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# DETERMINING SPATIAL DISTRIBUTION OF RISK TO INFORM MANAGEMENT MEASURES

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# Harbour Porpoise Bycatch: Determining Spatial Distribution of Risk to Inform Management Measures

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## ABSTRACT

Bycatch in static nets (i.e., gillnets, trammel nets and tangle nets) has been identified as the leading cause of harbour porpoise mortality globally. Various options are available for mitigating and managing this risk. However, selecting the most effective management measures to balance harbour porpoise conservation needs with sustainable fishing practice is challenging. By understanding the spatial variation of bycatch risk, it is possible to tailor mitigation and management options for a specific localised area or region. This study identified areas of potential interaction between harbour porpoise and static net fishing activity. An interaction index, a measure of the coincidence of porpoise and fishing activity, was developed. Using this approach, it was possible to differentiate between areas that potentially represented concentrations of higher bycatch risk and other areas with a lower but more widespread level of risk. For the Irish and Celtic Seas, an area recognised as having the highest harbour porpoise bycatch rate in European waters, there was a low to moderate interaction index, with the risk spread over a relatively large area. In the North Sea, in contrast, high values of the interaction index occurred in smaller areas, indicating that bycatch risk was more concentrated in this region. With the exception of some coastal areas, the interaction index was generally low for the West of Scotland and Ireland region. The identification of potential areas of interaction between harbour porpoise and static net fishing provides an opportunity to focus monitoring efforts and inform management decisions. For example, the use of area-based management encompassing small areas may be appropriate when spatially concentrated risk of bycatch is evidenced, whereas the use of technical measures, such as pingers, could be considered for areas with widespread lower risk of bycatch.

## 1 | Introduction

The declines in global biodiversity and increasing rate of species extinction now being observed are considered unprecedented (IPBES 2019). One of the primary drivers of this biodiversity crisis is food production, both on land and in the sea (UNEP 2022). Various international agreements and legal requirements focus on establishing frameworks that will deliver improvements for ecosystems, habitats and species alongside enabling or recognising the need for sustainable use of natural resources (Cork 2023). Examples of such agreements include the United Nations Convention on the Law of the Sea (UNCLOS 1982), the Convention on Migratory Species of Wild Animals (CMS 1979), the Convention on the Conservation of European Wildlife and Natural Habitats (Bern Convention), the Agreement on the Conservation of Small Cetaceans of the Baltic, Northeast Atlantic, Irish and North Seas (ASCOBANS n.d.) and the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR). These agreements focus on improving the conservation status of species or the condition of habitats designated for protection through international cooperation, whilst also taking account of economic requirements and the need to ensure that natural resources remain available for future generations.

Marine mammals are listed for protection in almost all such instruments, and bycatch is often identified as the most significant anthropogenic pressure on the species (Coram and Northridge 2018; Calderan and Leaper 2019; Evans, Carrington, and Waggitt 2021; Rogan, Read, and Berggren 2021; Pinn 2023). Interactions between marine mammals and fishing operations can occur wherever there is a spatiotemporal overlap (Moore et al. 2021).

The occurrence of bycatch can be identified from strandings and post mortem data (Leeney et al. 2008; IAMMWG, Camphuysen and Siemensma 2015; Deaville 2021). However, the scale or rate of bycatch within a particular fishery is usually derived from an understanding of annual fishing effort (as days at sea) and observations of bycaught animals made by on-board observers and/or remote electronic monitoring (REM) on commercial fishing vessels (ICES 2021; Kingston, Thomas, and Northridge 2021). When bycatch is considered to be having an unacceptable impact on a protected species, the need to develop effective bycatch mitigation measures presents a complex challenge, comprising scientific, sociocultural, and socioeconomic components (Komoroske and Lewison 2015).

The impact of bycatch on harbour porpoise (*Phocoena phocoena*) populations in European waters is a key conservation concern. The IUCN Red List status for harbour porpoise is 'Least Concern' both globally (Braulik et al. 2023) and for Europe (Sharpe and Berggren 2023); however, OSPAR lists harbour porpoise as a Threatened and Declining Species due to a significant threat of bycatch, which has resulted in the loss of the species from parts of its former range in European waters (OSPAR Commission 2009). The latest OSPAR Quality Status Report (2023) considered populations in the North Sea and West of Scotland and Ireland to be stable but noted large declines in abundance in the Irish and Celtic Seas (Hammond et al. 2021; Geelhoed et al. 2022). The Irish and Celtic Seas have previously been identified as having the highest harbour porpoise bycatch rate in European waters (ICES 2015; Northridge, Kingston, and Thomas 2019). Furthermore, recent estimates of bycatch rates in static net fisheries exceed conservation thresholds in all areas of the Northeast Atlantic (OSPAR-HELCOM 2019; ICES 2022; Taylor et al. 2022). Harbour porpoise bycatch is therefore considered to be a widespread and significant pressure throughout the OSPAR Maritime Area with the potential to impact conservation status.

The fishing industry is the cornerstone of many coastal communities, making significant contributions to regional economies and cultural heritage (Seafish 2019). Understanding and avoiding bycatch of protected species is also an important issue in working towards fisheries sustainability (Pinn 2022; Pons et al. 2022). A balance is needed that ensures fisheries operations are sustainable and profitable, enabling coastal communities to thrive, whilst also meeting our ambitions and commitments to marine mammal conservation. Harbour porpoise bycatch is a relatively rare event for the individual fisher (Hoos et al. 2019; Northridge, Kingston, and Thomas 2019; Pinn 2023), but these rare events accumulate and can result in a conservation issue across the fleet. Key to effective bycatch management is the use of the right measure in the right location at the right time (Pinn 2023).

