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Measuring nest incorporation of anthropogenic debris by seabirds: an opportunistic approach increases geographic scope and reduces costs

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Abstract

Data on the prevalence of anthropogenic debris in seabird nests can be collected alongside other research or through community science initiatives to increase the temporal and spatial scale of data collection. To assess the usefulness of this approach, we collated data on nest incorporation of debris for 14 seabird species from 84 colonies across five countries in northwest Europe. Of 10,355 nests monitored 12% contained debris, however, there was large variation in the proportion of nests containing debris among species and colonies. For several species, the prevalence of debris in nests was significantly related to the mean Human Footprint Index (HFI), a proxy for human impact on the environment, within 100 km of the colony. Collecting opportunistic data on nest incorporation of debris by seabirds provides a cost-effective method of detecting changes in the prevalence of debris in the marine environment across a large geographic scale.

Highlights

12% of 10355 nests examined contained debris, largely thread or sheetlike plastics

Prevalence of debris in nests related to intensity of local human activity

Opportunistic data can help answer the challenges in plastic pollution research

Keywords: Marine; Nesting material; Plastic; Pollution; Sentinel species

Introduction

Plastics are a persistent marine pollutant with negative socio-economic, aesthetic, and environmental consequences (Worm et al., 2017; IPBES Global Assessment 2019). With plastic production continuing to rise, which will continue to enter oceans unless substantial interventions are put in place (Andrady and Neal, 2009; Borrelle et al., 2020; Jambeck et al., 2015; Lau et al., 2020; Tinbergen, 1961), plastic pollution will increasingly impact marine species (Barnes et al., 2009; Gall and Thompson, 2015). Seabirds are particularly affected by anthropogenic debris (hereafter debris), predominantly plastics, through both entanglement and ingestion (Gall and Thompson, 2015).

Seabirds are currently facing a multitude of threats (Dias et al., 2019), and separating the population-level effects of plastics from other threats is difficult (Senko et al., 2020). However, sentinel species, specifically seabirds, are useful for evaluating the effectiveness of mitigation measures or policy tools in reducing plastics in the marine environment (van Franeker et al., 2011; Avery-Gomm et al., 2018; Provencher et al., 2020; Rochman et al., 2016). Obtaining data on incorporated debris in nests, and entanglement, may therefore play a part in both of these priorities, in terms of identifying species where entanglement from incorporated debris might be a risk, and in detecting changes in the amount of debris in an area related to local and national action, or lack of action, in reducing plastic pollution (Willis et al., 2018; Xanthos and Walker, 2017).

Monitoring debris incorporated into seabird nests is a relatively straight-forward and non-invasive method of investigating temporal and spatial changes in the local marine environment (Grant et al., 2018; Tavares et al., 2016) The debris incorporated into the nests of certain species reflects that in the local environment, while other species show selection preferences for certain types and colours of debris (Bond et al., 2012; O'Hanlon et al., 2019; Verlis et al., 2014). Although, these latter species may be less useful as monitors of all marine debris, in terms of reflecting the composition of different types of debris present in an environment, they still indicate that debris is available to them as nesting material, and can be useful for monitoring the prevalence of specific debris types.

Leveraging opportunities from existing research, ecotourism, and community science initiatives, with little additional effort, can greatly increase the temporal and spatial scale of data collection (Schläppy et al., 2017; Zettler et al., 2017). Although there can be challenges associated with data collected by community scientists, for example relating to potential measurement errors and spatio-temporal biases (Bird et al., 2014), without this effort broad-scale, long-term data are challenging to obtain, especially on pollutants such as plastics that are widespread and patchily distributed in the environment (Serra-Gonçalves et al., 2019.; Zettler et al., 2017).

We collated data on the prevalence of debris in nests collected during routine monitoring and ringing activities at seabird colonies during the breeding season to 1) establish whether compiling a large number of single observations into a single dataset can provide a greater understanding of which species and locations may be affected by debris; and 2) establish the pros and cons of this opportunistic approach as a wide-ranging and cost-effective method of recording debris in seabird nests.

Methods

Data on nest incorporation of debris were collected by multiple observers visiting seabird colonies during the breeding season for monitoring or ringing purposes. Most data were collected between 2018 and 2019 with occasional data also collected in 2016, 2017 and 2020. Observers were asked to record the number of nests containing no debris and the number of nests containing visible debris on their surface; this was specific for each species and colony. In 2019, observers were asked to record the number of nests containing visible debris at the surface by type as categorised by Provencher et al. (2017): sheet, thread, foam, hard, other including non-plastic items. In some cases, photographs were also provided from which we could identify the presence/absence of visible debris types. For each colony and species, the frequency of occurrence (FO) of nests containing visible debris at their surface was recorded.

Observers were also asked to record any entangled young and adult birds encountered at the nest, and how the nests were monitored, e.g., at the nest, during ringing or from a vantage point. The main recruitment of volunteers was in the UK to coincide with fieldwork for the fourth UK & Ireland seabird census (following up on Mitchell et al., 2004), however, we also put out a request for data more widely via the Seabird Group newsletters and social media to seabird rangers, researchers and ringers, including in Norway through the SEAPOP network.

To explore regional differences in the FO of debris in nests of different species, each colony was assigned to an OSPAR (The Convention for the Protection of the Marine Environment of the North-East Atlantic) subregion (Figure S1). To investigate whether the FO of nests containing debris varied in relation to anthropogenic activity within the vicinity of each colony we related it to the Human Footprint Index (HFI), which provides a global assessment of human influence on the environment taking into account population density, human land use, infrastructure and human access (Jagiello et al., 2019; WCS & CIESIN, 2005). We obtained data on the HFI from the NASA Socioeconomic Data and Applications Center (https://web.archive.org/web/20201209133136/https://sedac.ciesin.columbia.edu/data/set/wildareas-v2-human-footprint-geographic). In ArcGIS (ArcMap ver.10.7. ESRI, USA), we created a buffer with a radius of 100 km around each colony and used the spatial join operation to extract the mean HFI value of each colony buffer. Although individual seabirds are generally thought to collect nesting material, including debris, close to the colony, a radius of 100 km was used to reflect that debris washed up at or near colonies will likely come from multiple sources in the wider surrounding environment. Though the HFI is a terrestrial measure, it is positively correlated with mean fishing effort (between 2012 and 2016, extracted from Global Fishing Watch, www.globalfishingwatch.org; Merten et al., 2016) within 100 km of each colony ($r = 0.38$, $P < 0.001$), and therefore provides a useful measure of anthropogenic pressure in waters around seabird colonies from which birds are sourcing debris (Thaxter et al., 2012).

Statistical analysis

The sample sizes of nests monitored per species at each colony varied dependant on the size and accessibility of the colony and the time available to observers (range: 2 – 1022 nests). We included only data where at least 10 nests of a species at a colony were monitored, and therefore excluded 23 occasions where sample sizes of less than 9 nests were reported as these may not be representative of what is occurring at the colony level. We did include sample sizes of between 10 and 20 nests as these largely concerned Common Eiders *Somateria mollissima* and Great Black-backed Gulls *Larus marinus* which tend to form smaller, looser colonies and therefore a high proportion of nests at a given colony were monitored.

In addition to calculating FO, for colonies where incorporated debris was detected, we also estimated 95% confident intervals (CI), using the R package *placer* (Tavares et al., 2020), and the estimated error, the difference between the upper and lower CIs (Tavares et al., 2020), to provide an indication of confidence in the recorded FO based on the sample size of nests monitored (Table S1). For species-colonies that were monitored in two consecutive years, we performed a paired Wilcoxon signed rank test to determine whether FO of debris in nests were consistent between years. To explore among-species and spatial patterns we used data from the sampling year with the largest sample size, or data that were collected in the core sampling period of 2018 and 2019.

As the sample sizes of nests and/or colonies monitored were relatively small for some species we assigned each species to a species group based on their taxonomy and nesting behaviour: terns, gulls, auks, shags/cormorants, seaducks and Black-legged Kittiwakes *Rissa tridactyla* (Table S2). Black-legged Kittiwake were separated because their nesting behaviour (cliff nesting) differs from the other gull species (ground nesting).

To test for spatial structure in the FO of nests containing debris among species and colonies we performed Moran's I Index auto-correlation analysis (Legendre and Fortin, 1989; Moran, 1953, 1950) in the ape R package (Paradis and Schliep, 2019) with colony specific latitude and longitude. Moran's I Index ranges from +1 (spatially clustered) to -1 (spatially dispersed) (Legendre and Fortin, 1989; Moran, 1953, 1950).

We performed a generalized linear model with a binomial error structure to investigate variation among species and regions in FO of incorporated debris, as well as the influence of human pressure within the vicinity of each colony. The FO of nests containing debris was included as the response variable and species group, OSPAR subregion and mean HFI, plus the interaction between species group and mean HFI, were included as explanatory variables We used an information theoretic approach to identify the best-fitting model across all competing models (Burnham and Anderson, 2002). Akaike's information criterion (AICc), corrected for small sample sizes, and Akaike weights (ω_i) were calculated for all models in the R package MuMIn (Barton, 2012) and compared across candidate models to select the most parsimonious model with the lowest AICc.

To explore variation in the type of debris incorporated into nests, and establish the main debris types used as nesting material by each species group, we estimated 95% confident intervals (CI) of FO for each debris type category, using the R package *placer* (Tavares et al., 2020). All statistical analyses were performed in R 3.5.1 (R Core Team, 2018). Post-hoc multiple comparisons were carried out in the R package *emmeans* (Lenth et al., 2020).

Results

Data on nest incorporation of debris were obtained for 14 seabird species (Table 1) from 84 different colonies totalling 125 species-colony values across five countries in northwest Europe (Faroes Islands, Iceland, Norway and Svalbard, Sweden and the UK; Figure 1, Figure S2 a-j). Most data were collected in 2018 and 2019, supplemented with occasional data collected in 2016, 2017 and 2020 (Table S1). Among all species, 48% of colonies were monitored from a vantage point (either from the shore or boat), whilst 52% were carried out at the nest. Most (49%) data were collected during incubation, 31% during, predominantly early, chick-rearing, and 20% were not specified, or included colonies where there was a mix of nests containing eggs or small chicks. Three instances of entanglement at the nest were recorded, involving two adult European Shags and one adult Black-legged Kittiwake, all in Norway.

Among all colonies and species, 1200 (12%) of 10,355 nests monitored contained debris, however, there was large variation in the FO of nests containing debris among species and colonies (Table S1). In addition, data on FO from multiple years were collected for 19 species-colony combinations, which involved an additional 1840 monitored nests for six species (Table S1). There was no significant difference in the estimated FO of nests that contained debris for individual species-colonies that were monitored over two consecutive years (Wilcoxon signed rank test: V = 28, p = 0.69; also shown by the overlap of confidence intervals between years in all species-colonies except one, Figure 2).

The FO of nests containing debris by species, across all colonies, ranged from 0 to 67% (Table 1). We observed no spatial structure in FO of debris across species at the colony level (Moran's I = 0.07, P =

0.08). However, FO of debris incorporated into nests was significantly related to the mean HFI within 100 km of the colony, influenced by species group, and OSPAR subregion ($\chi^2_1 = 27.0$, $P < 0.001$, $R^2 = 0.64$; Table S3). For shags, gulls and, to a lesser extent, Common Eider colonies located in areas with higher mean HFI contained a greater proportion of nests containing debris (Figure 3). Conversely, for auks and Black-legged Kittiwakes, there was a negative relationship with human influence. No relationship between FO of debris in nests and human influence was observed for the small sample of tern colonies.

