MarPAMM Marine Protected Area Management and Monitoring

Interreg Northern Ireland - Ireland - Scotland European Union European Regional Development Fund

Report on the seabird ~ fisheries interactions modelling

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Summary

In the marine environment, human activities can shape the distribution and behaviours of species. Commercial fisheries are an important source of food for many seabird species globally, where many birds scavenge fisheries waste in various forms such as undersized commercial species, unwanted catch, or offal. As a result of this interaction, fisheries can have direct (bycatch) and indirect (competition for resources) impacts on seabird populations. Recent advances in examining seabird – fisheries interactions have demonstrated the advantage of contemporaneous tracking of both seabirds and fishing vessels, as it allows for more reliable estimates of seabird-fisheries interactions compared to other methods such as using broad overlap. Here we collated an extensive dataset of seabird tracking data amounting to 1,499 foraging trips from 490 individuals of 7 species across 13 colonies. By analysing these data in relation to concurrently tracked fishing vessels from Vessel Monitoring System (VMS) data, we show that tracked Black-legged kittiwake, Common guillemot, European shag, Razorbill, and Manx shearwater did not interact with fishing vessels. Tracking data from three breeding colonies of Northern gannet and three breeding colonies of Northern fulmar showed that on average 31% (gannets) and 42% (fulmar) of predicted area-restricted search behaviour was in association with fishing vessels. Both Northern gannet and Northern fulmar interacted most with trawlers, though considerable interactions with demersal seiners and gillnets were also identified in both species. We discuss our findings in relation to fishing activity within the Interreg-VA area, existing knowledge of these species and the need for additional tracking work within the area.

Introduction

Commercial fisheries have widespread impacts on marine ecosystems through various direct and indirect pressures (Pauly *et al*., 2005; Ortuño and Dunn, 2017). Fisheries bycatch has been identified as one of the most serious threats posed to many marine vertebrates (Lewison *et al*., 2004; Read *et al*., 2006; Dias *et al*., 2019). Because many of these species are within the upper trophic levels, their removal is likely to have impacts on lower ecosystem level functioning (Estes *et al*., 2011). One group that are particularly sensitive to commercial fisheries bycatch are seabirds (Anderson *et al*., 2011). Seabirds are long-lived K-selected species (low productivity and delayed maturity) and are therefore vulnerable to reductions in mortality caused by the various threats they face on land at their breeding colonies or while at-sea (Croxall *et al*., 2012; Dias *et al*., 2019). Global population trends suggest that over half of the world's monitored seabird populations are in decline (Paleczny *et al*., 2015), and fisheries bycatch is thought to threaten 28.7% of species worldwide (Dias *et al*., 2019). In order to understand the threats posed to different seabird species, it is necessary to examine the extent to which species interact with fishing vessels. These interactions are typically for scavenging purposes as many seabirds exploit fisheries discards in the form of undersized fish, offal or non-commercial species (Grémillet *et al*., 2008; Torres *et al*., 2013).

Various methods have been used to examine how and the extent to which seabirds interact with fisheries. Observer programmes on vessels have been used to make inference on species assemblages around vessels and quantify estimates of bycatch rates (Cherel *et al*., 1996; Fangel *et al*., 2015). However, in many areas these programmes are limited in space and time, and population-level assessments of impacts from bycatch cannot be made from these data alone as several key variables such as the breeding status and breeding colony location cannot be fully explored (Fangel *et al*., 2015). Examining spatiotemporal overlap is the most widely used method to explore seabird-fisheries interactions (Waugh *et al*., 2012; Clay *et al*., 2020). This method assumes that the co-occurrence of fishing vessels and seabirds is indicative of an interaction, but findings are heavily influenced by the spatial scale(s) at which this is assessed (Torres *et al*., 2013). Understanding these limitations, methods such as animal-borne cameras

(Votier *et al*., 2013) or the inclusion of technology to detect radar (Weimerskirch *et al*., 2020) have been made to examine direct interactions. Yet these solutions come at a high cost. A more cost-effective approach is to examine behaviours within existing seabird tracking datasets in relation to concurrently tracked fishing vessels through vessel monitoring system data (Bodey *et al*., 2014; Pirotta *et al*., 2018).

Across Britain and Ireland, 25 species of seabird breed and for some species these breeding populations are of international importance (e.g., the Manx shearwater (*Puffinus puffinus*) and Northern gannet (*Morus bassanus*); Mitchell *et al*., 2008). Population size estimates for these species range from just over 1000 individuals to over 1.2 million spread across several thousand breeding colonies, and their European Conservation status vary; Least Concern (19 *sp*.), Near threatened (3 *sp*.), Vulnerable (1 *sp*.) and Endangered (2 *sp*.). While the Natura network offers some protection to some seabirds at-sea, recent work has shown that many of these species have little at-sea protection through established Marine Protected Areas (MPAs), particularly pelagic species, and there is a need for revised marine conservation planning (Critchley *et al*., 2018). Any such assessment and recommendations on the management and/or designation of marine areas requires knowledge of the threats to be mitigated.

Here we collate a large seabird tracking dataset available within the MarPAMM area to explore how these seabirds interact with fisheries. Specifically, we build upon a recent behavioural state classification model (Pirotta *et al*., 2018) to determine seabird-fisheries interactions within concurrently tracked seabirds and fishing vessels with the three main aims:

- Assess seabird-fisheries interactions across species where tracking data is available,
- Examine what fisheries the seabirds are interacting with, and
- Outline what future work is needed to further our understanding of seabird-fisheries interactions across the Interreg-VA region.

Methods

Seabird tracking data

To carry out this analysis, we sourced seabird tracking data available within the Interreg-VA region. All bird handling, ringing and tagging was conducted under license by the appropriate national regularity bodies, the British Trust for Ornithology (BTO) and institutional ethics committees. GPS devices (iGot-U GT-120 or GT-200, MobileAction®, Taipei, Taiwan) were temporarily attached to mantle feathers of all birds, except for Northern gannets where tags were attached to tail feathers, using tape (Tesa® 4651, Hamburg, Germany). The frequency of GPS fixes was set between 90-600 seconds depending on the species (Supplementary Table 1). GPS equipped birds were recaptured after one or multiple foraging trips, and location data were downloaded using the manufacturer's software.

All seabird GPS tracking data were processed using the *adehabitatLT* package (Calenge, 2006) in the R statistical framework (R Development Core Team, 2016). GPS positions were transformed into Cartesian coordinates using a Universal Transverse Mercator (UTM) 29N or 30N projection. Tracks that had fewer than 10 locations were removed, and only complete trips were included in the analyses (i.e., partial tracks where tag batteries ran out before the birds returned to the colonies were excluded). GPS fixes that occurred near the colony were removed to exclude colony-associated behaviours like rafting and bathing that we were not interested in (Carter *et al*., 2016; McSorley *et al*., 2008). The distance from the colony where behaviours such as rafting occur vary across sites (McSorley *et al*., 2008). To avoid using an arbitrary distance across all colonies, across each track the distance of each GPS fix to the colony was calculated using the 'pointDistance' function in the *raster* package in R. These distances were then plotted, and GPS fixes were removed at the distance indicated by the tail of the initial peak in the histogram. Hidden-state models require regularly time-stamped data, and although GPS tags were programmed to record locations at regular intervals, availability of GPS signal often means fixes are not regular and gaps may occur where GPS fixes may have been missed (for example when a bird is diving) therefore it is necessary to fill gaps. Tracks were standardised using linear interpolation. Across all tracks, over 80% of successive GPS fixes were shorter than the chosen time intervals for interpolation, ensuring limited interpolation of locations.