Designing effective bycatch mitigation programmes is a complex process requiring a thorough understanding of the life histories of target and nontarget species, the interactions with the fishing gear, the effects of spatial and temporal shifts in fishing effort, socioeconomic impacts on the fishery and of the willingness of fishery participants to implement required management measures effectively. Mitigation strategies include spatial and temporal measures, such as prohibiting or restricting fishing in certain locations and/or seasons. There could also be technical measures applied more widely, such as regulations on mesh size, net length and soak time (i.e., the time that nets spend in the water) or the use of mitigation devices (e.g., acoustic devices such as pingers to deter cetaceans from approaching the fishing gear). Effective mitigation strategies need to be informed by knowledge of spatiotemporal variation in bycatch risk.

The decision on which measures are the most effective in reducing protected species bycatch needs to recognise that bycatch interactions are not uniform in space or time due to the dynamic nature of both fishing operations and movements of the species being protected. Management decisions and the effectiveness of any mitigation requirements imposed on a fishery are currently hampered by a lack of accurate bycatch assessments due to a scarcity of monitoring in many high-risk fisheries (OSPAR-HELCOM 2019; EFRA 2023). To be effective in balancing fishery and conservation objectives, management measures need to be of an appropriate scale in relation to the spatial and temporal pattern of bycatch risk, whilst being enforceable. The risk of bycatch for harbour porpoise might be concentrated in small spatially distinct areas of very high risk, in which case area-based management utilising closed areas or fishing bans/restrictions may be appropriate (Hazen et al. 2018; ASCOBANS 2020). Alternatively, if the risk is low but much more widespread, it would be more effective to employ technical fisheries measures applying to all vessels fishing in the area (Senko et al. 2014; Pinn 2023).

Natural systems (i.e., porpoise density) and human systems (i.e., distribution of fishing effort) are both inherently complex and uncertain. Risk mapping, however, has an important role to play in identifying where targeted monitoring and mitigation action might be required (OSPAR-HELCOM 2019; Defra 2022). The aim of this case study on harbour porpoise was to identify areas of potential bycatch risk and in light of that consider which management measures could provide the greatest conservation benefit with the least impact on fishing operations.

## 2 | Materials and Methods

The harbour porpoise assessment areas recommended by the OSPAR Marine Mammal Expert Group in 2021 were used for this study. These assessment areas were a revision of those previously used by OSPAR for the 2017 Intermediate Assessment (Mitchell, Macleod, and Pinn 2018) and proposed by NAMMCO-IMR (NAMMCO/IRM 2019) and used for the OSPAR Quality Status Assessment 2023. The assessment areas chosen for this study were the Greater North Sea (ICES Divisions 4a, 4b, 4c and

7d), West of Scotland and Ireland (ICES Divisions 6a, 7b and parts of 6b, 7c, 7k and 7j) and the Irish and Celtic Seas (ICES Divisions 7a, 7e, 7f, 7g, 7h, 8a and 8b) (Figure 1).

To assess spatial distribution of interaction between porpoise and fishing activity, the distribution and amount of static net fishing effort were compared to harbour porpoise density within each assessment area. Manipulation and analysis of spatial data were undertaken using R Version 4.2.1 (R Core Team 2022), R package 'terra' Version 1.7-46 (Hijmans 2023) and the geographic information system software ArcGIS (Version 10.8; Esri, Redlands, California). For the purposes of this study, the months of June and December were taken to provide a comparison between summer and winter, respectively. In addition, areas with water depths greater than 600 m were excluded because static net fishing is prohibited in those depths (EU Regulation 2019/1241 n.d.).

## 2.1 | Harbour Porpoise Density

The spatial distribution of harbour porpoise population density (number per km$^2$) was represented by the species distribution maps created by Waggitt (2019) for June and December to represent summer and winter distributions. These data were derived from survey data collected from 1980 to 2018, which Waggitt et al. (2020) analysed with a combination of Generalised Linear Models and General Estimating Equations in a hurdle approach to quantify associations between the species and environmental conditions. The Waggitt et al. (2020) data were provided as monthly summaries, aggregated across years. The original maps were in the Universal Transverse Mercator Zone 30N coordinate system (EPSG: 32630) at a spatial resolution of 10 km. For the purposes of this study, they were resampled to a spatial resolution of 20 km and projected to the Europe Albers Equal Area Conic coordinate system (WKID: 102013, Authority: Esri).

## 2.2 | Fishing Effort

Fisheries management and enforcement utilise the Vessel Monitoring System (VMS). These data are strictly confidential and not generally made available for use beyond fisheries managers. Consequently, estimates of the spatial distribution of fishing