At the species group level, auks had the highest FO of nests containing debris driven by the Atlantic Puffin *Fratercula arctica* (Figure 4), with 67% of nests containing debris, however only three colonies (two in Norway and one in Svalbard), and 130 nest crevices, were monitored. In contrast, no debris was found in the nests of Common Guillemot *Uria aalge*, although only 20 nests from one colony were monitored. The Herring Gull *Larus argentatus* and European Shag *Phalacrocorax aristotelis* had the next highest FO (26 and 25% of all nests monitored contained debris, respectively), with both species having a relative high number of nests and colonies monitored across the region (Herring Gull: 13 colonies, 1728 nests; European Shag: 27 colonies, 1243 nests). Great Cormorant *Phalacrocorax carbo*, Great Black-backed Gulls and Lesser Black-backed Gulls *Larus fuscus* had slightly lower FO, with between 9 and 18% of all monitored nests containing debris. By contrast, despite a relatively large number of Black-legged Kittiwake nests being monitored, from 33 colonies, only 4% of monitored nests contained debris. However, there was considerable variation among kittiwake colonies, with 20 colonies where no debris was recorded, whilst two colonies had FO of 31% and 49% (Table S1). Most Arctic Tern *Sterna paradisaea* (FO of nests with debris = 7%), Little Tern *Sternula albifrons* (FO = 6%) and Common Eider (FO = 3%) nests contained no debris, although relatively few nests were monitored. No debris was found in the nests of Black-headed Gulls *Chroicocephalus ridibundus*, Common Gulls *Larus canus* or Common Tern *Sterna hirundo*, although the number of colonies and nests monitored for these species was again low (range: 26 - 214 nests; 1 - 3 colonies). The Irish Sea (38 ± 21%) and the Norwegian Sea (16 ± 21%) had the greatest FO of nests containing debris (Figure 5) with differences among OSPAR subregions influenced by which species were monitored in each region.

Data on FO by debris type were recorded for 3102 nests (41 colonies, 10 species), of which 443 contained debris (Table 2). Focusing on the type of debris the different species groups incorporated into their nests, across colonies and OSPAR subregions, threadlike and sheet plastics were the most incorporated items (Figure 6). For Atlantic Puffin and the shags, a higher FO of nest contained threadlike followed by sheet plastics, with few nests containing hard and foamed plastic or other debris. For the gull species, sheet plastics were most often reported in nests followed closely by threadlike plastics and other debris. Black-legged Kittiwakes predominantly incorporated threadlike plastics. The small proportion of Common Eider and tern nests that contained debris involved a mix of debris types.

Discussion

Requesting data from those visiting seabird colonies for monitoring and ringing activities or other research projects provided an effective way to collect data on nest incorporation of debris over a large geographical scale, and wide range of species. Collecting data in this opportunistic way reduced the time and cost that would be required if all the seabird colonies included in this study were visited independently, especially colonies which require considerable planning and effort (i.e., in terms of logistics and permits) to access, such as offshore islands and locations in the Arctic (Mallory et al., 2018). Another crucial aspect is the additional environmental cost, in terms of carbon emissions, of travelling to these colonies, which are already being visited by other researchers (Arsenault et al., 2019). The cost of collecting the data included in this study by a single researcher would have been >£18,000 (2021 value, including travel and accommodation but not researcher costs) and would have involved travelling a minimum of 21,600 km, with associated carbon emissions of 3.76 metric tons (Table S4). This approach also removed the potential of additional disturbance to breeding seabirds from extra visits to colonies during the breeding season (Boersma et al., 2002). Lastly, it also reduced the reliance on "parachute science" and promoted or strengthened relationships with in-country partners (Stefanoudis et al. 2021).

The extent to which seabirds incorporated debris into their nests across the UK, and northwest Europe, varied by species and location. Cormorants and shags, and the three large gull species (Herring, Lesser Black-backed, and Great Black-backed Gulls), showed a greater tendency to incorporate debris into their nests, as previous studies observed (Battisti, 2020; Podolsky and Kress, 1988; Tavares et al., 2019; Thompson et al., 2020; Witteveen et al., 2016). Conversely, despite a large number of monitored nests and colonies, only a small number of Black-legged Kittiwake nests were found to contain debris. Although, four colonies had FO >10%, indicating that at a local level, particularly where thread-like debris is available, kittiwakes will incorporate debris into their nests as found by Hartwig et al. (2007). The highest FO of 49% was recorded from an oil rig in the Norwegian Sea, potentially attributed to a lack of available terrestrial vegetation, as has been suggested for other species (Lavers et al., 2013; Lee et al., 2015). The FO of debris in tern nests was low (0 – 10%), similar to previous studies (de Souza Petersen et al., 2016; Tavares et al., 2019), although the number of tern nests and colonies monitored was low in this study. The FO of Common Eider nests containing debris was also low (0 – 17%), with this being the first quantitative documentation of nest incorporation by this species that we are aware of. Unexpectedly, Atlantic Puffin, had the highest FO of nests containing debris, however only a small number of colonies were monitored. No data were collected on Atlantic Puffins in the UK as here this species generally breeds in deep burrows meaning that it is difficult to record nest contents, compared to the shallower nest cavities of Norway and Svalbard. Although Atlantic Puffin nest in burrows, they can line their nest with small items such as vegetation, and occasional fragments of paper and fishing net have been reported in burrows (Harris and Wanless, 2011). Monitoring burrow nesting species for debris presents different challenges to those nesting on the surface, however visual observation could be made of individuals returning to the burrow with nesting material, whilst endoscope cameras could be used to investigate the presence of debris within accessible burrow nests.

Spatial variation in the FO of nests containing debris, at the scale of OSPAR subregion, was also observed, with a higher FO of nests containing debris in the Irish Sea and Norwegian Sea than other subregions. Although we attempted to account for the different species monitored within each sub-region, the observed FO of nests containing debris in each subregion is likely influenced by the variation in the suite of species monitored in each region, as well as samples sizes of nests and colonies. In addition to a species' tendency to incorporate debris, the extent to which species incorporated debris was also influenced by the levels of debris within the vicinity of the colony. To be an effective indicator of marine anthropogenic debris, the levels of debris in seabird nests should relate to that in the local environment (Tavares et al., 2016). As we did not directly monitor levels of debris within the vicinity of each colony, we used a proxy for potential levels of local debris / human impact on the environment, the Human Footprint Index (Jagiello et al., 2019; WCS & CIESIN, 2005),. For the species groups that tended to incorporate a variety of debris types in their nests (shags, gulls and Common Eider), we found that colonies in areas with higher human influence on the environment did contain a greater proportion of nests containing debris than colonies in areas of lower human influence. These species therefore may be useful to monitor broad levels of marine debris, although more local influences are also expected to affect the extent of debris incorporated into nests, such as currents, local sources of pollution, as well as nesting behaviour (Bond et al., 2012; Grant et al., 2018; Thompson et al., 2020).

There were 19 instances where species-colonies were monitored in consecutive years, providing an opportunity to determine how consistent nest incorporation of debris was over the short-term. Although there was small variation in the recorded FO between years for some colonies and species, potentially due to different numbers of nests monitored in each year, there was generally high consistency in the estimated FO of nests that contained debris between consecutive years. The one exception was for a relatively large Herring Gull colony in west Scotland. In 2018, a whole island census of gull nests took place, and therefore all Herring Gull nests were monitored for debris. By contrast, in 2019 only a small sub-sample of nests were monitored from one section of island. Given that the FO of debris in nests is known to vary spatially on this island (Thompson et al., 2020), the sample of nests monitored in 2019 were in an area of the colony where a higher proportion of nests contained debris. These results highlight the importance of monitoring an adequate number of nests, which are representative of the entire colony, and if only a subsection of the colony is monitored, that the same subsection of nests is used when comparing between years. This is also highlighted by a Black-legged Kittiwake colony in Norway, where the FO% of debris in nests were recorded for the same nests from two locations, one above and one below the colony. The FO of nests containing debris differed (7% versus 28%), indicating the importance of consistency in how nests are monitored if comparisons are to made between years, and in the value of estimating confidence intervals around FO estimates to help prevent assuming differences between years, or colonies, attributed to biases in how data were collected (Figure S3).

In addition to providing information on the prevalence of debris in the environment, monitoring of debris incorporated into seabird nests is also important to improve our understanding on any potential impacts this behaviour has on seabirds and their populations. Although incorporated debris can result in direct injury and mortality of chicks and adults (Seacor et al., 2014; Slack, 1974; Votier et al., 2011), there is no evidence at present that incorporated debris has any impact on species at the population level, with current instances of entanglement appearing to be low, although there are few data available to explore this thoroughly. The report rate of entangled birds was also very low in this study. However, most of the data here were collected during incubation or early chick-rearing therefore instances of entanglement may have been missed, especially of large chicks, which potentially are more likely to become entangled.

Strengths and weaknesses of an opportunistic approach for monitoring debris incorporated in nests by seabirds

As the data included in this study were collected opportunistically, there was considerable variation in the number of nests and colonies included for each of the 14 species. Caution is therefore required when using these data to make broad conclusions on how species are affected by debris in different locations. However, as few existing data exist on nest incorporation of debris for some of these species, these data are a valuable resource to build upon our current understanding, and how routine visits to seabird colonies can be effectively used to monitor the extent to which seabirds incorporated debris into their nests, and to monitor local levels of marine debris pollution.

All data collected for this study were based on visual observations, as this is a straightforward method, with relatively low disturbance to breeding individuals. However, the distance from the nest visual observations were taken varied, attributed to the accessibility of nests and the type of routine monitoring that was taking place. Comparisons among studies will assume that all, or a similar proportion, of debris items are detected, identified and recorded accurately (Lavers et al., 2016). This may be the case in studies that collect all debris from within a nest, but is unlikely where visual, especially photographic, observations are used: large pieces of netting will have a greater detection probability than small, thin pieces. Photography will overlook debris incorporated within the nest that is not visible on the surface or from the angle the image is taken, will likely miss small debris items, and does not provide data on the size or mass of debris (Grant *et al*. 2018). However, combining visual observations with digital photographs can be useful as images can be scrutinised in more detail, causing less disturbance to the birds than trying to identify all debris and associated metrics whilst in the field. Digital images also provide an opportunity to update data in the future to ensure they reflect recommended best practice, especially with current uncertainty regarding the best way to categorise colour. Being able to collate digital images also provides an opportunity to open this type of monitoring to community science programs (Duckett and Repaci, 2015). Identifying debris type is important when using seabirds as indicators of marine pollution to determine long term changes in marine debris composition and identify suitable upstream interventions to close gaps in waste management systems (Pettipas et al., 2017; Ryan, 2008; van Franeker et al., 2011). Therefore, where time constraints limit the ability of observers to record FO by debris type in the field, photographs can provide a useful alternative to obtain this information.