Vessel monitoring system (VMS) data processing

Vessel Monitoring System (VMS) data are collected at 2-hour resolution from all vessels over 12 metres in length from 2012 – present, and vessels of >15 metres in length from 2009-2012. VMS data were processed using R (UK data) or SQL (Irish data) following the same procedure. VMS data were linearly interpolated to the same temporal resolution of each seabird tracking dataset (see Supplementary Table 1), the distance and bearing to the nearest vessel location in time and space was calculated for each seabird GPS location. Gear type was also extracted from the VMS data to allow inference to be made on how seabird-fisheries interactions may differ across vessel types. Access to VMS data were provided by Marine Scotland Science (all UK VMS data) and the Marine Institute (all Irish data).

Behavioural state classification

We initially looked for the potential for birds to be directly interacting with vessels by plotting the distances between all seabird and vessel locations. Preliminary analysis of all datasets showed that these data-driven models, which aim to specifically identify vessel associations, incorrectly identified locations as interactions that were at considerable distances from vessels when <1% of the data are within 1km of a fishing vessel. Therefore, datasets where <1% of seabird locations occurred within 1km of a fishing vessel were considered unlikely to be interacting directly with vessels, and vessel-association models were only run on datasets where >1% (Northern Gannet and Northern Fulmar) of locations occurred within 1km of vessels.

Hidden Markov Models (HMMs) have proven to be an effective method of classifying different behavioural states based on the features of an animal's movement (Michelot *et al*. 2016; McClintock and Michelot, 2018). Seabird movements are typically classified into three underlying states (resting, transiting and foraging) by the characterization of the distributions of step lengths and turning angles between consecutive locations. Pirotta *et al*. (2018) built upon this method for central place foragers, separating the movement phase and movement steps into two separate latent state processes allowing processes that may attract or repel animals to be discerned. Pirotta's model results in 6 states, as only area-restricted search and transit were included in the model across the three different movement phases (away from the colony, towards the attractor (the nearest fishing vessel, in this application) and returning to the colony). We added an additional 7th state to include resting behaviour that was present in some of the Northern Gannet and Northern Fulmar data (see Figure 1). The frequentist implication of Pirotta *et al*.'s model was implemented and expanded on in the R package *momentuHMM* (McClintock & Michelot, 2020). A Weibull distribution for the step lengths, a von Mises distribution for the bearing and a log-normal distribution for the distance to the nearest vessel were used as per the original formulation. Model constraints differ slightly in the frequentist implementation (see McClintock and Michelot (2020)) though the model assumptions discussed in Pirotta *et al*. (2018) were retained. The addition of the 7th state required an additional constraint on the scale of the step length whereby resting behaviour was defined by very small steps between locations consistent with drifting on the sea surface.

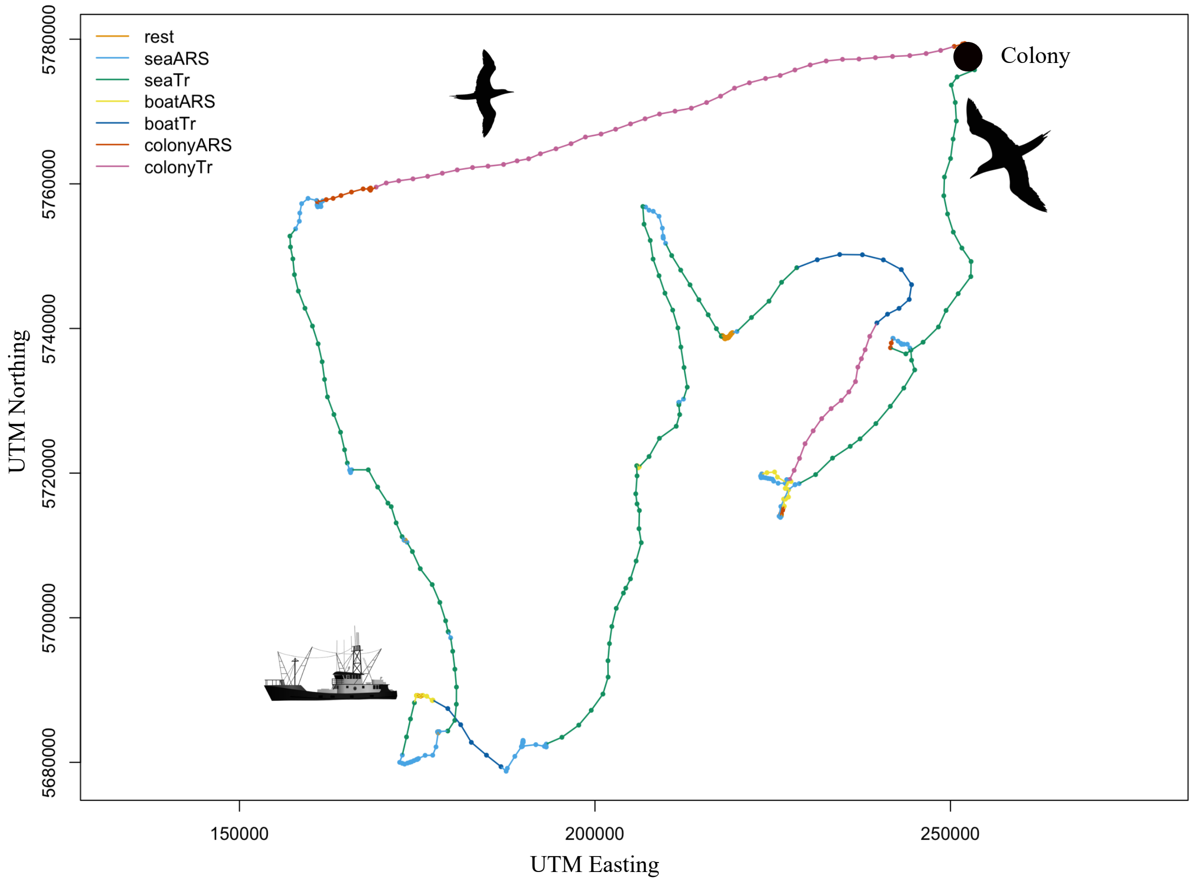

Figure 1. Northern Gannet track from Great Saltee in 2017 coloured by the behavioural states estimated by the 7-state hidden Markov model described above. Behavioural states assigned show resting, foraging (area-restricted search (ARS)) and transiting (Tr) behaviours. Foraging and Transiting states are defined by their movement bearing (i) to the sea, (ii) to the nearest fishing vessel ('boat') and (iii) to the colony.

Fisheries within the Interreg-VA area

To examine the distribution of fisheries activity within the MarPAMM area, Automatic Identification System (AIS) was sourced from Global Fishing Watch (GFW) outputs that are publicly available (at https://globalfishingwatch.org/datasets-and-code/fishing-effort). AIS was developed as a vessel safety system to avoid collisions, however it has now been recognised and used as a valuable resource in marine and fisheries research (Kroodsma *et al.*, 2018; McDermott *et al.*, 2019). Here we used gridded GFW data from 2012-2016 and plot the most recent year (2016) to provide a broad overview of the types of fishing activity within the programme area and relate this to our findings from behavioural state classification model outputs on the seabird tracking datasets.

Results

Tracking data

A total of 1499 complete foraging trips from 490 GPS tracked individuals of seven seabird species, were processed and used in this analysis (Table 1). All tracking data is shown for species that forage close to the coast (Figure 2) and those that carry out more pelagic foraging trips (Figure 3).