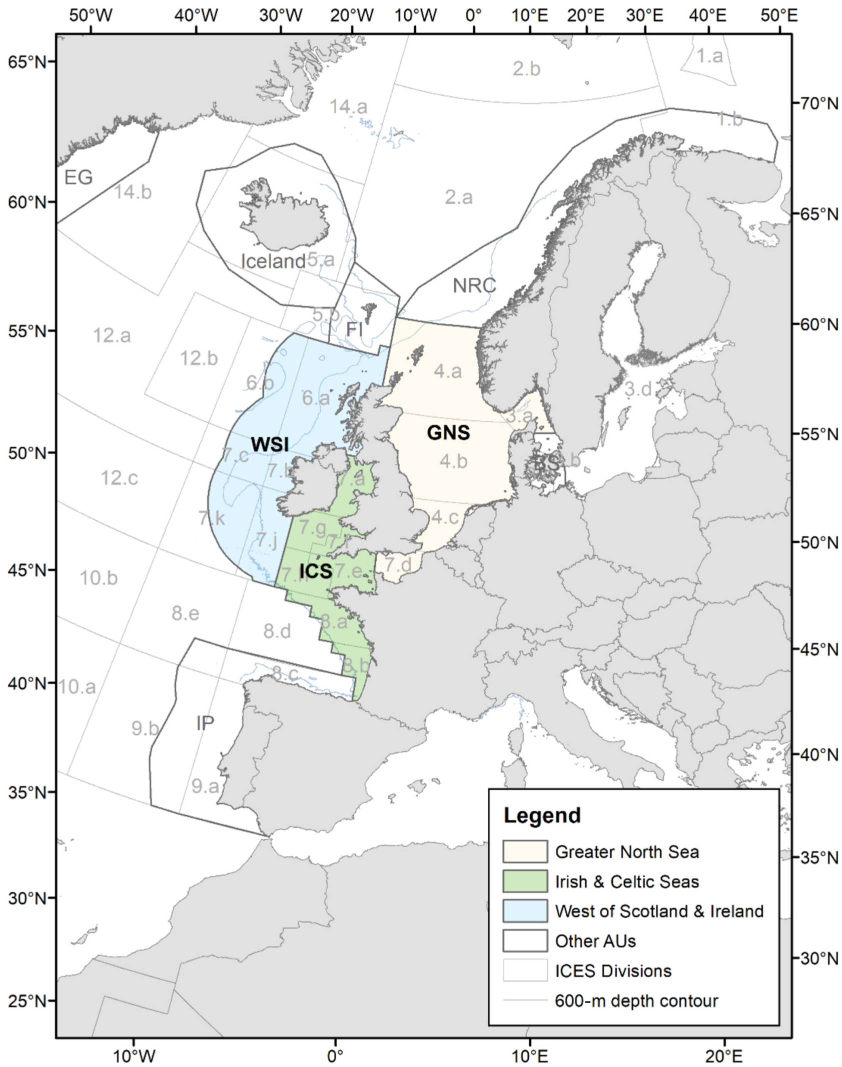


**FIGURE 1** | OSPAR Quality Status Report 2023 harbour porpoise assessment areas (with the three assessment areas used in this study highlighted) and ICES statistical areas. BS, Belt Sea; EG, East Greenland; FI, Faroe Islands; GNS, Greater North Sea; ICS, Irish and Celtic Seas; IP, Iberian Peninsula; NRC, Norwegian and Russian Coast; WSI, West of Scotland and Ireland.

effort were obtained from the Global Fishing Watch (GFW) open-access online platform (Global Fishing Watch 2022).

The GFW platform utilises data from the Automatic Identification System (AIS) and vessel registry data, which are analysed using two convolutional neural networks to identify commercial fishing vessels and determine where, when and with which gear they were fishing (Kroodsma et al. 2018). The International Maritime Organisation developed AIS to enable shipping to operate safely and efficiently, by providing a real-time picture of other vessels within the vicinity. It should be noted that although the AIS dataset does include some smaller fishing vessels, there is no requirement for nonpassenger vessels less than 300 t and, in European waters, for fishing vessels <15 m in length to utilise AIS equipment. The dataset is therefore biassed towards larger fishing vessels (as is also the case for VMS data, which are only required on fishing vessels 12 m or more in length operating in European waters). Static gear vessels <12 m in length operating in the study area equate to approximately 29% of the total European fishing fleet (STECF 2020; Seafish 2024).

Global daily fishing effort was obtained for the years 2012–2016 as hours of fishing classified by gear type at a spatial resolution of 0.01° of latitude and longitude in the World Geodetic System 1984. Data for the 'set gillnets' gear category in the area contained by longitudes 18°W to 10°E and latitudes 43°N to 62°N were extracted. Daily fishing effort was aggregated into total hours per month averaged over the 5 years of the study period for June and December. Values for December were rescaled to a 30-day month for comparability with June. Each monthly fishing hours' dataset was rasterised in the same coordinate system and with the same size and alignment of pixels as for the harbour porpoise population density. Although fishing effort is measured in hours or days at sea, that is not considered the best measure of fishing effort for static nets; soak time (i.e., the time that nets spend in the water) and net length are better measures, but such data were not currently collected as standard (Kindt-Larsen et al. 2023).

### 2.3 | Interaction Index

A measure of the potential interaction between harbour porpoise and static net fishing, referred to as the interaction index, was based on the concept that the probability of porpoise encountering fishing gear will be a function of their population density and the fishing effort (Gulland 1983). The probability of porpoise actually being captured by a gillnet will depend on a variety of additional variables related to 'catchability', for which we have no information at relevant spatial and temporal scales.

The interaction index could be expressed in absolute units of animal-hours per unit area, but to facilitate comparison with different protected species and fishing gears in future studies, it was considered useful to standardise the index to a common range of values. To do this, both population density and fishing effort were standardised to a 0–1 scale. The fishing area was identified as the collection of 20 × 20 km pixels within the selected OSPAR assessment areas that had nonzero static gillnet fishing effort in either June or December. Separately for population density and fishing effort, an empirical cumulative frequency distribution function (ECDF) was estimated from the nonzero values in both months combined (modelled population density was >0 in all pixels, but fishing effort was zero in some pixels in one or other month) using the 'ECDF' function in R Version 4.2.1 (R Project Team 2022). The resulting ECDF was then used to express each pixel value as its cumulative distribution value, that is, the proportion of the data less than or equal to the original value, subsequently referred to as the quantile proportion. Calculating the ECDF of fishing effort from nonzero values ensured that zero fishing effort had a quantile proportion of zero. By utilising the entire distribution of each measure in the standardisation, the index was not strongly influenced by individual extreme values. The treatment of the nonzero static gillnet fishing effort and use of quantiles to standardise the data differs from approaches that have been adopted in other research on cetacean bycatch risk. For example, Evans, Carrington, and Waggitt (2021) used the entire mapped area under consideration converting pixels with no data to zero rather than utilising only the nonzero pixels and standardised fishing effort by dividing each value by the maximum value. Such an approach renders the index sensitive to a single extreme value (e.g., the maximum).