In this study, data were collected on a range of species to understand which species incorporate debris as nesting material at different locations, as well as to increase the number of colonies where data were collected. Most data were obtained for European Shag, Black-legged Kittiwake and the three large gull species (Herring, Lesser Black-backed and Great Black-backed Gulls). This is likely attributed to the nests of these species being more accessible to monitor, as being surface structures, they can be viewed easily. Furthermore, all of these species have been recorded to incorporate debris into their nests (Hartwig et al., 2007; Thompson et al., 2020), therefore people may have been more willing to record data for these species. Although we requested data from colonies where no nest incorporation was observed, people may have been more inclined to submit data where they did observe debris in nests. Therefore, the prevalence estimates for species may be inflated. However, in general, the range of FO recorded across multiple sites were generally lower than those reported in single-site studies (Hartwig et al., 2007; Thompson et al., 2020) likely attributed to a larger number of colonies monitored, including where debris was not found to be incorporated in nests.

For this opportunistic approach we did not set a minimum sample size as not to limit the data collected when exploring the effectiveness of obtaining data through routine monitoring of colonies. However, low sample sizes for some species and colonies made it difficult to establish how reliable estimates of the prevalence of debris in nests were. Small sample sizes may be due to only a small number of nests being accessible/visible to monitor, or due to logistical limitation from people working in the field who have their own priority data to collect. In future, it would be valuable to include an indication of the proportion of nests in a colony that were monitored. To make the monitoring as quick and efficient as possible, we did not ask for this information in this study. The number of nests that should be surveyed to detect change in prevalence will vary depending on the level of prevalence and the level of detectable change required (Provencher et al., 2015; Tavares et al., 2020). One benefit of monitoring multiple species was not being constrained by the geographic range or breeding habitat of a single species. However, caution should be made when comparing the FO of debris in nests among species, given species-specific tendencies to incorporate debris (see Table S2).

A lack of data on nest incorporation of debris by seabirds, and other bird species, impedes identification of which nest-building species are most at risk of entanglement, under what conditions, and whether preferences for nesting materials or prevalence of debris items changes over space and/or time. More importantly, it means we lack a comprehensive understanding of the impacts of nest incorporation of debris, especially at the population level. To answer the grand challenges in marine plastic pollution research, robust, easily implemented methods that engage diverse participants and stakeholders are therefore needed to leverage existing efforts (Provencher et al., 2017). With the increased awareness of marine debris, and the realised and potential impact it may have on seabirds, research into debris incorporated into nests is increasing. However, opportunistic data can also be beneficial and should be incorporated into monitoring schemes to obtain additional information for a wide range of species and locations, especially relating to entanglement rates of individuals at the nest. Increased monitoring to record entangled individuals will help determine how frequent an occurrence this is. To ensure these data are widely available to allow comparison across species, time and space, all these data should be collated in a global database such as LITTERBASE (itterbase.awi.de). The prevalence of debris of difference types, likely from multiple sources – both fishery and consumer related – in some colonies emphases that improved waste management infrastructure is required to prevent these items entering the environment and being available as nesting material, or of being ingested. Nest incorporation is a relatively visible way in which species may be affected by plastic pollution but many other forms, such as entanglement away from the colony and ingestion, are hidden.

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CRediT author statement

Nina O'Hanlon: Conceptualization, Formal analysis, Investigation, Writing - Original draft preparation. **Alexander Bond:** Conceptualization, Writing - Review & Editing. **Elizabeth Masden:** Conceptualization, Writing - Review & Editing. **Jennifer Lavers**: Writing - Review & Editing. **Neil James:** Conceptualization, Writing - Review & Editing, Funding acquisition.

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Table 1. Frequency of occurrence (FO) % of nests containing anthropogenic debris summarised by species. Species are ordered from greatest to lowest FO of all monitored nests.

Common name	Scientific name	No. of colonies	Total no. of nests monitored	Number of nests containing debris	FO % of all nests	Mean ± SD (range) FO % among colonies	
Atlantic Puffin	*Fratercula arctica*	3	130	87	67	55 ± 40	(12 - 91)
Herring Gull	*Larus argentatus*	13	1728	450	26	16 ± 29	(0 - 78)
European Shag	*Phalacrocorax aristotelis*	27	1243	312	25	19 ± 25	(0 - 81)
Great Black-backed Gull	*Larus marinus*	8	348	61	18	18 ± 25	(0 - 53)
Great Cormorant	*Phalacrocorax carbo*	5	216	27	13	7 ± 10	(0 - 24)
Lesser Black-backed Gull	*Larus fuscus*	7	894	82	9	19 ± 23	(0 - 63)
Arctic Tern	*Sterna paradisaea*	3	108	8	7	6 ± 5	(0 - 10)
Little Tern	*Sternula albifrons*	1	49	3	6	6	NA
Black-legged Kittiwake	*Rissa tridactyla*	33	3762	139	4	4 ± 17	(0 - 49)
Common Eider	*Somateria mollissima*	11	338	11	3	4 ± 24	(0 - 17)
Gull spp.		10	1160	19	2	16 ± 23	(0 - 100)
Common Guillemot	*Uria aalge*	1	20	0	0	0	NA
Black-headed gull	*Larus ridibundus*	1	214	0	0	0	NA
Common Gull	*Larus canus*	3	119	0	0	0	NA
Common Tern	*Sterna hirundo*	1	26	0	0	0	NA
Total		127	10355	1199			

Figure 1. Map showing the geographical spread of colonies that were monitored for nest incorporation of anthropogenic debris by seabirds. Although most sites were in the UK, colonies were also monitored in Iceland, the Faroe Islands, Svalbard, Norway and Sweden. To see which species were monitored at each location see Figure S1.

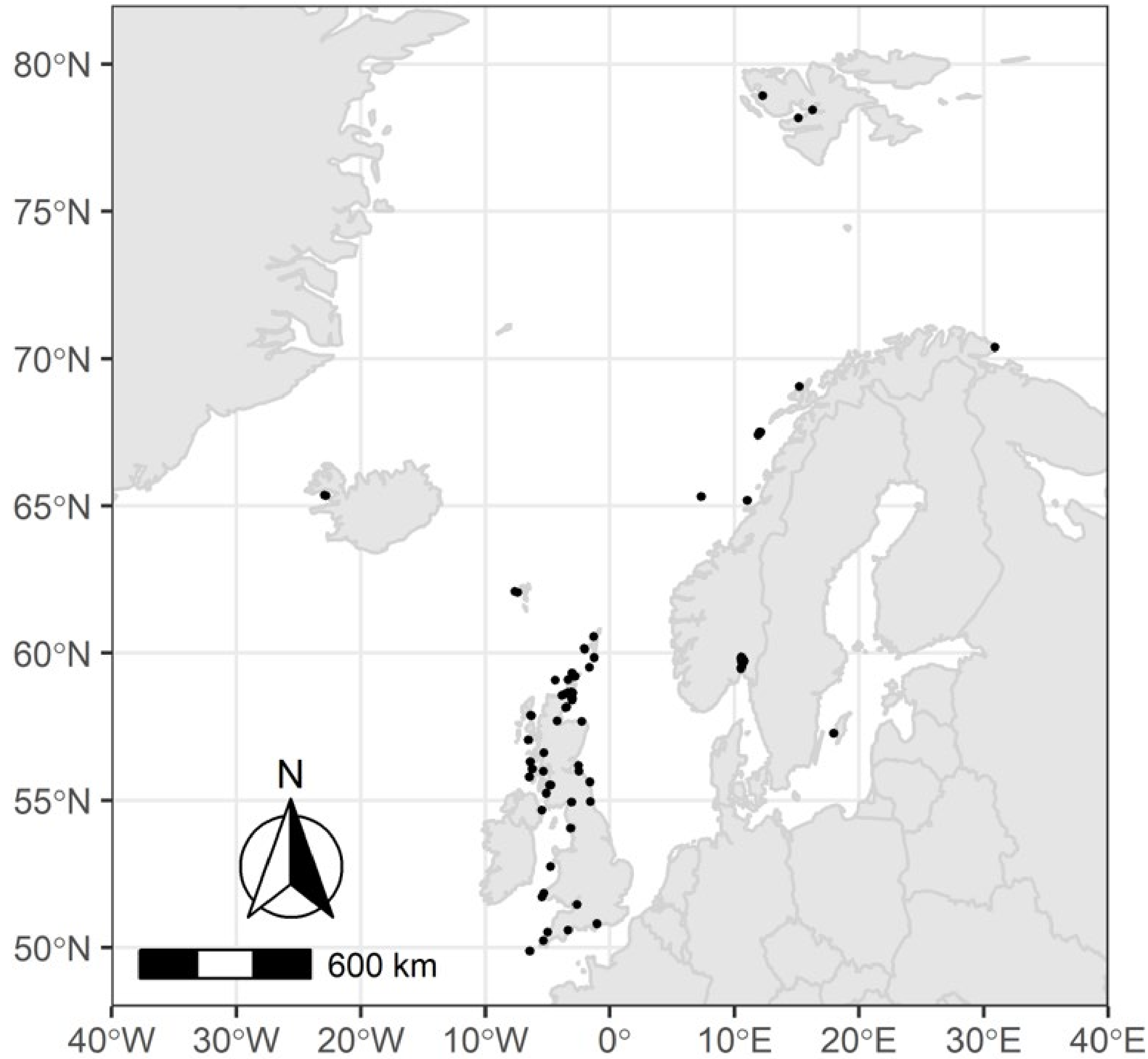
Figure 2. Comparisons of frequency of occurrence (FO) % of anthropogenic debris in nests and estimated 95% confidence intervals for colonies and species and colonies where data were collected in consecutive years. Overlapping 95% CIs indicates no difference in FO estimates. Numbers refer to sample size of nests monitored. 2017 – Red: 2018 – Light blue: 2019 – Dark blue: 2020 - Orange.

Figure 3. The presence of anthropogenic debris in seabird nests was positively related to the mean Human Footprint Index within 100 km of the colony for gull and shag species, and to a small extent for Common Eiders. This relationship was negative for auk species and Black-legged Kittiwakes. Each point at 0.00 (no incorporated debris) and 1.00 (incorporated debris) represents a nest. Solid lines indicate the trend lines with 95% confidence intervals (shaded area) predicted from a generalized linear model with a binomial error structure. Points depict the raw data.

Figure 4. Boxplot highlighting among-species group differences in the frequency of occurrence (%) of anthropogenic debris incorporated into nests across colonies. Boxplots show median (horizontal line), inter-quartile ranges (box), and minimum and maximum values (whiskers). Points represent raw data at the species-colony level. Species groups are ordered based on the lowest to highest mean frequency of occurrence of debris. Species groups with different letters above the boxes are significantly different from each other (Tukey's HSD post-hoc multiple comparisons $P < 0.05$) based on the results of a GLMM including OSPAR subregion and an interaction between species group and mean HFI (see text). Samples sizes of nests monitored for each species are also shown at the top of each boxplot.

Figure 5. Boxplot highlighting among-OSPAR subregion differences in the frequency of occurrence (%) of anthropogenic debris incorporated into nests across species. Boxplots show median (horizontal line), inter-quartile ranges (box), and minimum and maximum values (whiskers). Points represent raw data at the species-colony level. OSPAR subregion are ordered based on the lowest to highest mean frequency of occurrence of debris. OSPAR subregion with different letters above the boxes are significantly different from each other (Tukey's HSD post-hoc multiple comparisons $P < 0.05$) based on the results of the GLMM including an interaction between species group and mean HFI (see text), therefore results are averaged over the levels of species group. Samples sizes of nests monitored for each species are also shown at the top of each boxplot.

