Increased exposure was observed for post-smolts from eastern populations emigrating later in the year (e.g., during mid-May to June), while contrastingly, there was a lower exposure for post-smolts emigrating at this time from western rivers. Across the North Atlantic, smolts have been observed to initiate their seaward migration 2.5 days earlier per decade (between 1960 and 2010) in response to global climate change (Otero et al., 2014). The results presented here suggest that this climate-driven shift to an earlier migration might reduce the risk of bycatch for some populations if the pelagic fishery remains stable in space and time (ICES, 2024). However, pelagic fishing activity varies with target species distribution and abundance, which fluctuate with environmental conditions (ICES, 2024).

In the common-north post-smolt region in June, landings appeared to be lower than in the eastern region. However, the fishing activity quantified in the Norwegian Sea in this study did not include the Russian and Faroese fleets. While this study could not analyse landings data from these nations due to incomplete data submissions, combined fishing effort from these nations in the common-north region was equal to or greater than the total fishing effort from the 11 nations considered in this study. This indicates that the time series of landings in the common-north region (Figure 5) are lower bounds on the total landings from all nations. By estimating the potential increase in landings in the common-north region contributed by these additional fishing nations (2–5 times), exposure categories were updated, and the August common-north region was increased from a medium to a higher risk level. The missing data from the Russian and

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TABLE 1 The mean landings (tonnes/km^2) per fishery and month within the regions occupied by post-smolts (SW = southwest, W = west, E = east, C-N = common-north) between 2000 and 2022.

Months and post-smolt regions	Mackerel	Herring	Horse mackerel	Sardine	All species (summed)	All species (increased according to additional fishing effort)
April SW	0.0097	5×10^{-5}	0.0025	0.0028	0.0158	M
April W	0.0034	2×10^{-5}	0.0017	2×10^{-5}	0.0051	M
April E	2×10^{-4}	0.0020	2×10^{-4}	3×10^{-5}	0.0024	M
May W	0.0017	2×10^{-4}	7×10^{-4}	0	0.0026	M
May E	0.0013	0.0240	5×10^{-4}	3×10^{-5}	0.0258	H
May C-N	2×10^{-4}	0.0068	1×10^{-4}	0	0.0071	M
June W	5×10^{-4}	0.0013	2×10^{-4}	0	0.0020	M
June E	0.0017	0.0700	2×10^{-4}	5×10^{-6}	0.0719	H
June C-N	0.0034	0.0265	2×10^{-5}	0	0.0299	H
July C-N	0.0055	0.0206	1×10^{-5}	0	0.0261	H
August C-N	0.0076	0.0084	0	0	0.0160	H
Total (summed)	0.0352	0.1599	0.0064	0.0029		

Note: Boxes are shaded according to lower values of mean landings (blue = less than 0.002 tonnes/km^2), moderate values (yellow = between 0.002 and 0.02 tonnes/km^2), and higher values (orange = greater than 0.02 tonnes/km^2). The bold outlined black boxes display the cells where the landings would be notably increased if data from the Russian and Faroese fleets were included. The final column updates exposure levels to estimate the inclusion of these additional fishing nations by multiplying the all-species exposure level by the factors calculated using a comparison of fishing effort between nations.

Faroese fleets did not, however, affect the conclusions for the rest of the study domain, as fishing effort from these nations was concentrated in the Norwegian Sea.

Interannual fluctuations in pelagic fisheries landings suggested differences in post-smolt exposure levels among years. The broad post-smolt migration regions were kept constant across years (2000–2022) due to the lack of specific annual data. Actual post-smolt migration routes, however, are expected to vary with interannual changes in environmental conditions (Borland et al., 2025; Moriarty et al., 2016; Mork et al., 2012). Considering shifting migration paths alongside pelagic landings was beyond the scope of this study. Future work could calculate exposure using specific annual modelled post-smolt migration routes, potentially increasing interannual variability in estimated exposure. Migration paths of post-smolts are also known to vary among populations (Gilbey et al., 2021; Rodger et al., 2025), suggesting some populations will have greater exposure than others to pelagic fishing activity.

As post-smolts increase in body size, the likelihood of bycatch may change. There is some evidence to suggest that larger fish are more likely to be bycaught (subject to mesh size, Dubost et al., 2023; Bhanja et al., 2024; Bisch et al., 2024). It may be hypothesised that the risk of bycatch is higher when post-smolts are a similar size to the fishery target species, but at present, there is no evidence to confirm this. The size composition of landings is not generally available, but minimum landing sizes in the fisheries considered here vary from 15 cm for horse mackerel to 30 cm for mackerel (ICES, 2019), a range that overlaps with post-smolt body length over their first months of migration.