For each pixel in the fishing area, the interaction index was calculated as the product of the quantile proportion of population density and the quantile proportion of fishing effort. Values approaching 1 indicated the highest densities of harbour porpoises co-occurring with the highest levels of fishing effort, representing the greatest potential risk of porpoise encountering static gillnets. Values approaching 0 occurred where the lowest densities of harbour porpoise corresponded with lowest levels of fishing effort, representing the lowest potential risk of encounters. Intermediate values could arise from a range of intermediate to high values of one variable combined with a complementary value of the other.

Skewness (b1) of the interaction index was calculated with the skewness function of the R package 'e1071' (Meyer et al. 2023), with 95% confidence intervals calculated from 1000 bootstrap replicates. Differences in the interaction index between months and among assessment areas were also tested by taking a random sample of one third of the nonmissing values from each of the June and December rasters of the interaction index and assigning them to their respective month and assessment area. A linear model with the factors month, assessment unit and their interaction had significant spatial autocorrelation in the residuals (Moran's $I = 19.6$, $p < 0.001$), so a spatial simultaneous autoregressive lag model and a spatial simultaneous autoregressive error model with factors month, assessment area and their interaction were fitted using functions in R packages 'spatialreg' and 'spdep' (Pebesma and Bivand 2023). The interaction index was arcsine transformed prior to model fitting to improve the distribution of the residuals. Spatial weights were applied with a distance-weighted neighbours list. The spatial lag and spatial error models led to similar conclusions. The spatial error model was favoured on the basis of a lower value of Akaike's Information Criterion.

## 3 | Results

Harbour porpoise population density varied spatially, but the spatial distribution did not vary to any great extent between June and December (Figure 2). The highest population densities occurred in the east-central and southern North Sea primarily in the waters of Denmark, Germany and the Netherlands. The distribution was slightly more concentrated there in December. There was also an area of higher density in the Irish Sea, along the northwest coast of England. Harbour porpoise density was lower in the northern North Sea, in the Irish and Celtic Seas and the western English Channel.

Static net fishing effort was generally more widespread and higher in June compared to December, particularly in the Celtic Sea and east-central and southern North Sea (Figure 3). In December, static net fishing was more concentrated in some areas, such as west of Denmark, west of Ireland in the vicinity of Porcupine Bank and in the eastern margin of the Bay of Biscay.

The interaction index indicated that the highest potential co-occurrence of harbour porpoise and gillnet fishing occurred in the east-central and southern North Sea, and in the eastern English Channel in both months, though with a greater spatial coverage of higher values (e.g., >0.6) in June (Figure 4). Also in June, there were small areas with intermediate to moderately high values (0.4–0.8) of the interaction index to the west of Shetland and along the east coast of Britain. The area between southern Ireland and southwest England in and the northern part of the Irish and Celtic Seas assessment area had intermediate values (e.g., 0.4–0.6) of the interaction index in June but lower values in December (<0.4) (Figure 4). In the southern part of the Irish and Celtic Seas assessment area, particularly in the Bay of Biscay, values of the interaction index

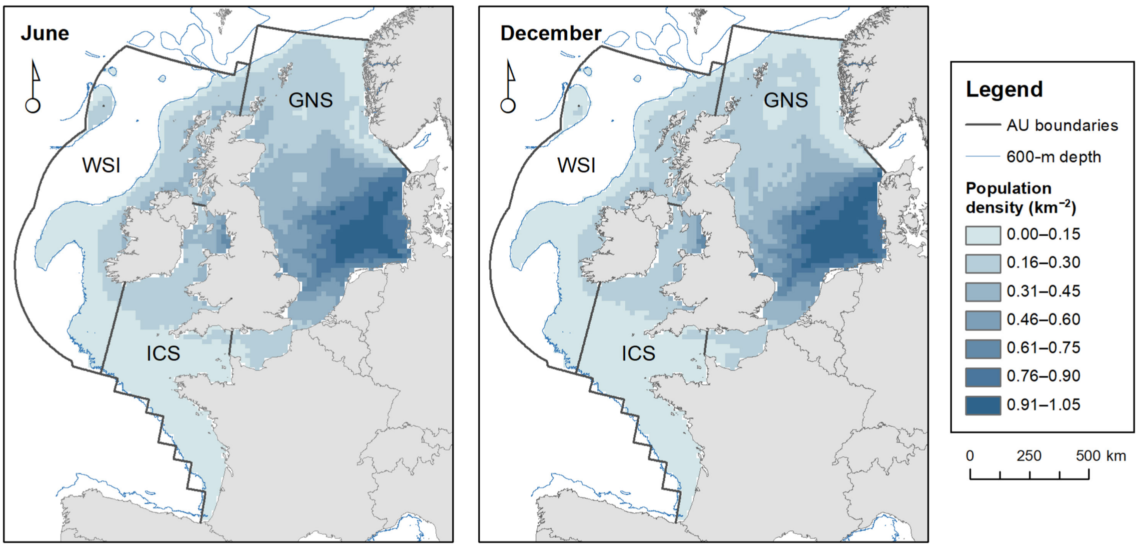


**FIGURE 2** | Spatial distribution of harbour porpoise population density (number per km$^2$) in June and December within selected assessment units (AU) and in water depths <600 m, derived from surveys between 1980 and 2018 (based on data from Waggitt et al. 2020). Assessment units: Greater North Sea (GNS), West of Scotland and Ireland (WSI) and Irish and Celtic Seas (ICS).