Figure 6. Comparisons of frequency of occurrence (FO) % of anthropogenic debris in nests and estimated 95% confidence intervals (CI), by debris type category, per species group. Overlapping 95% CIs indicates no difference in FO estimates. T – threadlike plastics, S - sheet plastics, O – debris classified as other, H - hard plastics and F – foamed plastics.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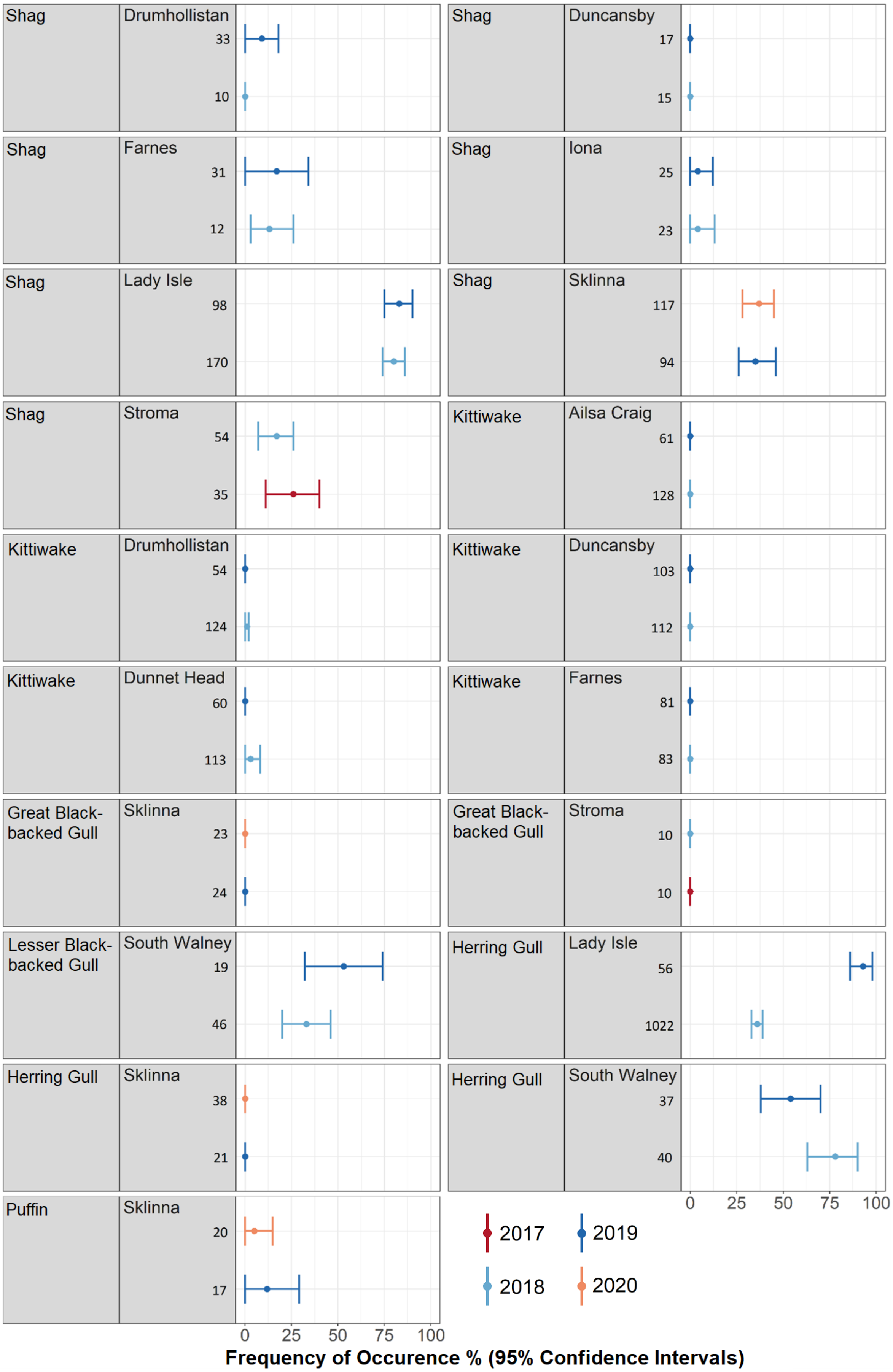
600 km

Figure 1.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Lady Isle
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170
Shag
Sklinna
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Stroma
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Kittiwake
Ailsa Craig
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Kittiwake
Drumhollistan
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Kittiwake
Duncansby
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Kittiwake
Dunnet Head
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Farnes
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Great Black-backed Gull
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Lesser Black-backed Gull
South Walney
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Herring Gull
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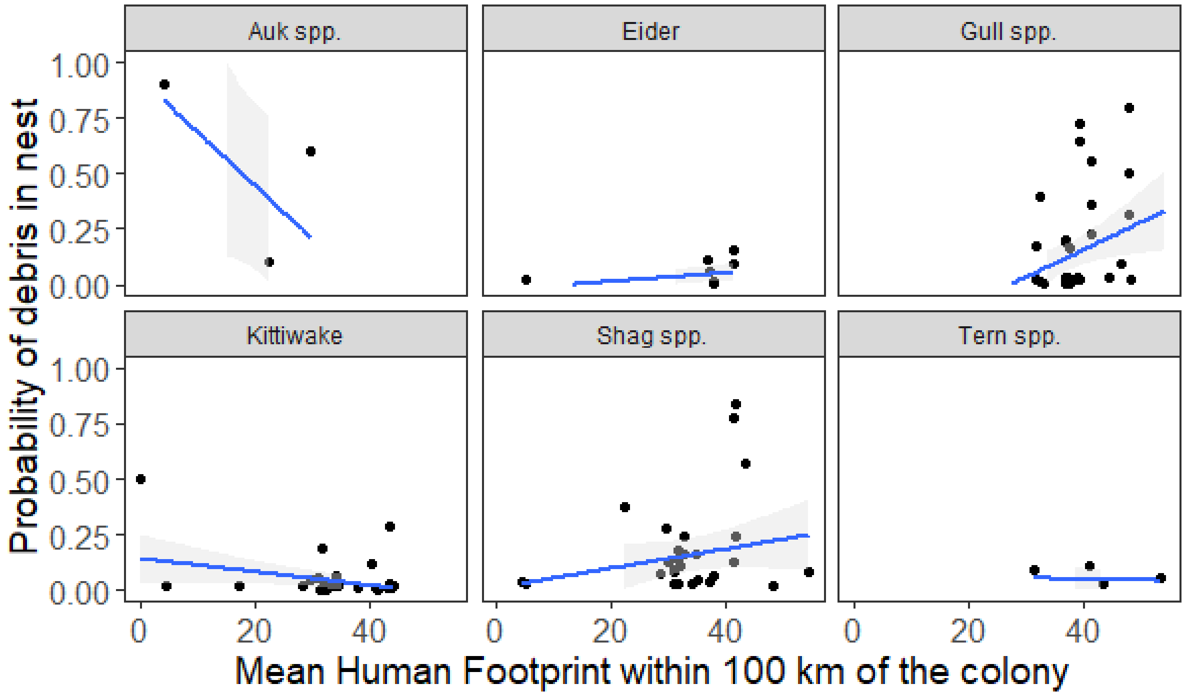
Frequency of Occurence % (95% Confidence Intervals)

Figure 2.

656



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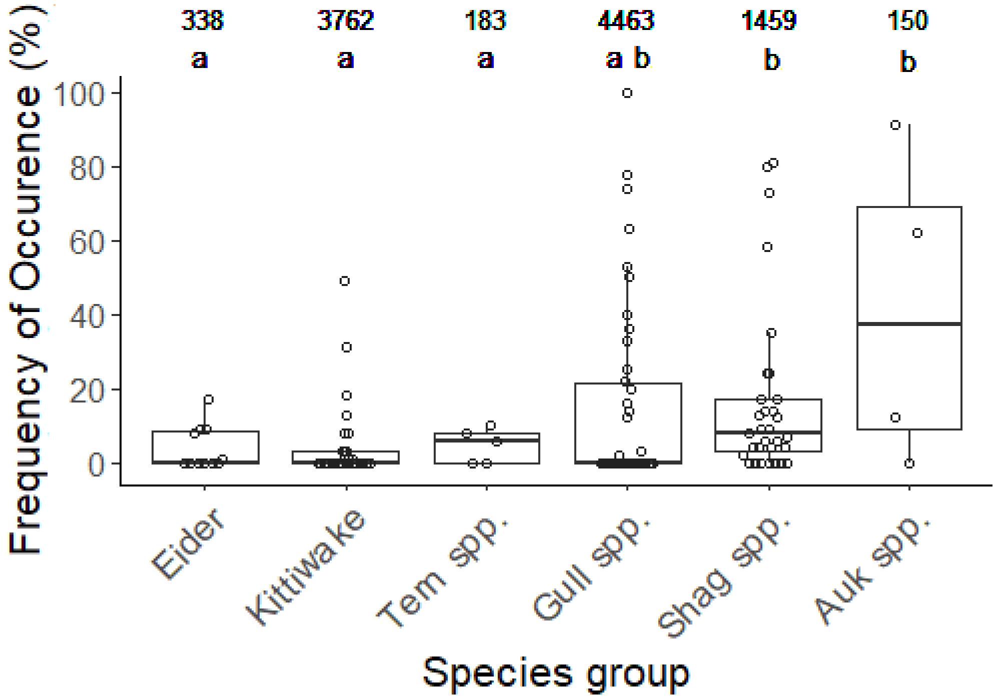
658 **Figure 3**.