Table 1. Outline of the seabird telemetry data sourced for use in the seabird ~ fisheries modelling

Species	Colony	Individuals	No. of tracks	Years
Black-legged Kittiwake	Cape Wrath	5	18	2014
Black-legged Kittiwake	Colonsay	72	150	2010-2014
Black-legged Kittiwake	Rathlin	9	30	2012-2013
Common Guillemot	Colonsay	77	240	2010-2014
Common Guillemot	Lunga	3	12	2014
Common Guillemot	Shiants	1	1	2014
European Shag	Colonsay	40	185	2010-2014
European Shag	Lunga	10	39	2014
European Shag	Rathlin	1	6	2013
Razorbill	Flannan Isles	4	21	2014
Razorbill	Colonsay	41	216	2010-2014
Razorbill	Lunga	7	36	2014
Razorbill	Rathlin	1	5	2012
Razorbill	Shiants	4	12	2014
Northern Fulmar	Eynhallow	42	76	2009-2012; 2017
Northern Fulmar	Kilda	38	57	2011-2012
Northern Fulmar	Little Saltee	10	14	2018-2019
Manx Shearwater	High Island	47	140	2014-2016
Manx Shearwater	Great Blasket	16	35	2014-2015
Northern Gannet	Sule Skerry	2	14	2011
Northern Gannet	Ailsa Craig	16	94	2011
Northern Gannet	Great Saltee	44	98	2017-2019
7 species	**13 Colonies**	**490 Individuals**	**1499 tracks**	**2009-2019**

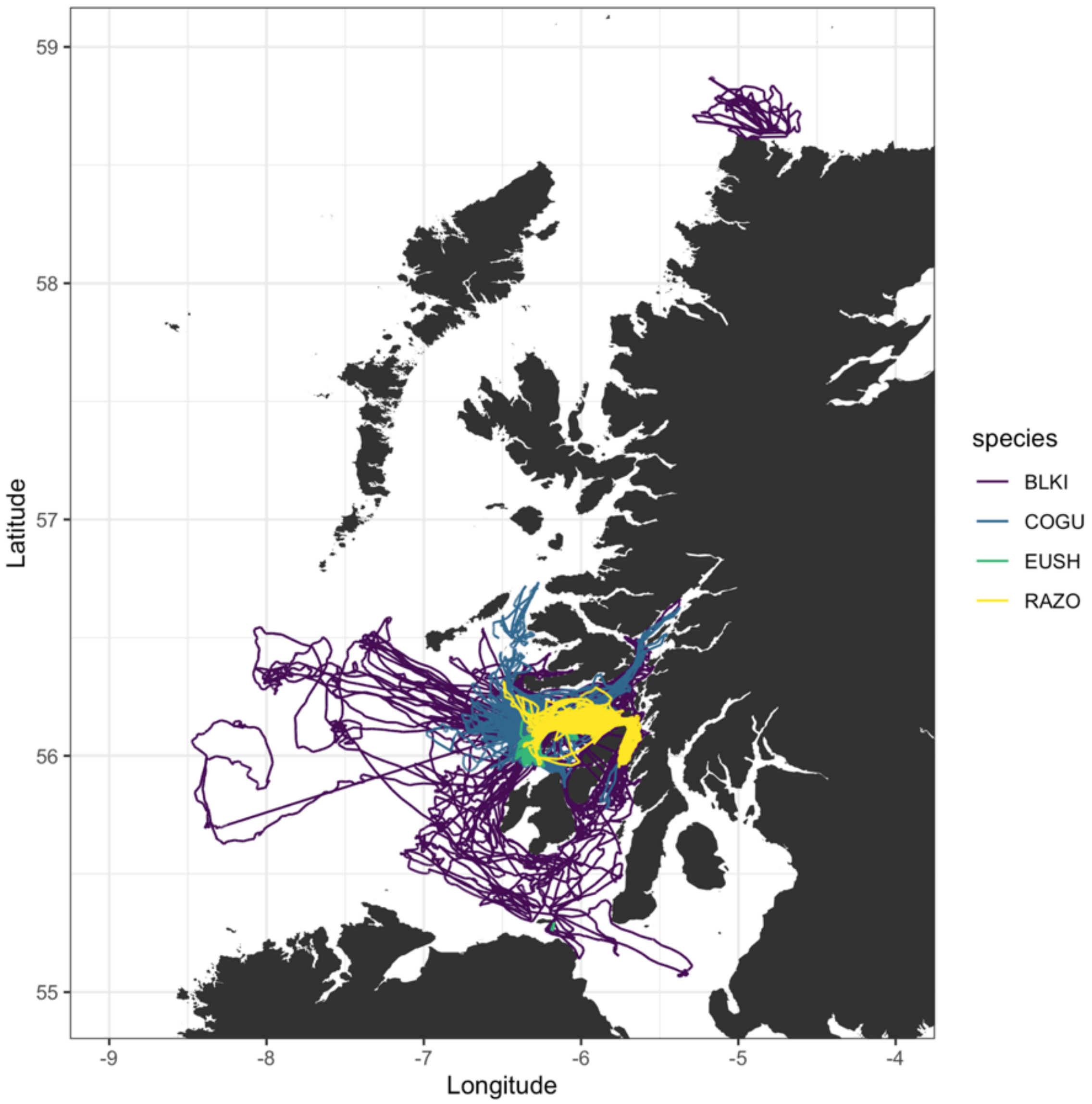

Figure 2. All tracking data from four coastal foraging seabird species within the MarPAMM area: Black-legged Kittiwake (BLKI; *Rissa tridactyla*), Common Guillemot (COGU; *Uria algae*), European Shag (EUSH; *Phalacrocorax aristotelis*) and Razorbill (RAZO; *Alca torda*). Tracking datasets include data from four colonies across 2010-2014.

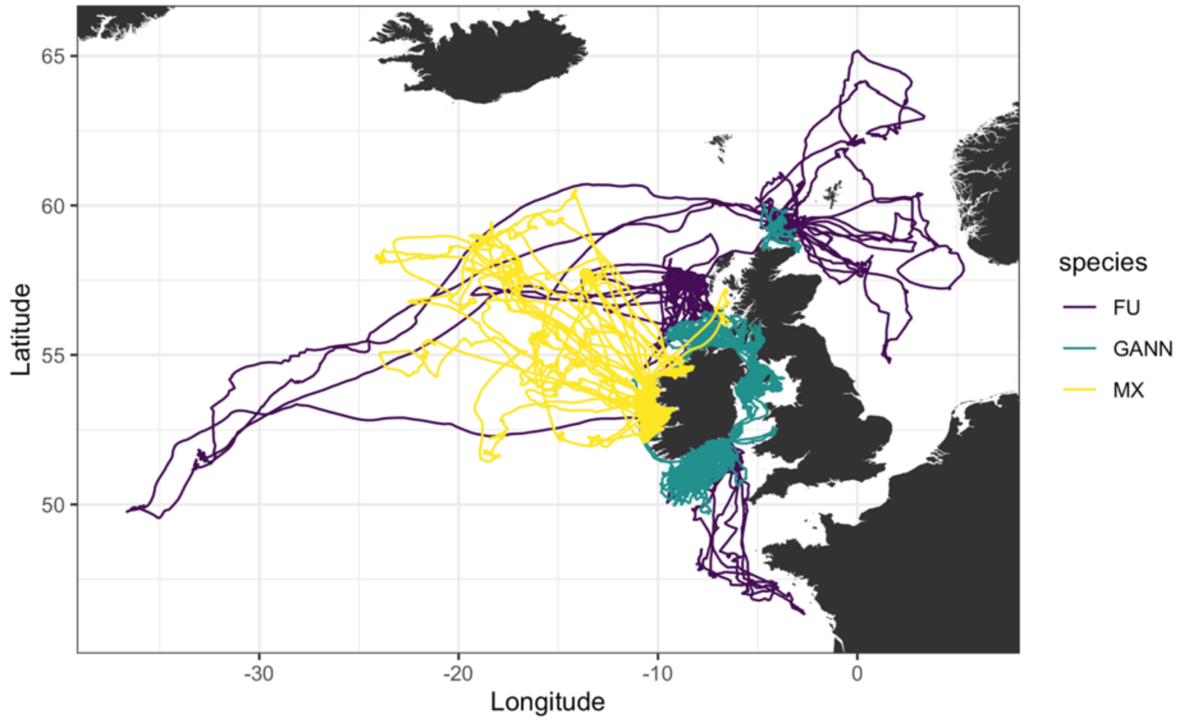

Figure 3. All tracking data from three pelagic foraging seabird species within the MarPAMM area: Northern Fulmar (FU; *Fulmarus glacialis*), Northern Gannet (GANN; *Morus bassanus*) and Manx Shearwater (MX; *Puffinus puffinus*). Tracking datasets include data from six colonies across 2009-2016.