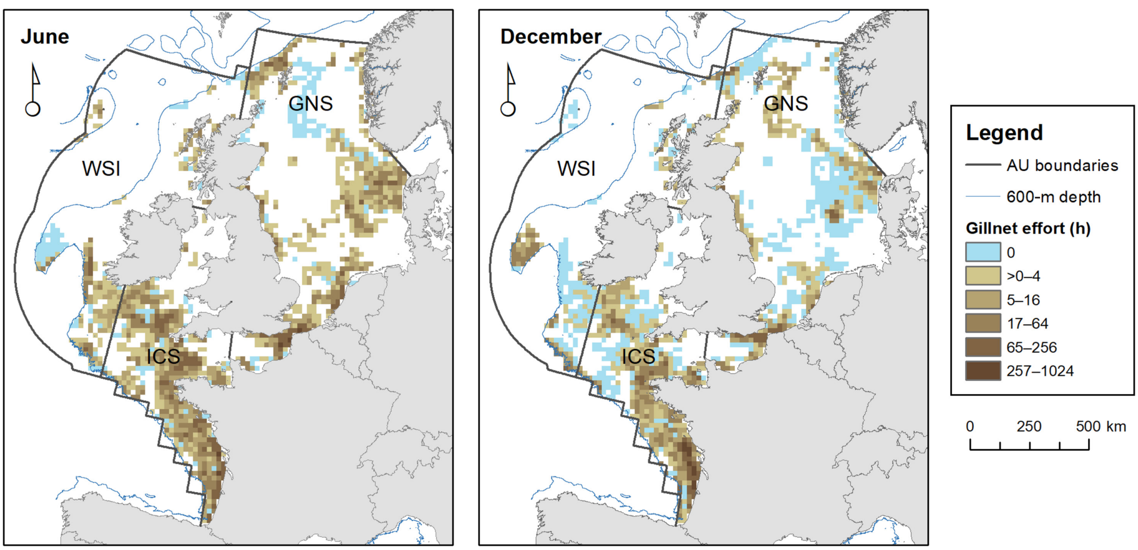


**FIGURE 3** | Static gillnet fishing effort (mean hours per month) for June and December averaged for the years 2012 to 2016 within selected assessment units (AU) and in water depths <600 m (based on data from Global Fishing Watch 2022). Blue pixels represent areas where there was zero fishing effort in 1 month but nonzero effort in the other. Assessment units: Greater North Sea (GNS), West of Scotland and Ireland (WSI) and Irish and Celtic Seas (ICS).

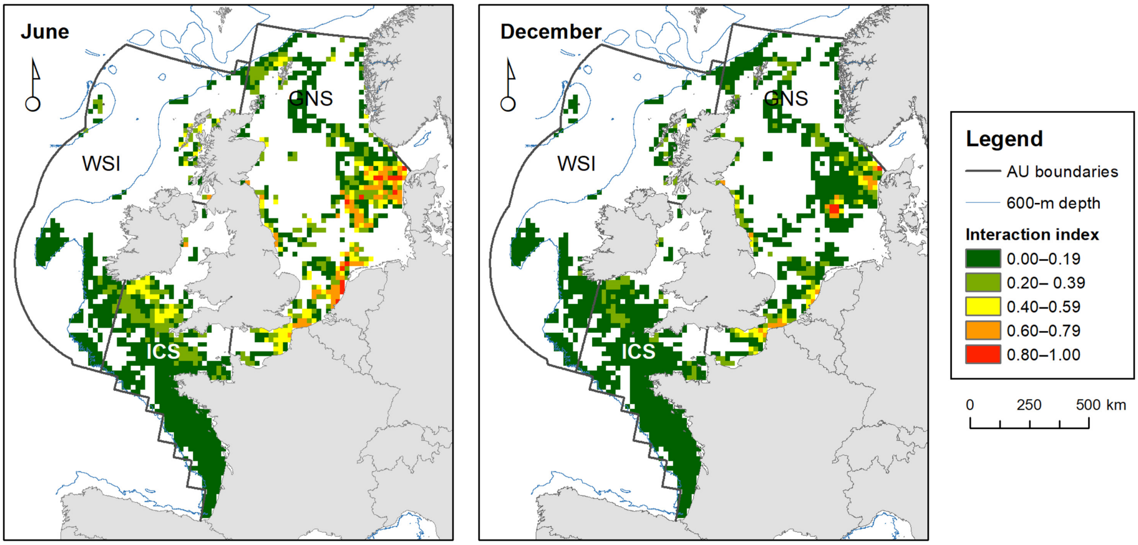


**FIGURE 4** | Interaction index between harbour porpoise population density and static gillnet fishing effort in the years 2012–2016 for June and December. Assessment areas: Greater North Sea (GNS), West of Scotland and Ireland (WSI) and Irish and Celtic Seas (ICS).

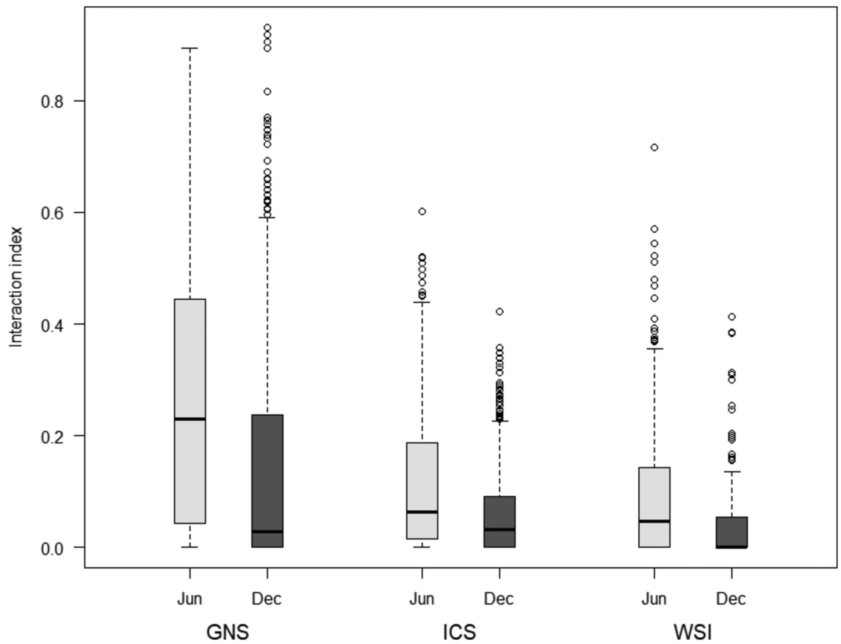


**FIGURE 5** | Box plot of the interaction index values by assessment area and month. Assessment areas: Greater North Sea (GNS), West of Scotland and Ireland (WSI) and Irish and Celtic Seas (ICS).