659 **Figure 4.**

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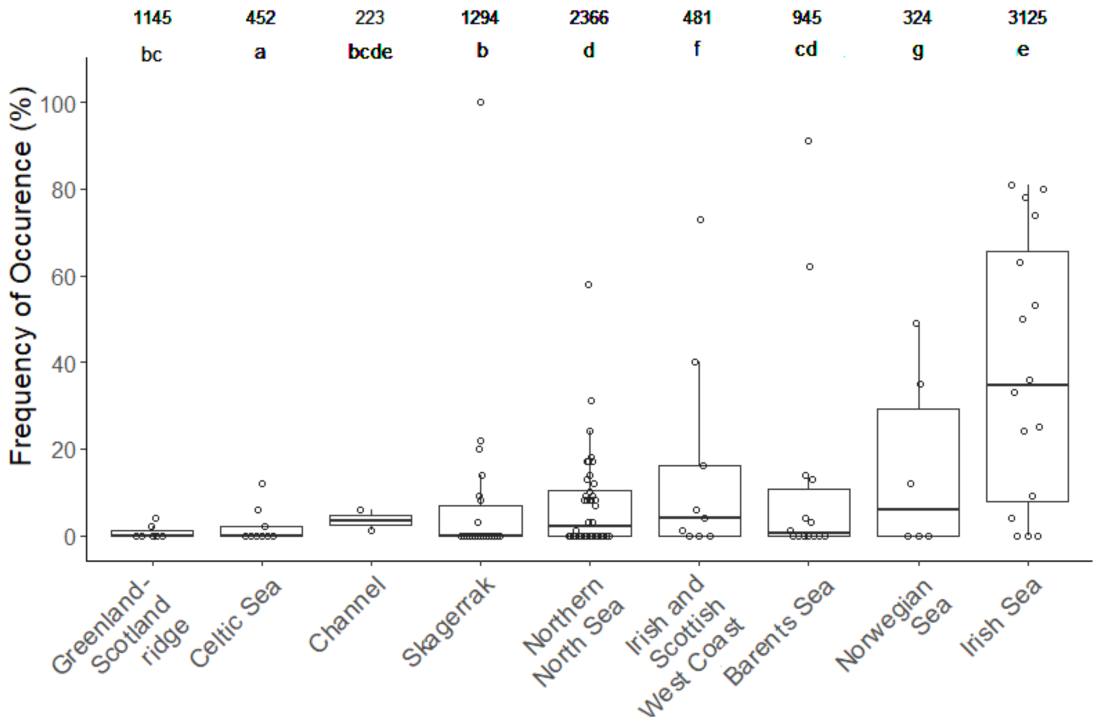


662 **Figure 5.**

663

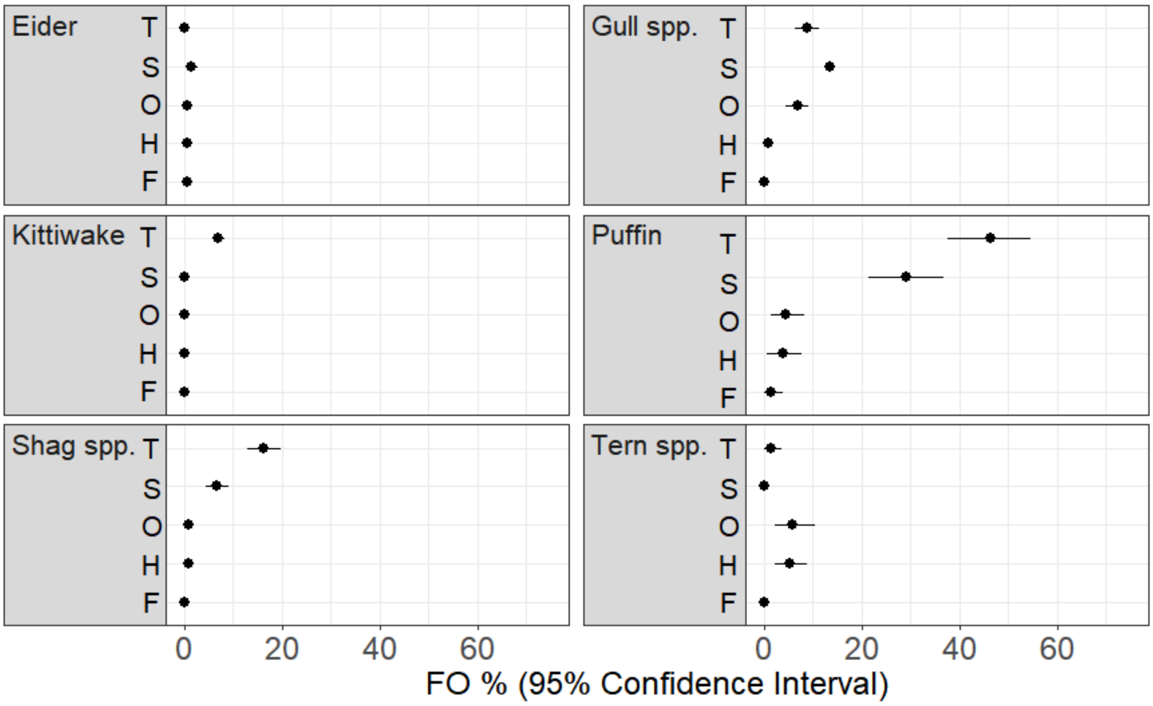


Figure 6.

Table 2. The frequency of occurrence (FO) of debris categorised by type, as a percentage of all monitored nests, for each species.

Species	No. of colonies	Number of nests examined	Number of nests containing debris (%)		FO of debris by type (%) [1]				
					Sheet	Thread	Foam	Hard	Other
European Shag	10	422	96	(23)	7	18	0	1	1
Great Cormorant	1	50	2	(4)	0	4	0	0	0
Common Eider	9	273	7	(3)	1	0	1	1	1
Black-legged Kittiwake	9	1596	115	(7)	0.1	7	0	0	0
Great black-backed Gull	2	35	19	(54)	37	3	0	0	17
Herring Gull	3	99	69	(70)	39	33	1	4	16
Lesser Black-backed Gull	3	52	22	(42)	12	13	0	0	17
Gull spp.	9	312	15	(5)	3	1	0	0	1
Arctic Tern	2	84	8	(10)	0	2	0	6	8
Little Tern	1	49	3	(6)	0	0	0	4	2
Atlantic Puffin	3	130	87	(67)	29	46	2	4	5

[1] Standardised debris type categories as recommended by Provencher et al. (2017). For the three large gull species (Great black-backed Gull, Herring Gull, Lesser Black-backed Gull), the relative high FO % of items categorised by 'other' was largely due to the incorporation of plastic-coated wire in nests. In some cases, data on debris by type were only available from photographs or for a subset of monitored nests at

a colony. It was, therefore, not always clear if this was a random sample of nests or if observers focused on collecting these data in areas where nests contained debris, which would explain the higher FO for the three large gulls species than reported in Table 1.

Supplementary Material

Measuring nest incorporation of anthropogenic debris by seabirds: an opportunistic approach increases geographic scope and reduces costs

Nina J O’Hanlon, Alexander L Bond, Elizabeth A Masden, Jennifer L Lavers and Neil A James

Table S1. Frequency of occurrence (FO) % of nests containing anthropogenic debris for all species and colonies. See separate spreadsheet.

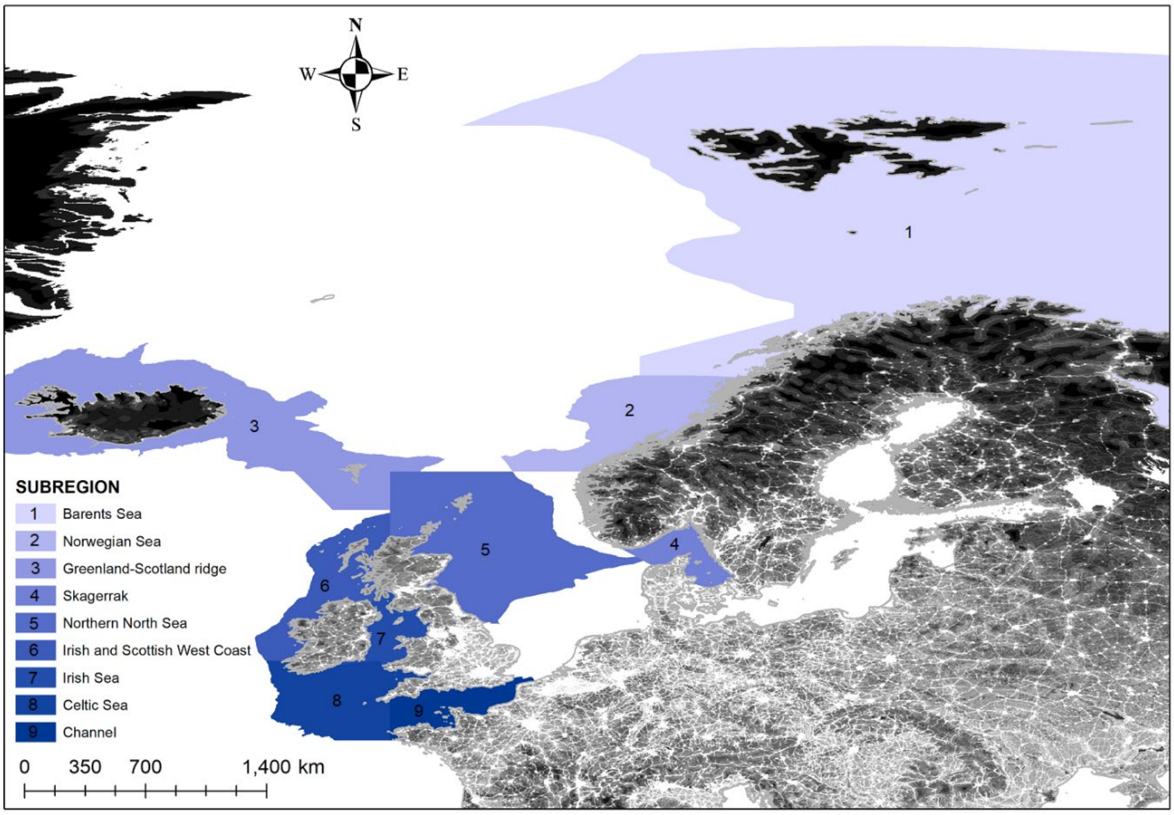
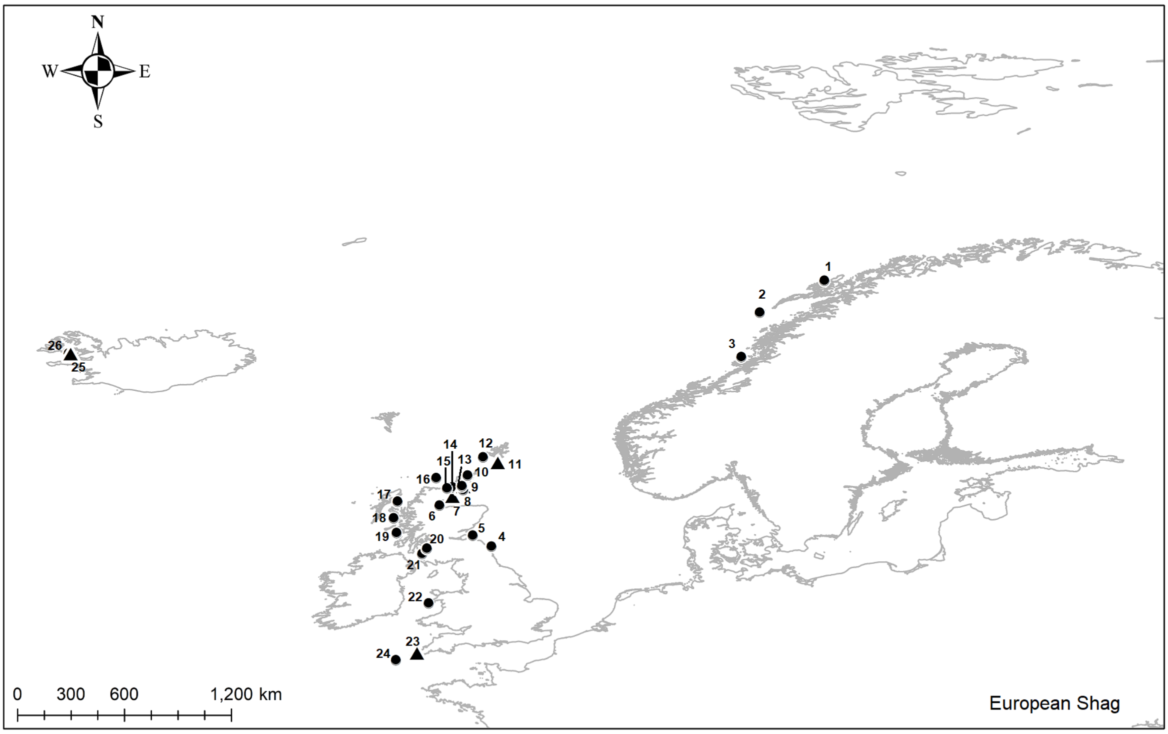