Fisheries interactions

Across species comparisons

By processing concurrently tracked seabird and fishing vessel locations, we found no seabird interactions with fishing vessels in tracked Black-legged kittiwake, Common guillemot, European shag, Razorbill and Manx shearwater (Figure 4). Seven-state hidden Markov models were run on 206 and 83 trips across 3 colonies of both Northern gannet and Northern fulmar, respectively. These models included data from 4 years of tracking Northern gannet and 7 years of tracking Northern fulmar (Table 1). Models showed that on average, across all data, 31% and 42% percentage of all predicted area-restricted search was associated with fishing vessels in Northern gannet and Northern fulmar respectively. Fisheries interactions varied across colonies, a greater proportion of area-restricted search behaviour was associated with vessels in Northern gannets tracked on Sule Skerry (42%) and Great Saltee (38%) compared to those tracked on Ailsa Craig (23%; Figure 5). Similar variation in fisheries interactions was observed across Northern fulmar colonies, with a higher proportion of vessel associated area-restricted search in birds tracked from Eynhallow (48%) and Little Saltee (53%) than those tracked from St. Kilda (13%; Figure 5). Where tracking data were available for more than one year, interactions with vessels varied, with the highest rates of interactions observed in 2018 (38.2%) for Northern gannet tracked on Great Saltee (30% in 2017; 38% in 2019), and 2012, 2011 and 2019 for Northern fulmar tracked on Eynhallow, St. Kilda and Little Saltee respectively.

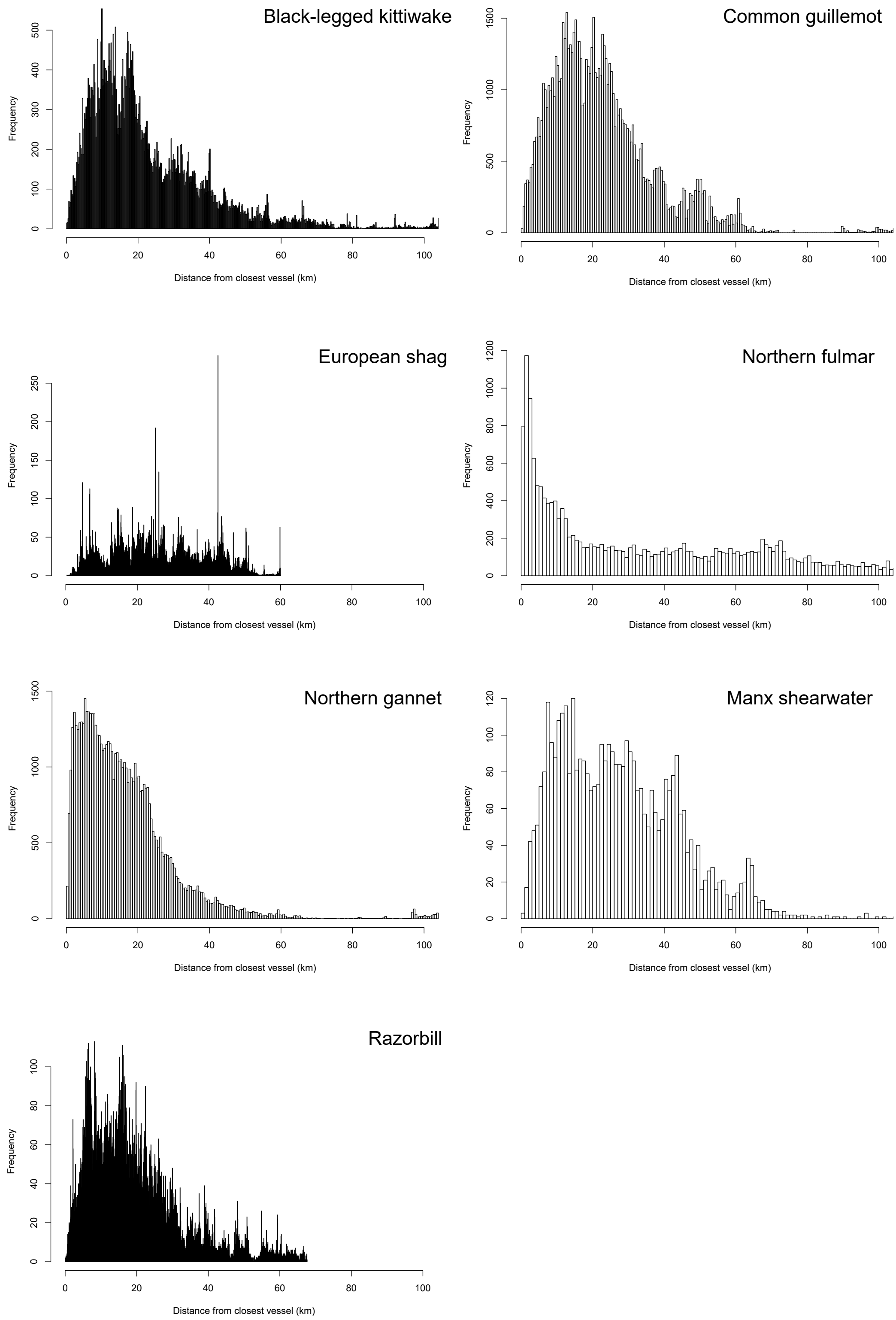

Figure 4: Histograms of the distance (km) to the closest fishing vessel for all locations from seven GPS tracked seabird species.

