Environmental Pollution 255 (2019) 113152

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Monitoring nest incorporation of anthropogenic debris by Northern Gannets across their range☆

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A R T I C L E I N F O

Article history:
Received 22 May 2019
Received in revised form
30 August 2019
Accepted 30 August 2019
Available online 6 September 2019

Keywords:
Marine
Nesting material
Plastics
Pollution
Seabird
Sentinel species
Sulidae

A B S T R A C T

Anthropogenic marine debris is a recognised global issue, which can impact a wide range of organisms. This has led to a rise in research focused on plastic ingestion, but quantitative data on entanglement are still limited, especially regarding seabirds, due to challenges associated with monitoring entanglement in the marine environment. However, for seabird species that build substantial surface nests there is the opportunity to monitor nest incorporation of debris that individuals collect as nesting material. Here, we monitored nest incorporation of anthropogenic marine debris by Northern Gannets (*Morus bassanus*) from 29 colonies across the species' range to determine a) the frequency of occurrence of incorporated debris and b) whether the Northern Gannet is a suitable indicator species for monitoring anthropogenic debris in the marine environment within their range. Using data obtained from visual observations, digital photography and published literature, we recorded incorporated debris in 46% of 7280 Northern Gannet nests, from all but one of 29 colonies monitored. Significant spatial variation was observed in the frequency of occurrence of debris incorporated into nests among colonies, partly attributed to when the colony was established and local fishing intensity. Threadlike plastics, most likely from fishing activities, was most frequently recorded in nests, being present in 45% of 5842 nests, in colonies where debris type was identified. Comparisons with local beach debris indicate a preference for threadlike plastics by Northern Gannets. Recording debris in gannet nests provides an efficient and non-invasive method for monitoring the effectiveness of actions introduced to reduce debris pollution from fishing activities in the marine environment.

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1. Introduction

Anthropogenic marine debris, including plastics (hereafter referred to simply as ‘debris’), is a global issue that is a recognised threat to marine species (IPBES Global Assessment 2019). Debris can disperse far and wide from its origin, becoming widely distributed throughout the oceans, even in remote areas (Lavers and Bond, 2017; Lebreton et al. 2017; Chiba et al. 2018). In the marine environment, debris can impact a wide range of organisms, from crustacea and fish to apex predators such as marine mammals and seabirds, largely through ingestion and entanglement (Laist, 1997; Gall and Thompson, 2015). Seabirds are particularly impacted with 36% of species reported to have been entangled in debris, and 39% to have ingested debris (Gall and Thompson, 2015; Ryan, 2018).

The increased awareness of the prevalence of debris in the marine environment has resulted in a rise in the number of scientific publications documenting incidences of ingestion (Gall and Thompson, 2015). However, we still have little quantitative information on entanglement and nest incorporation of marine debris for most seabird species, and locations (Provencher et al. 2015; O'Hanlon et al. 2017; Jagiello et al. 2019). Seabirds are particularly at risk of entanglement from marine debris (Kühn et al. 2015), but monitoring entanglement of seabirds with debris is challenging as the probability of detecting an entangled bird is low (Laist, 1987).

☆ This paper has been recommended for acceptance by Maria Cristina Fossi.
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https://doi.org/10.1016/j.envpol.2019.113152
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Therefore records of entanglement away from breeding colonies are largely anecdotal (although see Camphuysen, 2001; Rodríguez et al. 2013; Ryan, 2018). Conversely, entanglement of seabirds, or potential entanglement risk, can be monitored at breeding colonies, as several species incorporate debris into their nests (reviewed in Tavares et al. 2016; Jagiello et al. 2019). Incorporation of debris in nests can result in direct injury and mortality of chicks and adults (Votier et al. 2011; Seacor et al. 2014). Seabird species that collect nesting material to build surface nests, such as gannets, boobies, and cormorants (Sulidae and Phalcrocoracidae), appear to be particularly susceptible to incorporating debris (Podolsky and Kress, 1989; Montevecchi, 1991; Grant et al. 2018; Ryan, 2018; Tavares et al. 2019).

In addition to providing information on how nest incorporation of marine debris may affect seabird species, monitoring debris in seabird nests can also provide a relatively straightforward measure of local debris pollution (Montevecchi, 1991; Tavares et al. 2016). Northern Gannets (*Morus bassanus*) are north Atlantic sulids that build nest mounds from mud, vegetation, and increasingly debris (Votier et al. 2011; Bond et al. 2012). Nest mounds can be used over multiple years, meaning they are often large structures up to 100 cm tall (Nelson, 2002). Though some colonies have been the focus of individual studies, and relationships with debris availability have been explored (Bond et al. 2012), the extent of debris in Northern Gannet nests across their range, and what factors may be driving its abundance have not been investigated. By quantifying the extent of nest incorporation of debris by Northern Gannets from multiple locations across its entire range, we aim to establish whether gannets can be a useful monitor of debris in the marine environment of the N Atlantic Ocean.