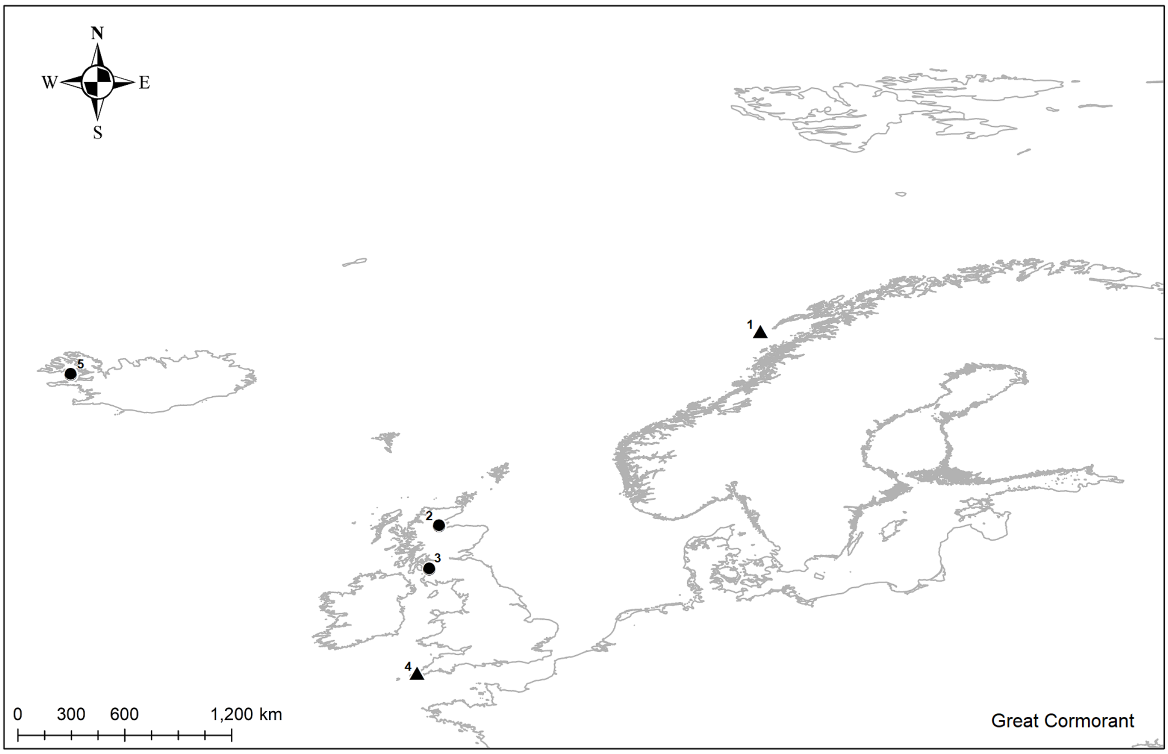
Figure S1. Map showing the OSPAR subregions where colonies included in this study were monitored, and the Human Footprint Index (HFI), a measure of human influence on the terrestrial environment from high (white) to low (black).

Figure S2. Map showing the location of seabird colonies included within this study (Table S1). Triangles indicate colonies where no anthropogenic debris was recorded, circles indicates colonies where debris was recorded. a) European Shag; b) Great Cormorant; c) Common Eider (zoomed in boxed map shows the location of colonies in Oslo Fjord); d) Black-legged Kittiwakes (zoomed in boxed map shows the location of colonies in north-west Scotland); e) Herring Gull; f) Lesser Black-backed Gull; g) Great black-backed Gull; h) black - gull spp., blue – Common Gull, red – Black-headed Gull (zoomed in boxed map shows the location of colonies in Oslo Fjord); i) black – Arctic Tern, blue – Common Tern, red – Little Tern; j) black – Atlantic Puffin, red – Common Guillemot.

a)



b)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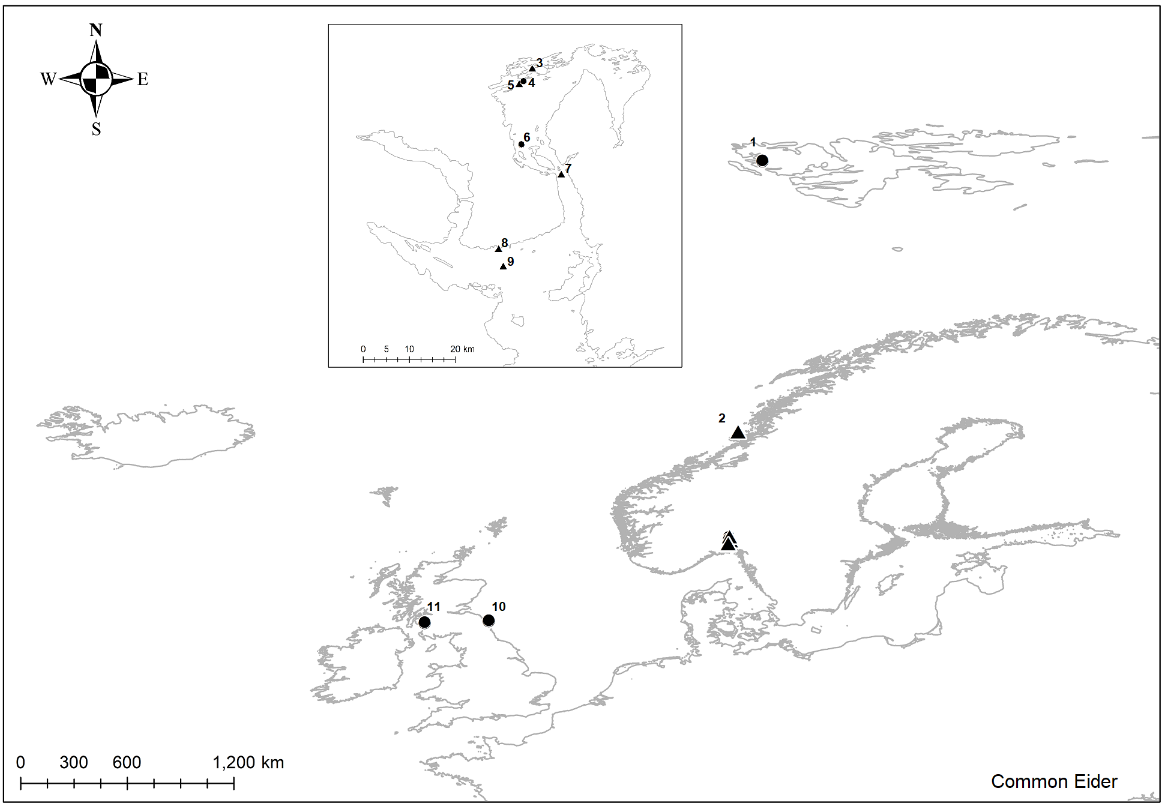
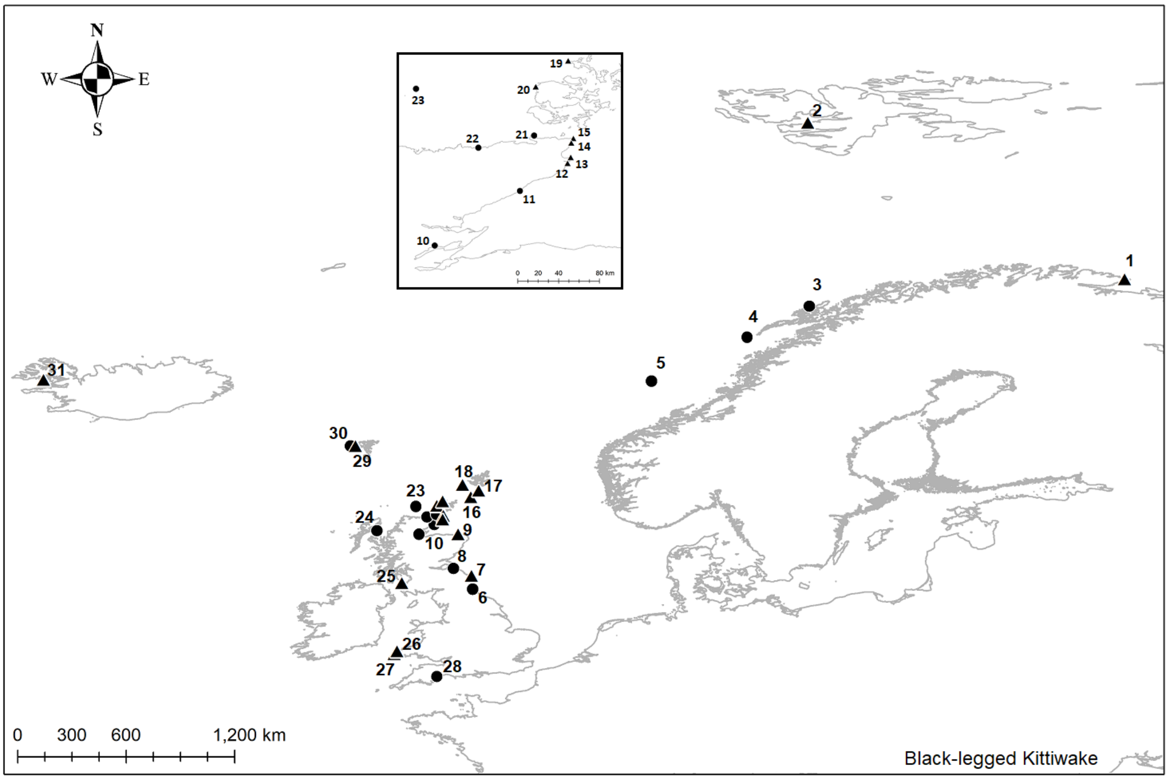
1,200 km
Great Cormorant