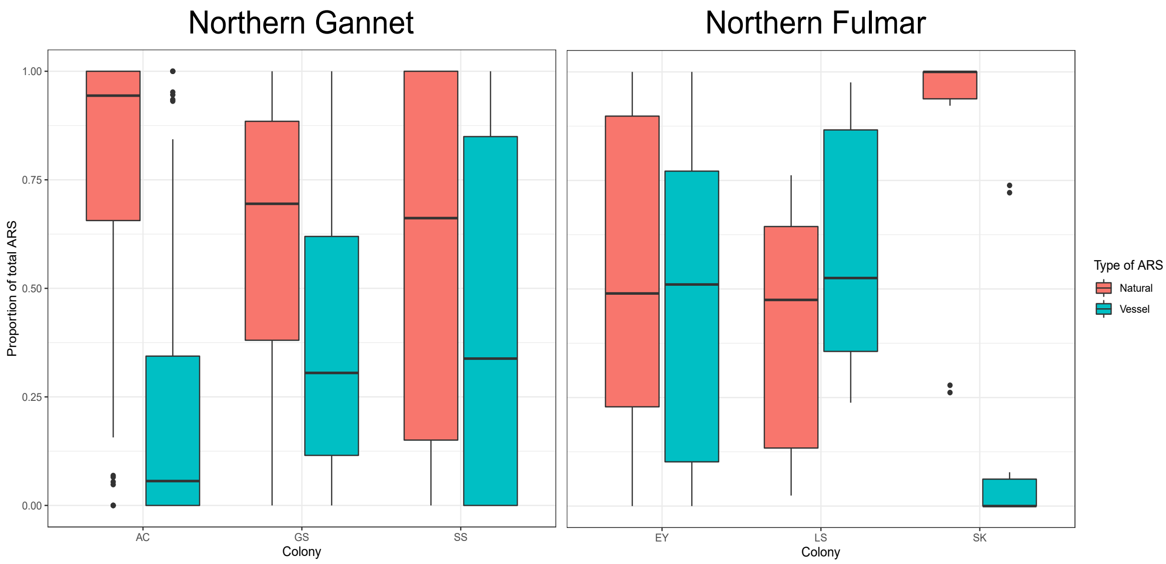

Figure 5: Proportion of all predicted foraging behaviour (area-restricted search; ARS) that was associated with vessels in foraging trips of Northern Gannet and Northern Fulmar both tracked across three colonies. Northern Gannet were tracked on Ailsa Craig (AC), Great Saltee (GS), Sule Skerry (SS) and Northern fulmar were tracked on Eynhallow (EY), Little Saltee (LS) and St. Kilda (SK).

By extracting information on fishing vessel gear type from the VMS data, we examined the types of vessels Northern gannet and Northern fulmar were interacting with. Across all colonies for both species, birds interacted most with trawlers (Figures 6 and 7). Interactions identified in tracking data of Northern fulmar from St. Kilda were exclusively around trawlers (Figure 7). Interactions with demersal seiners and gillnets were recorded in birds tracked from two of the three study colonies in both Northern gannet and Northern fulmar. Across species and colonies, interactions with dredges, hook & lines, and traps were recorded to a lesser extent. In both species, variation in gear types that birds interacted with differed, particularly on the Saltee islands located off the south east coast of Ireland (Figures 6 and 7). Where tracking data were available for more than one year, some yearly variation was present (Supplementary Figures 1 and 2).

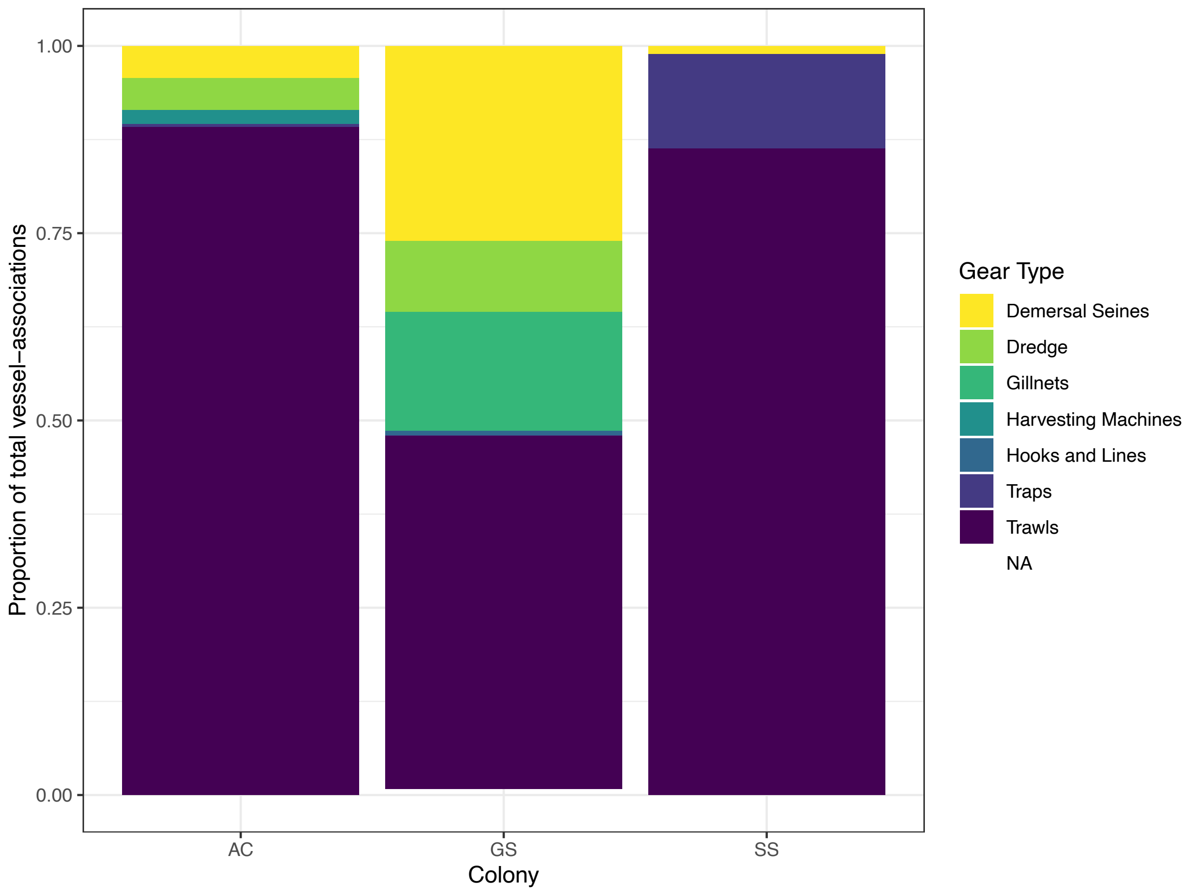

Figure 6: Proportion of total vessel-associated behaviours within each fishing gear type across three Northern Gannet (*Morus bassanus*) colonies; Ailsa Craig (AC), Great Saltee (GS) and Sule Skerry (SS).