were predominantly very low (<0.2). In the West of Scotland and Ireland assessment area, the spatial distribution of static gillnet fishing activity was more restricted, and values of the interaction index were generally low, apart from some small areas around the Western Isles and mainland west coast of Scotland and to the west of Shetland in June, where there were isolated pixels with intermediate values (0.4–0.7).

For all three assessment areas in both months, the frequency distribution of the interaction index was positively skewed (Figure 5 and Table 1). On average, the interaction index was highest for the Greater North Sea, particularly in June, with maximum values >0.8 in both months (Figure 5). The combination of low median value and extreme outliers for the Greater North Sea in December reflected the spatial concentration of high values in small areas in that assessment unit and month (Figure 4). Within months, the medians of the interaction index for the Irish and Celtic Seas and for the West of Scotland and Ireland were lower than in the Greater North Sea (Figure 5). The

**TABLE 1** | Skewness ($b_1$) of the interaction index by assessment area and month. Values in brackets are 95% bootstrap confidence limits, none of which encompass zero.

| Assessment area | June | December |
|---|---|---|
| Greater North Sea | 0.6 (0.39–0.85) | 1.7 (1.34–2.14) |
| Irish and Celtic Seas | 1.2 (0.86–1.52) | 1.4 (1.10–1.85) |
| West Scotland & Ireland | 1.9 (1.29–2.97) | 2.3 (1.56–3.68) |

difference between months was less marked in these assessment units than was observed for the North Sea.

The largest effect in the spatial simultaneous autoregressive error model was related to month: The interaction index was on average 0.05 ± 0.001 units higher in June than December (effect ± SE; Z = 10.35, $p < 0.001$) (Figure 6). There was also a significant interaction between the effects of month and assessment unit ($\chi2 = 137.1$, $df = 5$, $p < 0.001$), indicating that the magnitude of the difference between months varied among assessment areas (or vice versa). In particular, the monthly difference was 0.02 ± 0.0011 less in the Irish and Celtic Seas ($Z = -4.35$, $p < 0.001$).

## 4 | Discussion

The interaction index provides a measure of the potential for harbour porpoise to interact with static nets. This index was based on the concept that the probability of porpoise encountering fishing gear will be a function of their population density and the gillnet fishing effort. The index provides a measure of the risk that bycatch could occur but does not provide a definitive assessment that can be used for management purposes. Because of the limitations in the underlying fisheries data, such as the incomplete coverage of smaller inshore vessels (Pinn 2023) and the way in which fishing effort is calculated (Kindt-Larsen et al. 2023) or possible underestimate or overestimate of the harbour porpoise population density at a particular location (Waggitt et al. 2020), there may be discrepancies between the interaction index and actual bycatch rates. The interaction index provides information that can be used to target additional studies.

### 4.1 | Data Considerations and Influences

There has been some debate about the value and use of AIS data in representing fishing effort when VMS data are used for fisheries management purposes (McCauley et al. 2016; Russo et al. 2016; Shepperson et al. 2018; Thoya et al. 2021). However, VMS data are generally not publicly available, and, where it is released for use by scientists, the data are aggregated at a coarse scale (Hinz et al. 2013; Shepperson et al. 2018), rendering it unsuitable for the type of analysis undertaken in the current study.

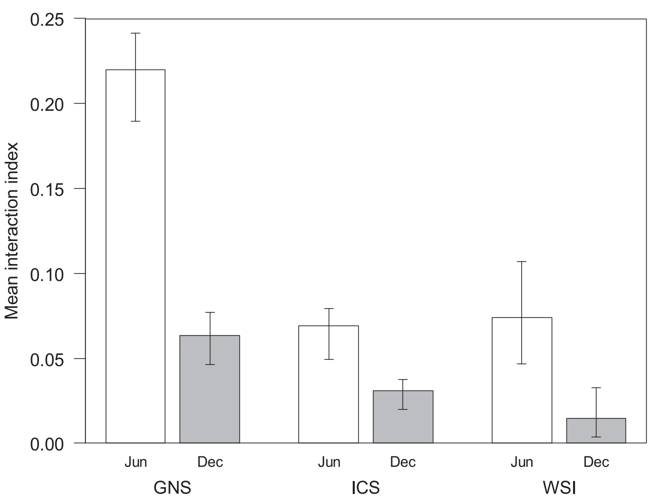


**FIGURE 6** | Predictions of the interaction index by assessment area and month from a spatial autoregressive error model. Error bars are 95% bootstrap confidence intervals. Assessment areas: Greater North Sea (GNS), West of Scotland and Ireland (WSI) and Irish and Celtic Seas (ICS).

A number of advantages and disadvantages of the AIS and VMS datasets have been identified. There are differences in the frequency of signal transmission between AIS and VMS, that is, the poll frequency. Notably, AIS can provide more detailed information in relation to vessel movements because the poll frequency is much greater, that is, at 30–60 s intervals in comparison to every 2 h for VMS (Shepperson et al. 2018; Thoya et al. 2021). Consequently, AIS data have a much better temporal resolution and are generally better suited for mapping fishing effort compared to VMS which needs to be interpolated (Thoya et al. 2021). However, unlike VMS, vessel skippers have some control over the AIS signal, which can be turned down or switched off for safety reasons (e.g., to prevent piracy). As a result, AIS data can lack consistent coverage, particularly where a skipper may not want the vessel's activity to be detected (McCauley et al. 2016; Malarky and Lowell 2018). Conversely, when a vessel has unexplained gaps in transmission, particularly in areas where fishing restrictions exist, it can act as a 'red flag' and lead to further investigation (Cutlip 2016; Malarky and Lowell 2018).