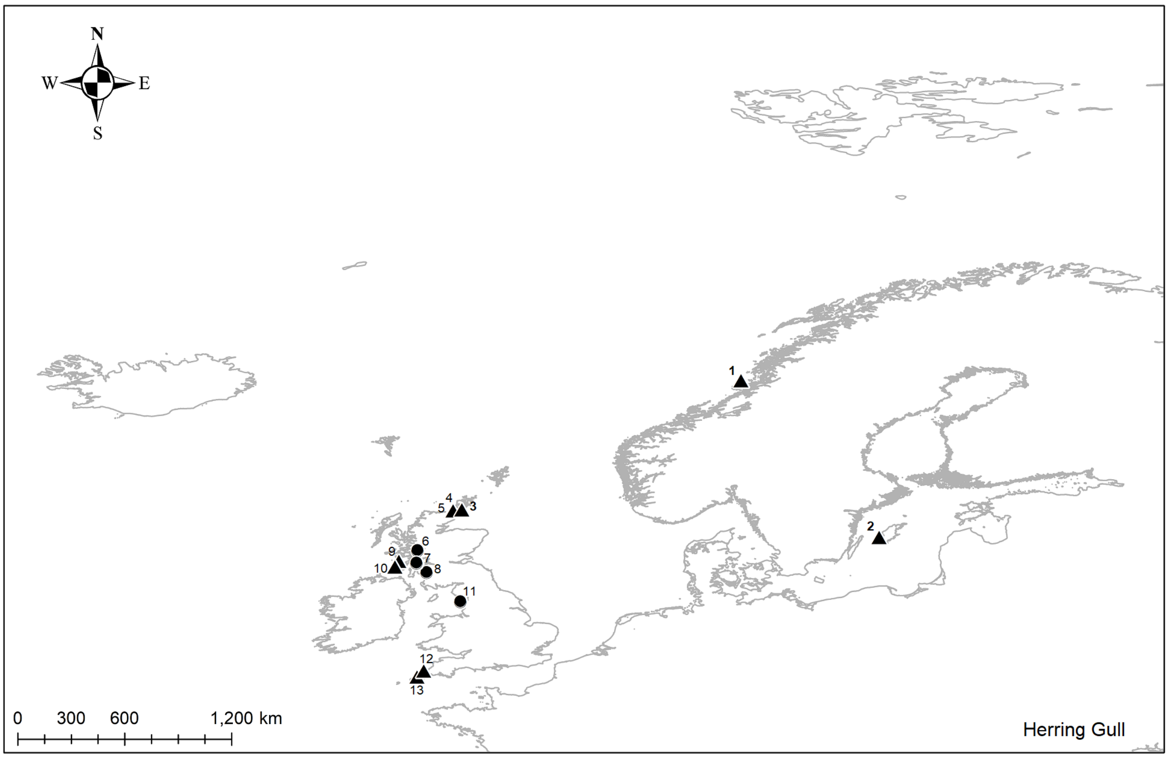
c)


N
W
E
S
3
5
4
6
7
8
9
0
5
10
20 km
1
2
11
10
0
300
600
1,200 km
Common Eider

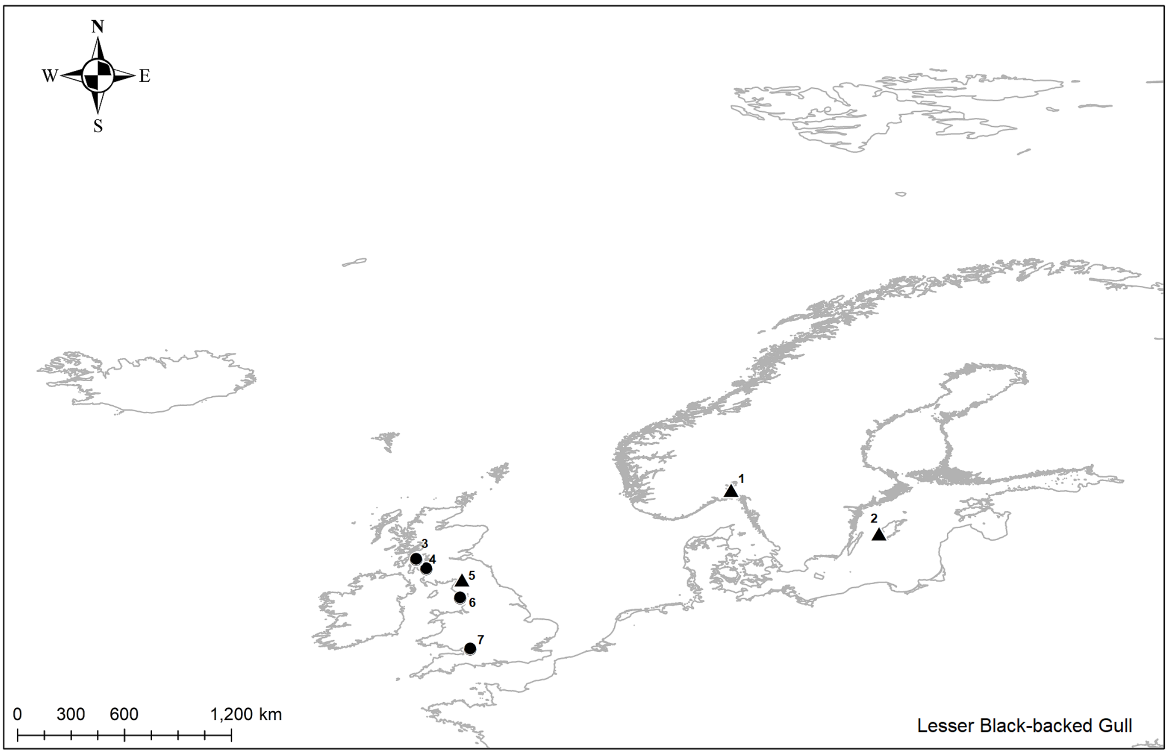
d)


N
W
E
S
19
20
23
22
21
15
14
13
12
11
10
0 20 40 80 km
1
2
3
4
5
31
30
29
18
17
23
16
24
10
9
8
7
6
25
26
27
28
0 300 600 1,200 km
Black-legged Kittiwake

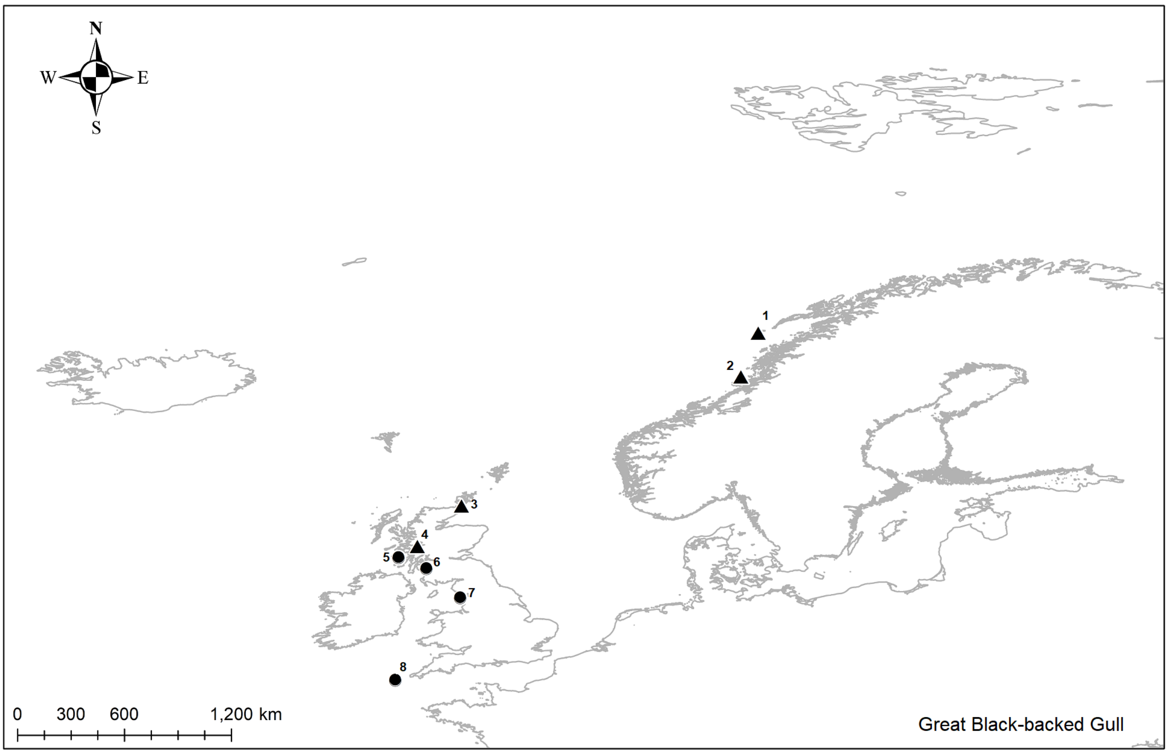
e)


N
W
E
S
1
2
4
5
3
6
9
7
10
8
11
12
13
0 300 600 1,200 km
Herring Gull

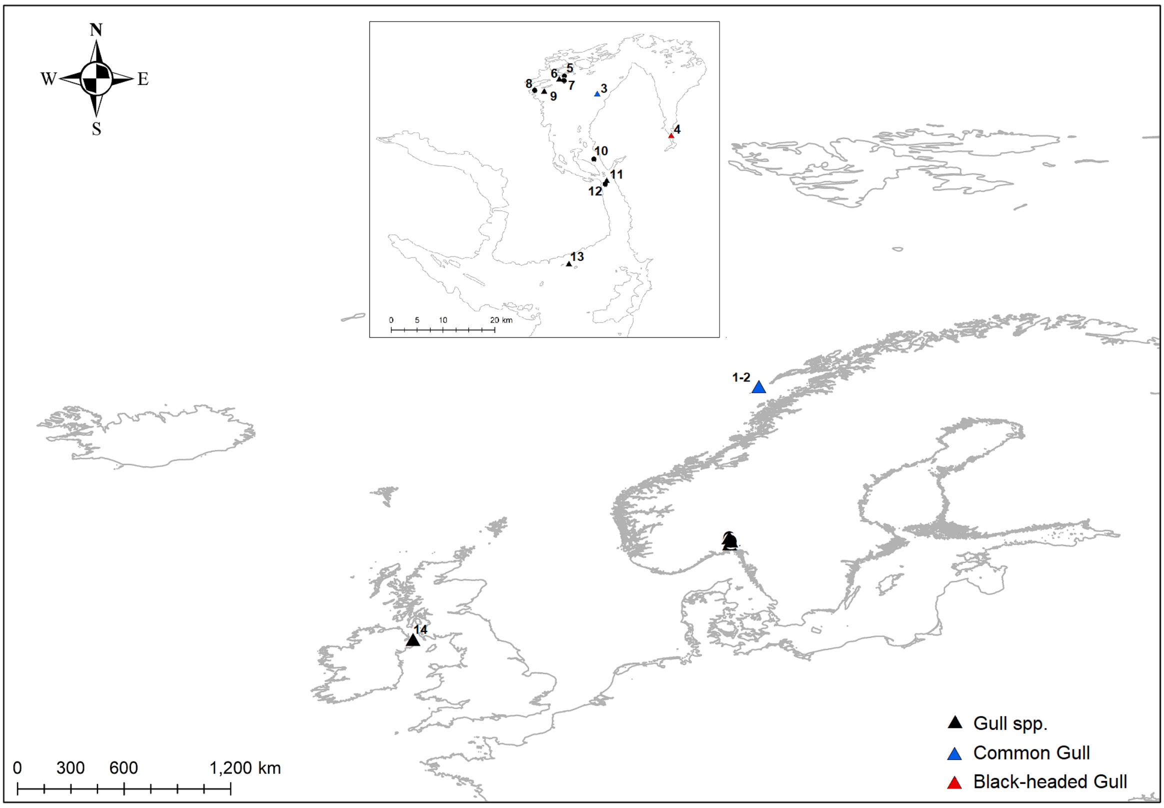
f)