2. Methods

During early egg incubation of the 2018 breeding season (11–27 May) we visited six gannet colonies across northern Scotland (Fig. 1, Table 1): one on the Scottish mainland (Troup Head), four in the Shetland Islands (Fair Isle, Noss, Foula and Hermaness) and one in the Orkney Islands (Noup Head). In addition, we visited Sule Skerry, Orkney (9–13 July) and Ailsa Craig, Firth of Clyde (2–3 August) during early to mid-chick-rearing 2018, and Mykineshomur, Faroe Islands during mid-incubation 2019 (7–10 June). Active gannet nests were observed, by the same observer (NJOH), from vantage points on land using a 20–60 × telescope, with the exception of Sule Skerry where 8 × 30 binoculars were used at the edge of the colony. The mean maximum (±SD) distance from which plots were viewed was 93 ± 49 m (range 20–190 m, n = 44). Only nests where the surface facing the observer was unobscured were included. For each colony we recorded the frequency of occurrence (FO) of nests containing visible debris at their surface. For nests that contained debris, we recorded the percentage by surface area of each nest that was comprised of different debris, estimated to the nearest 5%. In cases where <5% of the nest's surface was comprised of that debris, the surface area of visible debris was estimated to the nearest 1%. Debris was categorised by type (sheet, thread, foam, hard, other including non-plastic items) as specified by Provencher et al. (2017), and potential source (fishing activities, consumer items, unknown). As the size of the nest, and its position within the colony, may influence the amount of debris incorporated, we also scored each nest as being small (ca. <10 cm tall), medium (ca. 10–30 cm tall) or large (ca. >30 cm tall), using nearby Northern Gannets for size reference. Where feasible, multiple plots were monitored per colony, otherwise, single plots were selected that were representative of the colony. Plots were categorised as being located either in the colonies' core or periphery (approximately within 10% of the colony edge). The number of nests monitored at each colony varied depending on colony size, visibility of nests from accessible vantage points on land and time available. Data from visual observations by different observers were also obtained from three additional colonies: Grassholm, Wales (3 August, from within the colony); Bempton Cliffs, England (6–7 June, from land vantage points); and Bonaventure Island, Canada (multiple visits in May and June). Data on FO were recorded from all three colonies, whilst data on FO and the percentage by visible surface area of individual nests by debris type and potential source were recorded from Bempton Cliffs and Bonaventure Island.

For 14 additional colonies (Table 1) we obtained photographs of nests or plots, which we used to determine the FO of nests containing debris. From visible nests within these images, we also recorded FO by type and potential source. All digital images were taken from land or boat with the exception of Bass Rock, Scotland and Karlinn, Iceland, which were taken from an aeroplane and unmanned aerial vehicle (UAV), respectively. The methods used to obtain data on nest incorporation were selected based on the accessibility of the colony. Where feasible, nests were observed from a suitable vantage point, however aerial and UAV images were used where this was not possible. Finally, we obtained published data on nest incorporation of debris by Northern Gannets from Bond et al. (2012) for two Canadian colonies, Funk Island and St. Cape Mary's, and Merlino et al. (2018) for Porto Venere, Italy. Where data on nest incorporation was available for multiple years we used data from the most recent year that the colony was monitored (previous years data are listed in Table S1).

To establish whether the type and potential source of debris found within Northern Gannet nests represented that found in the local environment, we obtained data on beach debris from Marine Conservation Society (MCS) organised beach clean-ups. We extracted information on the type and potential source of all debris collected during beach surveys between 2012 and 2017 within 20 km of each UK colony. To explore whether variation in the FO of nests containing debris varied in relation to fishing activity (Bond et al. 2012), we extracted mean fishery effort within 100 km of each colony between 2012 and 2016, from Global Fishing Watch (www.globalfishingwatch.org; Merten et al. 2016; Kroodsma et al. 2018) measured as log-transformed fishing hours. Using scripts available from Global Fishing Watch, we calculated the mean total fishery effort between 2012 and 2016 at 0.25° resolution in R 3.5.1 (R Core Team, 2018). A buffer of 100 km was created around each gannet colony to extract a value for the mean fishery effort for each colony using the spatial join operation in ArcGIS (ArcMap ver.10.7. ESRI, USA).