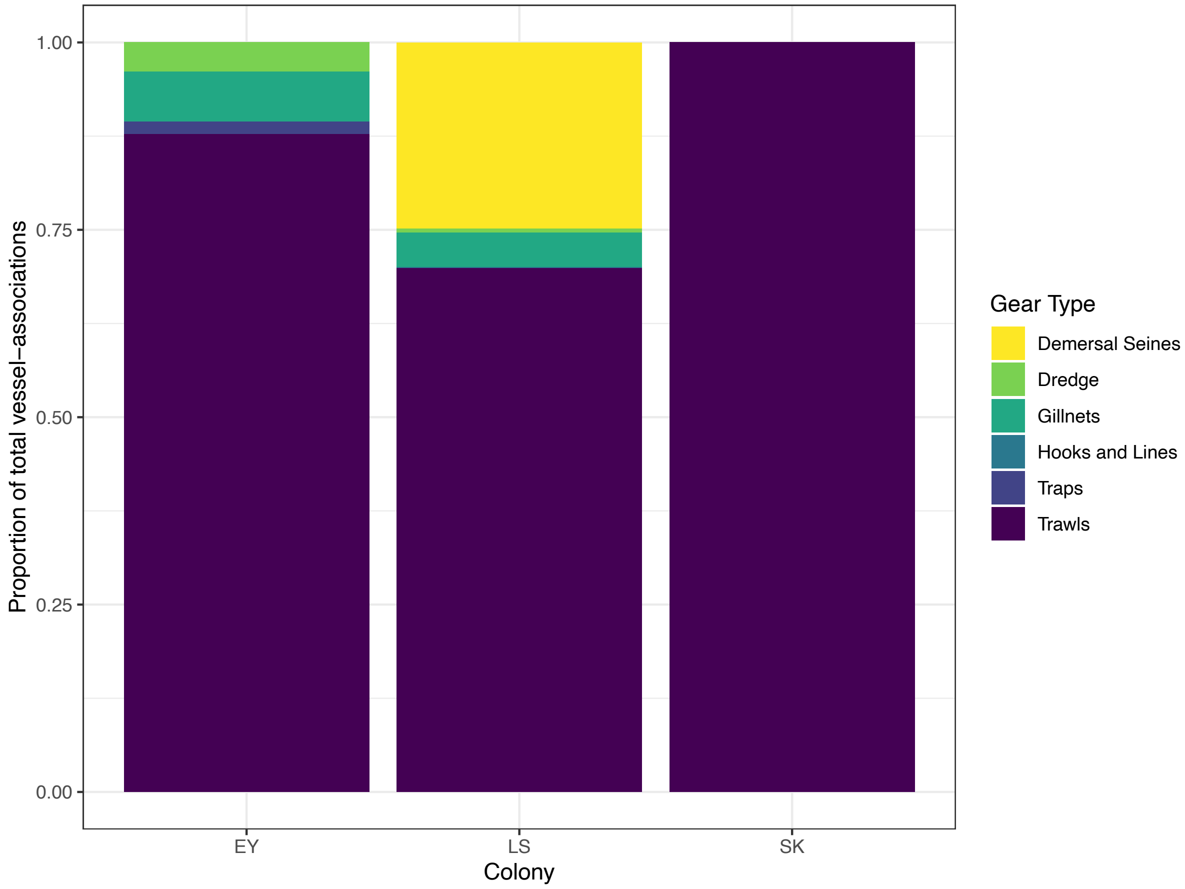

Figure 7: Proportion of total vessel-associated behaviours within each fishing gear type across three Northern Fulmar (*Fulmarus glacialis*) colonies; Eynhallow (EY), Little Saltee (LS) and St. Kilda (SK).

Fisheries within the Interreg-VA area

Fisheries data from GFW's AIS dataset showed a consistent pattern across 2012-2016 and suggest that the majority of fishing activity within the programme are is carried out by trawlers (80% ± 7% S.D.). Considerably less fishing effort is predicted by vessels grouped into GFW fishing gear types categories of fixed gear types (20% ± 6% S.D.), drifting longlines (1.75% ± 0.7% S.D.), purse seines (0.15% ± 0.2% S.D.) and other fishing (0.15% ± 0.08% S.D.). Another gear type identified in GFW's AIS dataset that was not recorded fishing in the programme area is squid jiggers. The distribution of all fishing effort predicted by GFW within the programme area in the most recent year of publicly available data (2016) is shown on Figure 8.

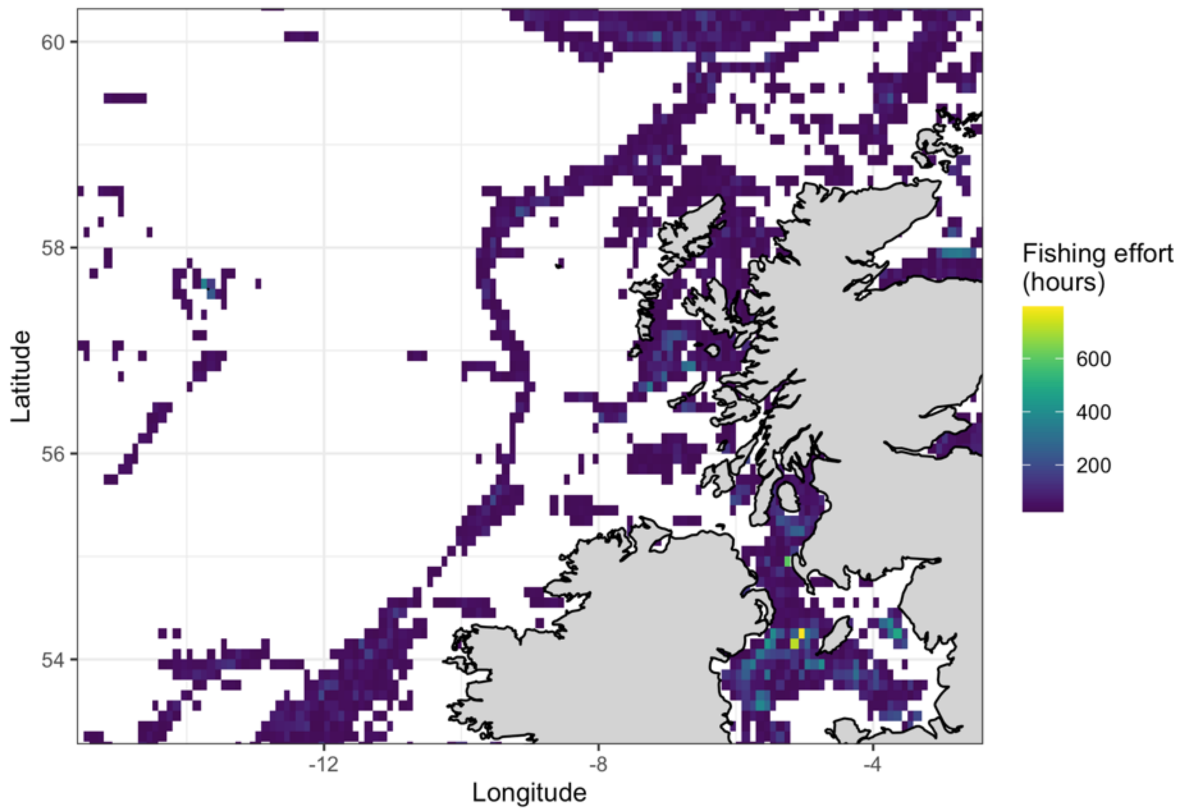

Figure 8: Distribution of fishing effort across the Interreg-VA area predicted using Automatic Identification System (AIS) data by Global Fishing Watch in 2016.

Discussion

By analysing GPS tracking data of seven seabird species in relation to concurrently tracked fishing vessels, we highlight differences in seabird fisheries interactions across species that will be related to fisheries bycatch risk. No direct interactions with fishing vessels were recorded in telemetry data for five of the seven species considered, namely Black-legged kittiwake, Common guillemot, European shag, Razorbill and Manx shearwater. Interactions with fishing vessels were recorded in Northern gannet and Northern fulmar. We found that on average, 31% and 42% of all predicted foraging behaviour was around fishing vessels in the tracked Northern gannets and Northern fulmars respectively. The main gear types these species interacted with were trawlers and demersal seiners. Using the most recent publicly available AIS dataset from Global fishing watch (2012-2016), we show that on average 80% of all predicted fishing effort within the programme area was carried out by trawlers, followed by static gears and longlines.

We find no direct interactions with vessels in Black-legged kittiwake, Common guillemot, European shag, Razorbill and Manx shearwater with less than 1% of all locations found to be within 1km of a vessel. While these findings suggest that the individuals tracked across these colonies were not directly interacting with vessels observed in the VMS data, it does not mean these species are not at risk of bycatch. Some fisheries, such as those using static nets, leave equipment unattended for extended periods of time that would not be identified in VMS data. Limited knowledge of bycatch rates in such fisheries within the Interreg-VA region limits the ability to determine the extent to which this activity threatens these populations. Both the rate of bycatch and the species at risk vary substantially across fisheries dependent on the gear types they use and the distribution of their fishing grounds (Fangel *et al*., 2015). For example, through an extensive on-board bycatch observer programme Fangel *et al* (2015) showed that the pelagic Greenland halibut longline fishery resulted in high bycatch of Northern fulmar, while more coastal gillnet fishing activity resulted in a wider range of bycaught species, predominantly auks. Similarly, bycatch of Black-legged kittiwake has been reported in the Spanish Gran Sol longline fishery (BirdLife International, 2015) while little bycatch has been reported in the North Atlantic (Dunn and Steel, 2001). While further work may look at spatiotemporal overlap of foraging behaviours in relation to the distribution of fishing effort of static fisheries, this work needs to be accompanied by a comprehensive on-board observer programme or remote electronic monitoring to determine region and gear-specific bycatch rates.