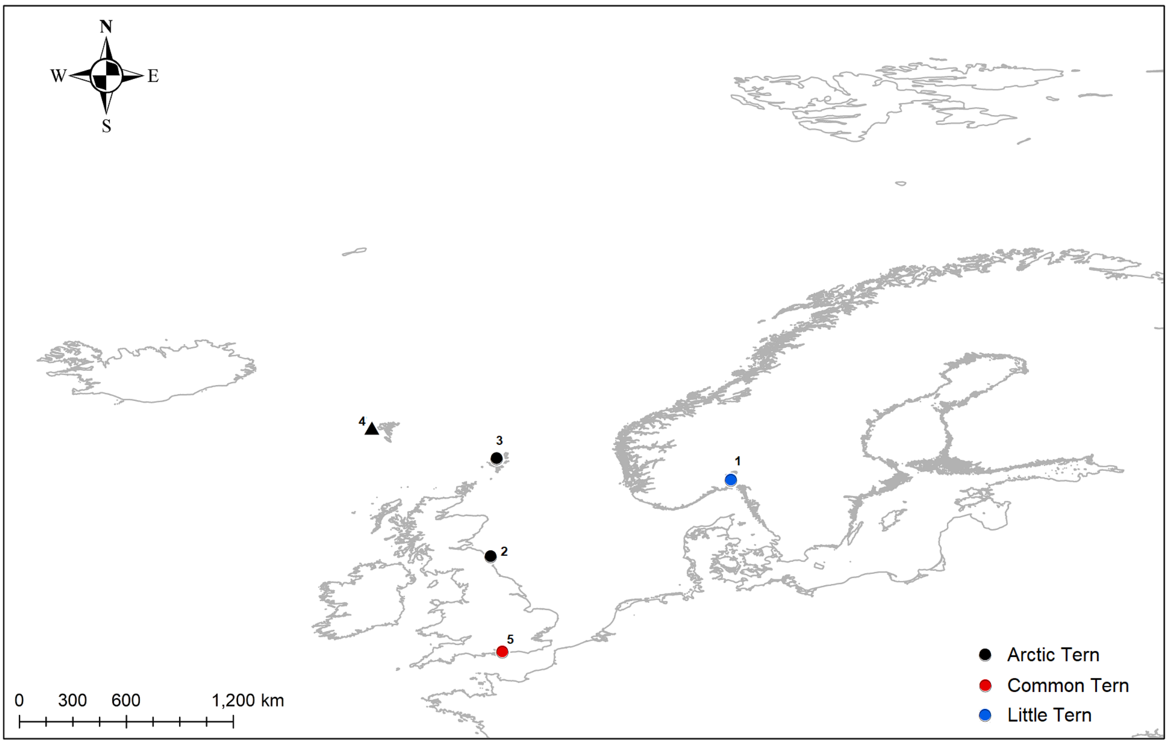

N
W
E
S
1
2
3
4
5
6
7
0
300
600
1,200 km
Lesser Black-backed Gull

g)

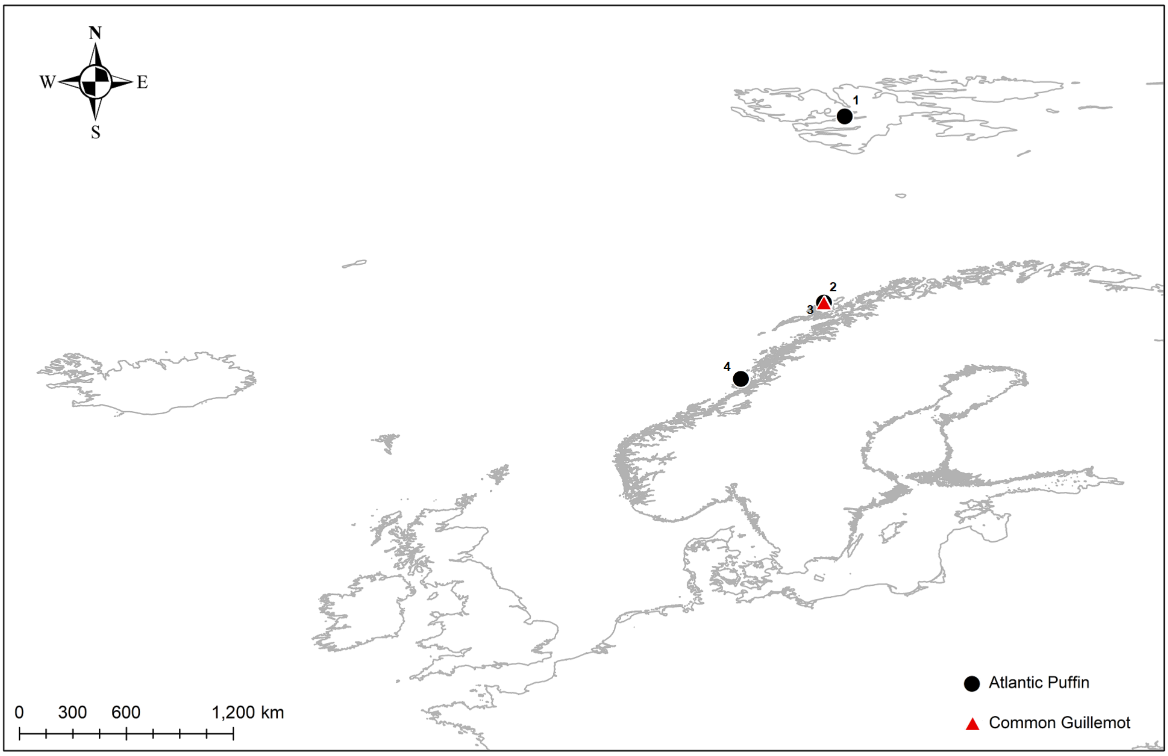

N
W
E
S
1
2
3
4
5
6
7
8
0
300
600
1,200 km
Great Black-backed Gull

h)


N
W
E
S
8
6
5
7
9
3
4
10
11
12
13
0 5 10 20 km
1-2
14
0 300 600 1,200 km
▲ Gull spp.
▲ Common Gull
▲ Black-headed Gull


N
W
E
S
4
3
1
2
5
0 300 600 1,200 km
● Arctic Tern
● Common Tern
● Little Tern

i)


N
W
E
S
1
2
3
4
Atlantic Puffin
Common Guillemot
0
300
600
1,200 km

j)

Table S2. Frequency of occurrence (FO) % of nests containing anthropogenic debris summarised by species group.

Species group	No. of species	No. of colonies	Total no. of nests	Number of nests containing debris	FO % of all nests	Mean (± SD) FO % across colonies
Kittiwake	1	31	3823	139	4	4 ± 10
Eider	1	11	338	11	3	4 ± 24
Tern [1]	3	5	183	11	6	5 ± 5
Gull [2]	5	32	4463	612	14	15 ± 23
Shag [3]	2	27	1459	339	23	18 ± 24
Auk [4]	2	3	150	87	58	41 ± 43

[1] Arctic Tern, Common Tern and Little Tern. [2] Black-headed Gull, Common Gull, Great Black-backed Gull, Herring Gulls and Lesser Black-backed Gull. [3] Great Cormorant and European Shag. [4] Crevice nesting Common Guillemot and Atlantic Puffin.

Table S3. Rank of general linear multivariate regression models explaining variation in FO of nests containing debris by species group, OSPAR region and mean Human Footprint Index (HFI) within 100 km of the colony using Akaike's information criterion corrected for small sample size (AICc): *k* is the number of estimated parameters included, ω_i is the Akaike weight, and ΔAICc is the AICc difference. The most parsimonious model (ΔAICc < 2) is shown in bold.

Variables included in the model	*k*	AICc	ΔAICc	ω_i
Mean HFI + Species group + OSPAR subregions + Mean HFI * Species group	**20**	**1431.1**	**0**	**1**
Species group + OSPAR subregions	14	1892.0	460.93	0
Mean HFI + Species group + OSPAR subregions	15	1894.3	463.22	0
Mean HFI + OSPAR subregions	10	2331.0	899.92	0
OSPAR subregions	9	2331.8	900.70	0
Mean HFI + Species group + Mean HFI * Species group	12	2380.4	949.25	0
Species group	6	2771.9	1340.80	0
Mean HFI + Species group	7	2773.7	1342.57	0
Intercept only	1	3458.4	2027.34	0
Mean HFI	2	3460.0	2028.91	0

Table S4. Minimum estimates of distance travelled, carbon emissions and monetary costs oi the lead author collecting the data included in the study, instead of requesting data from those already visiting the included colonies for research, monitoring and ringing purposes. See separate spreadsheet.

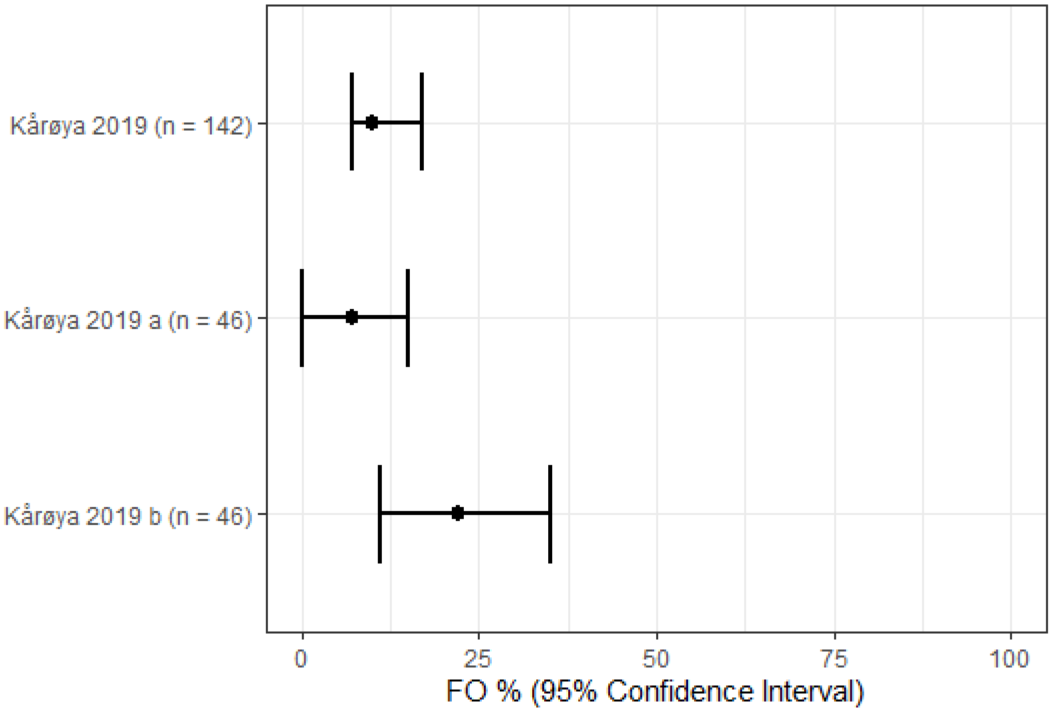


Figure S3. Comparisons of frequency of occurrence (FO) % of anthropogenic debris in nests and estimated 95% confidence intervals (CI) for two Black-legged Kittiwake plots in Kårøya, Norway: one involving 142 nests and the second 46 nests. The second plot was monitored from below and above the colony, highlighting how the reported FO can change based on the view of the monitoring plot. Overlapping 95% CIs indicates no difference in FO estimates.