The AIS and VMS datasets also differ in terms of the coverage of fishing vessels, although there has been some convergence in the datasets for European waters (MMO 2023). Both datasets are thought to underestimate fishing effort due to the bias in mandatory coverage towards larger vessels (i.e., >12 m for VMS and >15 m for AIS) (Thoya et al. 2021). This situation is changing with, for example, the introduction of requirements for inshore VMS (i-VMS) on all fishing vessels <12 m in length fishing in Welsh waters via the Sea Fishing Operations (Monitoring Devices) (Wales) Order (2022). Similar requirements are expected to be introduced for the rest of the UK by 2026 (Marine Directorate 2023; MMO 2024) and the EU fleet by 2028 (Directorate-General for Maritime Affairs and Fisheries 2024). However, i-VMS data will be subject to the same confidentially issues as VMS, so although the requirement to use i-VMS will be beneficial for fisheries managers, it is unlikely to improve data transparency for the scientific and wider community.

As a result of the uncertainties highlighted, it is essential that evidence of the risk of bycatch is obtained from field studies (e.g., corroboration via stranding data or from monitoring via on-board observers or REM) prior to any fisheries management being introduced. Any measures also need to balance fishery and conservation objectives at an appropriate scale for the spatial and temporal patterns of bycatch risk.

### 4.2 | Evaluation of the Interaction Index Output

The results of this study indicate that harbour porpoise bycatch risk was low to moderate in the Irish and Celtic Seas assessment area but spread over a large area. In contrast, there is a greater potential for interaction in the North Sea assessment area but in small, localised areas, indicating a more concentrated risk of bycatch. Areas identified as being of potential concern include the eastern English Channel, southern North Sea and in east-central North Sea, whereas for the West of Scotland and Ireland assessment area, the potential bycatch risk appears to be relatively low overall, except in some localised coastal areas. The majority of these fishing areas correspond with known static net fisheries for hake (*Merluccius merluccius*), monkfish (*Lophius piscatorius*) and pollack (*Pollachius pollachius*) (Gerritsen and Kelly 2019; Evans, Carrington, and Waggitt 2021).

OSPAR (2008) listed harbour porpoise as a threatened and declining species on the basis of bycatch occurring in the English Channel and southern North Sea, which had led to severe declines in abundance. ICES (2015) identified the highest levels of bycatch in the Celtic Seas, particularly ICES Divisions 7e (western English Channel), 7f (Bristol Channel) and 7h (Celtic Sea south), whereas moderate levels occurred in Area 7e (eastern English Channel). More recently, Evans, Carrington, and Waggitt (2021) identified the highest harbour porpoise bycatch risk areas for gillnets as being the eastern part of the English Channel (year-round), the western English Channel (between July and September) and the Skagerrak and the German Bight (particularly between April and June). Focusing on UK waters, McFarlane (2020) identified a small area to the west of the Northern Isles as being potentially high risk, whereas for inshore English waters, Greig (2021) noted that the potential risk of bycatch was likely greatest around Cornwall (western English Channel) and the southeast (eastern English Channel). Given the variety of datasets and modelling approaches employed by these different studies, the similarity of outcomes adds weight to the potential value of the interaction index developed in this study as a mechanism for focusing monitoring and, once a bycatch issue has been evidenced, consideration of suitable mitigation options.

The bycatch rate for the Irish and Celtic Seas assessment area is recognised as the highest in European waters (ICES 2015; Northridge, Kingston, and Thomas 2019). The low to intermediate values of the interaction index for this assessment area suggest that bycatch is an extensive issue (i.e., there is a relatively low risk of occurrence but the risk is widespread). In contrast, the prevalence of smaller areas of higher interaction potential in the North Sea assessment area combined with the moderate interaction index with high outliers suggests that bycatch may potentially be an acute issue in small, localised areas.

### 4.3 | Fisheries Management Considerations

Due to the rarity of bycatch events in the static net fleet, it would be necessary to monitor almost the entire fleet in order to estimate the severity of any bycatch issue. This is not feasible. Risk mapping is therefore considered to have an important role in identifying where targeted monitoring would be beneficial (OSPAR-HELCOM 2019; Defra 2022). Once the risk of bycatch has been confirmed and is considered sufficiently high to require management and mitigation, then the most appropriate measure to introduce needs to be considered.

A variety of management tools are available to reduce the bycatch of protected species, ranging from technical measures through to area closures. Technical measures are more likely to be accepted and implemented by fishers than other restrictions on fishing activity, such as area and seasonal closures, because they enable fishing to continue on known grounds. Pingers (acoustic deterrents) have generally proven very effective at reducing harbour porpoise bycatch in static nets (Kindt-Larsen et al. 2019; Brennecke et al. 2022; Königson et al. 2022; Moan and Bjørge 2023). A benefit of pingers is that they allow fishing activities to continue without substantially altering the gear or fishing regime. Since 2004, vessels 12 m or more in length deploying static nets in European waters have generally been required to use pingers through EU and UK legislation. In contrast, there is no such requirements for smaller vessels that generally operate close to shore, although some EU Member States (e.g., the Netherlands and Finland) have enabled the voluntary use of pingers (Scheidat, Couperus, and Siemensma 2018; ICES 2020), whereas Norway has made their use mandatory in all static net fisheries (Moan and Bjørge 2023).