Comparisons between patterns in pelagic landings and salmon marine return rates did not reveal any consistent associations. There are several explanations for this finding based on recognised data limitations and the complex interrelations among multiple drivers of variation in marine survival (Elliott et al., 2026; Sobocinski et al., 2021; Vollset et al., 2022). Marine return rates were only available for a small subset of monitored salmon rivers (11 of 1456 rivers shown in Figure 1), with poor representation of populations in southern France and Spain. The return time series coverage is also very limited for salmon populations entering the North Sea. Further, we only considered pelagic landings during the first 3–5 months of salmon migration, whereas 1SW marine return rates will undoubtedly be influenced by many factors operating across up to 18 months at sea. Finally, 1SW return rates are not directly equivalent to marine survival rates as fish may delay maturation if marine conditions are poor and remain another year at sea, exposing them to continued marine pressures (ICES, 2024; Tréhin et al., 2024). For these reasons, the absence of associations should not be interpreted as evidence that survival is unaffected by these fisheries. It is also possible that any effect of bycatch is not large-scale and consistent enough to be revealed through this correlative analysis. Whilst this study was restricted to considering the direct effects of pelagic fishing on salmon, secondary indirect effects, such as the reductions in important post-smolt prey items (e.g., blue whiting or herring larvae Dadswell et al., 2022, Haughland et al., 2006) and alterations to interspecific competition (Utne et al., 2021), may also contribute to declining returns.

4.2 | Conservation measures

According to the available data, salmon post-smolt exposure to pelagic fishing was highest in the mackerel and herring fisheries. Accordingly, we suggest that the highest priorities for post-smolt

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bycatch protection and future research should be: (1) the herring fishery operating in the North Sea between April and June and the Norwegian Sea between June and August; and (2) the mackerel fishery in the Bay of Biscay and the shelf-edge west of the British Isles in April and the Norwegian Sea between June and August. Followed by (3) the horse mackerel fishery in the Bay of Biscay and the shelf-edge west of the British Isles in April; and (4) the sardine fishery in the Bay of Biscay in April. These suggestions align with the estimated risks associated with different fisheries proposed by ICES (2023a).

A critical step in refining risk analyses is evaluating sensitivity levels (i.e., the bycatch rates of salmon per tonne of landings), which could then be combined with the exposure values defined here to provide a complete picture of salmon bycatch. Given the logistical challenges of detecting bycaught post-smolts using onboard fisheries observer programmes, we suggest that eDNA analysis of landings and/or port landings observations is the most feasible method for this analysis (Yin et al., 2024). A proportion of pelagic finfish landings considered in this study is for human consumption. These are normally processed by fish producer organisations, where opportunities exist for the identification and reporting of bycaught species. If made mandatory, these data, along with fishing effort data, could provide a valuable source for further analysis of salmon bycatch risk. Furthermore, to generate updated exposure estimates in the future, fishing effort data could be collected for the higher-priority fisheries identified in this study. Once high-risk fisheries have been established, methods to reduce bycatch rates of salmon could be considered, as implemented in some North Pacific fisheries (Yochum et al., 2021). Any future management actions taken to estimate bycatch sensitivity levels, or eventually reduce bycatch rates, will require coordination across fishing nations. The areas defined by the post-smolt migration regions are each covered by the exclusive economic zones (EEZ) of multiple nations, and the common-north region also includes areas of international waters (Figure S9).

In conclusion, the total bycatch exposure of salmon post-smolts during the initial 4 months of their marine migration was highest for the mackerel and herring fisheries, with medium exposure levels present for the horse mackerel and sardine fisheries in April. These fisheries are suggested as the focus of future work investigating salmon bycatch. However, with strong declines in salmon populations observed across their range, and evidence of reduced marine survival, additional measures to reduce mortality at sea should be considered. Understanding the drivers of salmon marine mortality is an ongoing challenge, but this work improves understanding of the conditions experienced by salmon at sea, informing the ongoing discussion about why salmon populations continue to decline despite concerted efforts to protect them in their natal rivers.

AUTHOR CONTRIBUTIONS

Aislinn Borland: Formal analysis; investigation; methodology; writing (original draft and review and editing). **Sophie Elliott**: Methodology; supervision; writing (review and editing). **Jonathan Gillson**: Methodology; supervision; writing (review and editing). **Kjell Utne**: Methodology; supervision; writing (review and editing). **Neil Banas**: Funding acquisition; methodology; supervision; writing (review and editing). **Simon Toms**: Writing (review and editing). **Emma Tyldesley**: Methodology; writing (review and editing). **Hlynur Bárðarson**: Writing (review and editing). **Colin Bull**: Conceptualisation; funding acquisition; methodology; supervision; writing (review and editing).

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DATA AVAILABILITY STATEMENT

The pelagic landings dataset is held by the International Council for the Exploration of the Seas (ICES), and the authors do not have permission to share these data. A summary of the data is provided in ICES (2025). Working Group on North Atlantic Salmon (WGNAS). ICES Scientific Reports. Report. https://doi.org/10.17895/ices.pub.28777226.v1.

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