Both Northern gannet and Northern fulmar were found to interact with fishing vessels. These findings are consistent with previous studies in these two species (Votier *et al*., 2010; Bodey *et al*., 2014; Pirotta *et al*., 2018). A greater proportion of area-restricted search in Northern fulmar was associated with vessels compared to Northern gannets, suggesting that Northern gannets have a more flexible foraging strategy (Montevecchi *et al*., 2009). In both species these interactions were predominantly with trawlers, the most abundant fishery in the Interreg-VA area, and a fishery that has higher rates of discards compared to others (Anon, 2011). These findings are based on tracking data predominantly collected prior to the implementation of the EU Common Fisheries Policy Landings Obligation across all TAC species in 2019, with the exception of data from the Saltee islands in 2019. The implementation of this may lead to a shift in the types of fisheries birds interact with, leading to potential changes in bycatch rates and bird mortality. Soriano-Redondo *et al*. (2016) showed that Scopoli's shearwaters (*Calonectris diomedea*) switched to scavenging on baited hooks from longlines as an alternative food source when trawlers were not actively fishing (and therefore producing discards) in an area. Both Northern gannet and Northern fulmar have been reported as longline bycatch (Dunn and Steel, 2001; Oliveira *et al*., 2015), and this threat is of increasing concern for Northern fulmar across their distribution (Dunn and Steel, 2001; Fangel *et al*., 2015; Northridge *et al.*, 2020; Miles *et al*., 2020).

Colony variation

Variation in foraging distribution and behaviours across colonies has been widely documented in several species (Wakefield *et al*., 2013; Mendez *et al*., 2017). For all seven species we examined potential interactions with fisheries from at least two breeding colonies (Table 1). In Black-legged kittiwake, Common guillemot, European shag, Razorbill and Manx shearwater, no direct interactions were found across all colonies included in this analysis. In Northern gannet and Northern fulmar, the proportion of foraging that was associated with fishing vessels varied. This variation may be explained by a number of factors including; (i) the subset of birds tagged on colonies may contain different proportions of individuals that specialise on fisheries discards (Bodey *et al*., 2018), (ii) varying availability of natural prey in the year tags were deployed (Le Bot *et al*., 2019) and (iii) differing proportions of interactions with vessels not detected by VMS (see further discussion below). Variation in the proportion of vessel associations around different fishing gear types across colonies is likely due to differences in the fisheries operating in the areas surrounding colonies. Other factors such as competition (bother interspecific and intraspecific) around trawlers which have higher discard rates could force tagged birds to forage around other gear types (Garthe and Hüppop, 1994).

Limitations of the approach

As with all tracking data studies on a subset of a breeding population, a key assumption is that the behaviours recorded in tagged birds is representative of the wider breeding population. This assumption is particularly important for colonies where the number of birds tagged was low (Table 1). Various limitations and assumptions are associated with using VMS data to examine seabird-fisheries interactions. First, we assume that we have tracking data for all vessels that these birds are likely to interact with. VMS data were only available for fishing vessels greater than 15 metres in data prior to 2012, while for later years changes in the legislation around VMS requirements meant that data is available for all vessels greater than 12 metres. However, this still misses a significant proportion of the inshore fishing fleet, primarily using set nets and pots. Second, VMS data are collected at a coarser temporal scale (2 hours) than the seabird tracking data. However, the effect of this interpolation has been tested in this approach (see appendices of Pirotta *et al*., 2018), and has little effect on the model outputs. Another limitation of the VMS dataset is the inclusion of data from foreign fishing fleets. While the data provided by the Irish Marine Institute includes non-Irish vessels operating in Irish waters, the degree to which non-UK vessels operating in UK waters is included within the UK VMS data is unclear. Furthermore, any Illegal, Unreported and Unregulated (IUU) fisheries will not be included. Thus, the vessel interactions we report here are likely underestimates. Ultimately, this suggests that some of the interactions that are predicted to be natural by our models may in fact be around vessels. Lastly, as previously discussed, an important limitation of this approach is that models require a direct interaction with a vessel, and interactions with unattended gears are not detected by our models.

Further work

Noting the limitations and our findings in the context of existing literature, there is a clear need for further work to fully assess the potential risks fisheries pose to seabirds within the programme area including:

1. Collection of more fine scale tracking data for several key species known to consume discards (for example all gull *sp.*; Tyson *et al*., 2015) that were not included in this analysis is required. These data were not available within the programme area, or where data was available, they were not collected at a temporal resolution that is suitable for behavioural state classification modelling such as the gull tracking data

collected at 30-minute fixes in several west coast colonies by the University of Glasgow.

2. While additional tracking data will allow for a greater understanding of the differences in fishery interactions across species and across colonies, data from a dedicated bycatch observer programme across a range of gear types is required to make inference on any population level effects. Bycatch rates within the fisheries identified as having greatest seabird-vessel interactions in this study are limited in the Interreg-VA area. Without these data, our ability to assess potential population level impacts for these species through bycatch is limited. Emerging approaches that have proven useful in other taxa where bycatch data is limited may help this undertaking (see Luck *et al.*, 2020).

3. In order to determine population level effects, data from censusing and monitoring programmes must be incorporated, and for many colonies within the Interreg-VA area, no long-term monitoring programmes are in place. The collection of more recent population census data and formation of regular monitoring at key sites will not only aid inference on population level effects of bycatch within the region but also supplement national census efforts.

4. Further work is needed to quantify the extent to which the limitations and assumptions around the use of VMS data within our analyses underrepresent the rates at which seabirds interact with fisheries. In order to quantify seabird-fisheries interactions with smaller inshore fisheries, change is needed so that all vessels regardless of size are equipped with VMS. A potential alternative is to utilise recent advances in biologging that detect radar to identify vessel presence in the absence of VMS/AIS data (Weimerskirch *et al.*, 2020). Currently these methods are expensive, and the devices are too large to be deployed on many of the species considered here, however, as this approach develops it may prove useful.