Once the risk of bycatch in a fishery has been confirmed via monitoring, the interaction index has the potential to inform management options. The use of area-based management might be considered most applicable to locations in the southern North Sea and in the eastern English Channel, particularly where such locations overlap with areas identified as being important to the species, for example, Special Areas of Conservation (SAC) designated through Council Directive 92/43/EEC on the Conservation of Natural Habitats and of Wild Fauna and Flora (i.e., the Habitats Directive 1992). For mobile species such as harbour porpoise, SACs represent areas that have been identified as being of particular importance, encompassing areas with higher densities of individuals present over several generations (Sveegaard et al. 2011; Pinn, Macleod, and Tasker 2021).

Such an approach is exemplified by prohibition of gillnet and entangling nets in the Sylter Aussenriff and Östliche Deutsche Bucht SACs in German waters (EU Delegated Regulation of 8 December 2022 amending EU Regulation 2017/118 n.d.). Within the German National Park Schleswig-Holstein Wadden Sea, all gillnet fisheries are prohibited within 3 nautical miles (NM) of the coast, and there are restrictions on net length, height and mesh size beyond 3 NM (ASCOBANS 2020). In contrast, for two other SACs in German waters (Borkum-Riffgrund and Doggerbank), the risk of harbour porpoise bycatch was considered to be much lower, so a limit on static net fishing effort was thought to provide sufficient risk mitigation (EU Delegated Regulation of 8 December 2022 amending EU Regulation 2017/118 n.d.).

The close proximity of an SAC to an area of potential bycatch risk could provide an indication that the site boundaries need to be altered or other management measures introduced. For example, the Southern North Sea SAC, designated for harbour porpoise by the UK in 2019, is located adjacent to the concentration of high potential risk in the eastern English Channel at its southern boundary. It should be noted, however, that any proposal to change the site boundary would need to be based on evidence that the area outside the current SAC boundary is important for harbour porpoise and that there is a genuine bycatch issue in the static net fisheries operating in the adjacent area.

The Irish and Celtic Seas assessment area appeared to have widespread low risk of bycatch, particularly in the north of this area, and consequently, if this pattern of risk were to be confirmed, area-based management would be less suitable. The use of technical measures and/or effort control would be more appropriate as they can be applied and enforced over the entire region. Significant declines in harbour porpoise abundance have been noted for this assessment area (Hammond et al. 2021; Geelhoed et al. 2022), suggesting that effort controls such as preventing further expansion of the static net fleet are unlikely to reduce the bycatch risk. The use of pingers is already required on the larger static net fishing vessels (i.e., those ≥12 m in length) operating in ICES Areas 7e-h and 7j (EU Regulation 2019/1241 n.d.). In order to further reduce the occurrence of harbour porpoise bycatch, this requirement could be extended to all static net vessels operating in the Irish and Celtic Seas assessment area. However, rather than the blanket use of pingers on all static net vessels, further research investigating monthly trends of bycatch risk could help to distinguish if there were more sensitive months and/or seasonal small-scale fisheries in which the use of pingers would be most effective, as the present study considered the potential interaction only in June and December.

For the West of Scotland and Ireland assessment area, both the bycatch rate and index of potential interaction were low. This might suggest that bycatch is not a major issue for the region. However, OSPAR's Quality Status Report 2023 concluded that the bycatch of harbour porpoise in static net fisheries in this assessment area was exceeding conservation thresholds (OSPAR-HELCOM 2019; Taylor et al. 2022). The majority of potential interaction locations identified in the present study occur along the boundaries of or within the Inner Hebrides and the Minches SAC, which was specifically designed for harbour porpoise in 2016.

To date, the bycatch of harbour porpoise has not been perceived as an issue in Scottish waters. For example, there have been relatively few occurrences of bycatch being identified as a cause of death in stranded animals (e.g., Davison, ten Doeschate, and Brownlow 2020; Davison and ten Doeschate 2021). Current management of the Inner Hebrides and the Minches SAC takes an evidence-based approach for all activities including the need for fisheries management measures. Because bycatch is a very rare event for the individual fisher in West of Scotland and Ireland assessment area, achieving acceptance by fishers of any new management measure will be extremely challenging and will need to be balanced against the need to tackle other threats to the species. For example, based on postmortem examinations, bottlenose dolphin and grey seal attacks and collisions with shipping are much more common causes of harbour porpoise death (Davison, ten Doeschate, and Brownlow 2020; Davison and ten Doeschate 2021), whilst disturbance from seal scarers (acoustic devices used by the salmon farming industry) has also been raised as a significant issue (Scottish Government 2021).

## 5 | Conclusions

In order to achieve effective marine mammal conservation alongside the sustainable use of our natural resources, management of human activities needs to become more adaptive, dynamic and holistic. All countries of the Northeast Atlantic have committed to minimising and, ultimately eliminating, the bycatch of protected species such as the harbour porpoise. Given the rarity of such events, intergovernmental and other organisations have recommended the development of risk-based approaches with the potential to highlight and/or define where bycatch monitoring would be most effective in order to focus management resources most effectively (e.g., OSPAR-HELCOM 2019; Defra 2022; ASCOBANS 2023). This study provides an example of such an approach, providing provisional indications of where more focused bycatch monitoring would be beneficial. The potential to use REM (e.g., installing cameras onboard vessels to detect bycatch events) in building the evidence base for smaller vessels where observers cannot be accommodated will be invaluable, especially in those areas where the risk is uncertain and for confirming the level of risk suggested by the index in particular locations. Once evidence of the bycatch risk has been established, the most effective mitigation option(s) can be adopted.

### Ethics Statement

No ethical and permit approvals were required for this work.

### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

All data used were publicly accessible via Global Fishing Watch (https://globalfishingwatch.org/data-download/datasets/public-fishing-effort) and for the distribution map of harbour porpoise via Dryad (10.5061/dryad.mw6m905sz).

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