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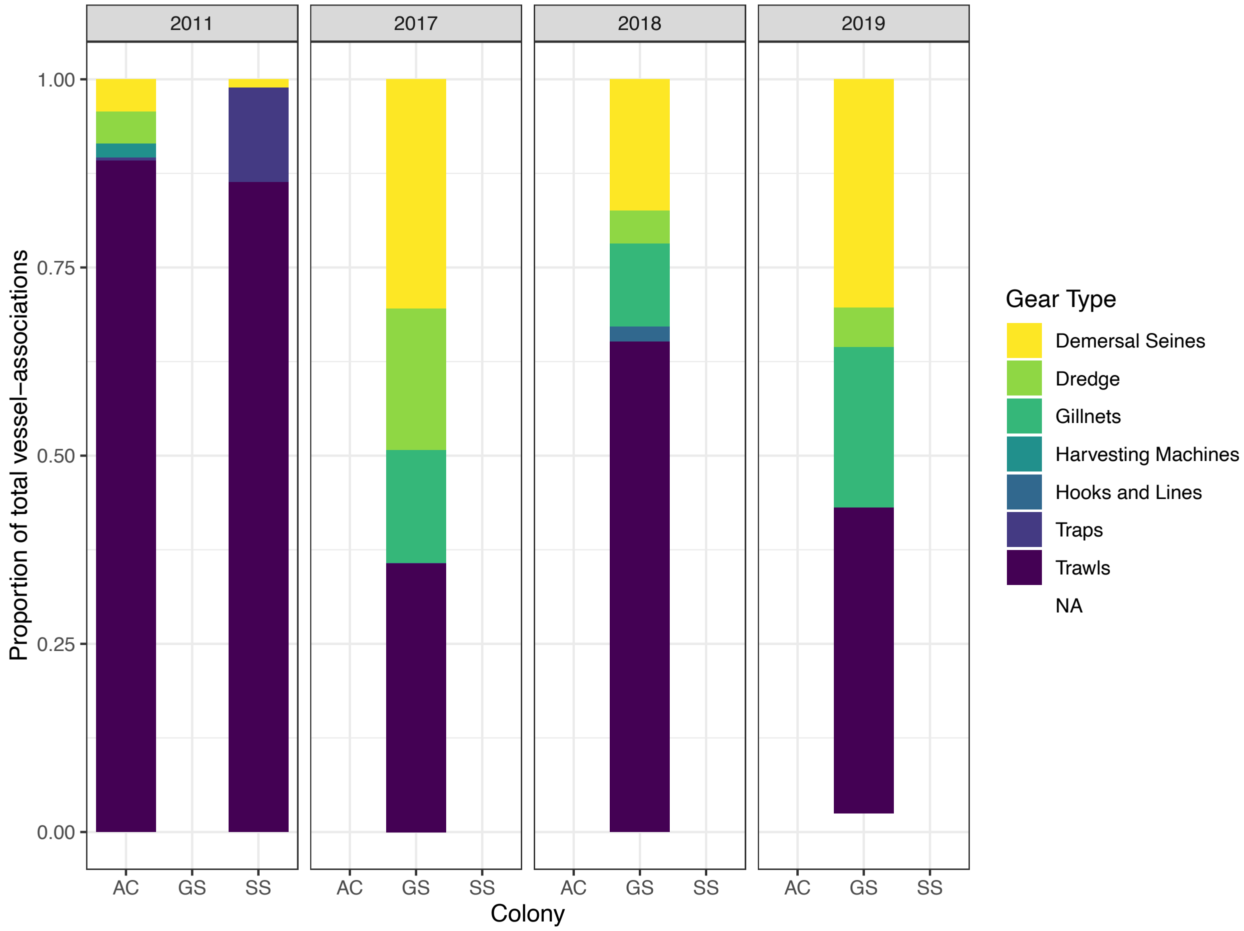
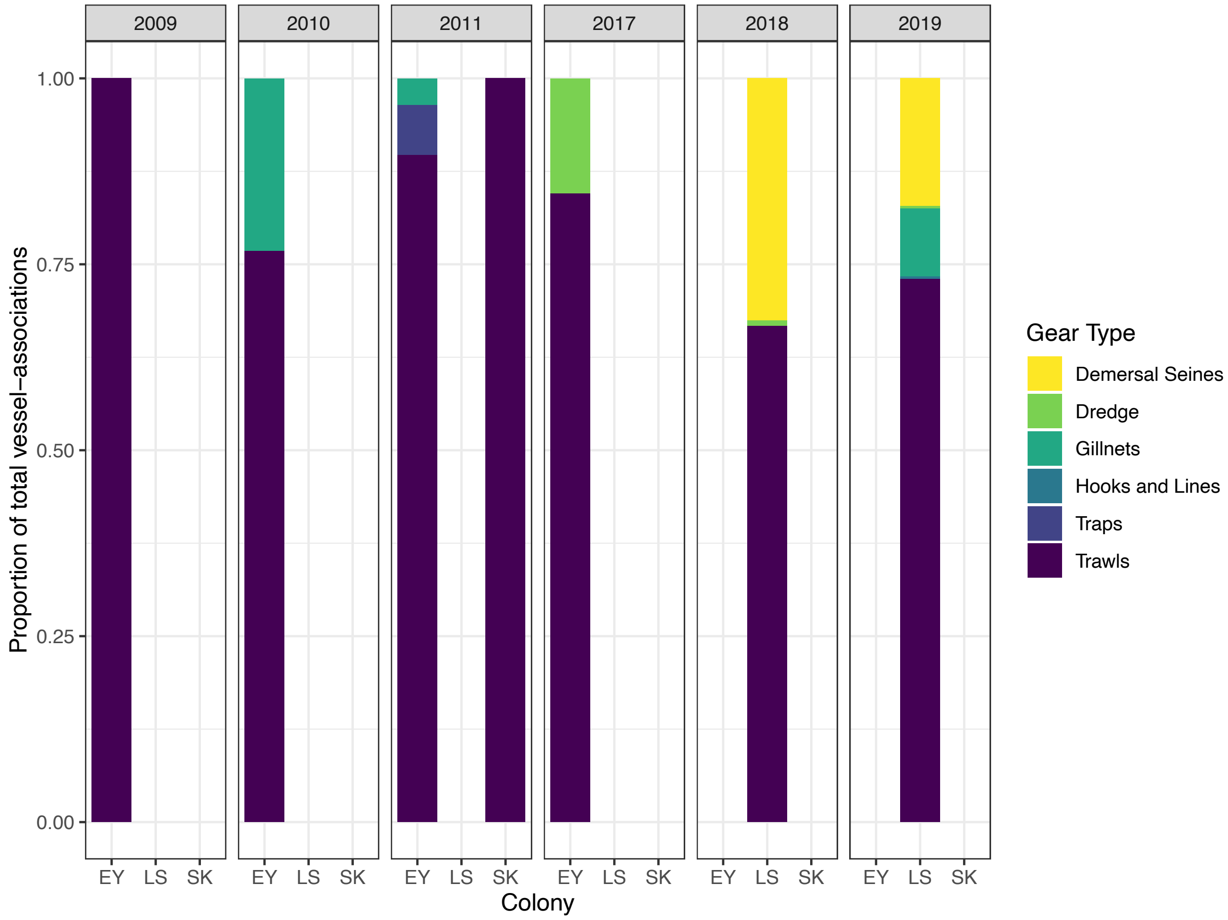
Supplementary

Supplementary Table 1: Additional details on the interpolation of GPS tracking datasets across datasets used in this analysis.

Species	Colony	Programmed intervals (sec)	Interpolation (sec)
Black-legged Kittiwake	Cape Wrath	100	100
Black-legged Kittiwake	Colonsay	100	100
Black-legged Kittiwake	Rathlin	100	100
Common Guillemot	Colonsay	100	100
Common Guillemot	Lunga	100	100
Common Guillemot	Shiants	100	100
European Shag	Colonsay	100	100
European Shag	Lunga	100	100
European Shag	Rathlin	100	100
Razorbill	Flannan Isles	100	100
Razorbill	Colonsay	100	100
Razorbill	Lunga	100	100
Razorbill	Rathlin	100	100
Razorbill	Shiants	100	100
Northern Fulmar	Eynhallow	600	600
Northern Fulmar	Kilda	600	600
Manx Shearwater	High Island	240-840	300
Northern Gannet	Sule Skerry	120	300
Northern Gannet	Ailsa Craig	120	300
Northern Gannet	Great Saltee	180	180



Supplementary Figure 1: Proportion of total vessel-associated behaviours within each fishing gear type, separated by year, across three Northern Gannet (*Morus bassanus*) colonies; Ailsa Craig (AC), Great Saltee (GS) and Sule Skerry (SS).



Supplementary Figure 2: Proportion of total vessel-associated behaviours within each fishing gear type, separated by year, across three Northern Fulmar (*Fulmarus glacialis*) colonies; Eynhallow (EY), Little Saltee (LS) and St. Kilda (SK).

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