2.1. Statistical analysis

All statistical analyses were performed in R 3.5.1 (R Core Team, 2018). To test for any spatial structure in the FO of nests containing debris among colonies we performed Moran's I Index autocorrelation analysis (Moran, 1950, 1953; Legendre and Fortin, 1989) using the *ape* R package (Paradis and Schliep, 2019), including colony specific latitude and longitude. Moran's I Index ranges from −1 (spatially dispersed) to +1 (spatially clustered) (Moran, 1950, 1953; Legendre and Fortin, 1989).

In some colonies, all nests contained debris leading to a lack of variance. Consequently, to compare the FO of nests containing debris among colonies we used a generalized estimating equation (GEE) with a binomial error structure and logit link function (Grant et al. 2018) in the R package *geepack* (Højsgaard et al. 2005), followed by Tukey post-hoc tests using the *lsmeans* package (Lenth, 2016). We performed a generalized linear model (GLM) with a binomial error structure to explore whether spatial variation in FO of nests containing debris related to the year a colony was

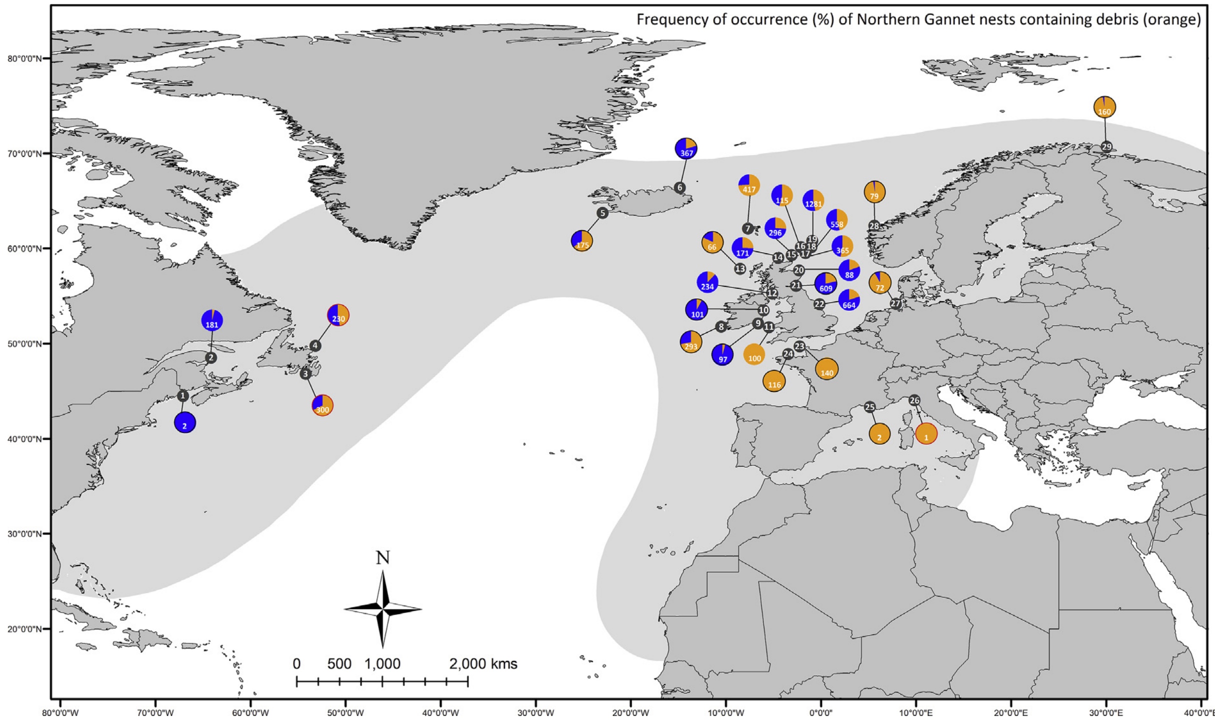

Fig. 1. Map showing the location of Northern Gannet colonies included within this study (Table 1). Pie charts show the FO of nests containing debris in orange, with numbers referring to the sample size of nests monitored. The outline of the pies depicts the source of data: red - from the literature, black - from photographs in this study, no outline - from visual observations in this study. The range of the Northern Gannet is shown in light grey (Birdlife 2019). 1. Machias Seal Island. 2 Bonarparte Islands. 3 Cape St. Mary's. 4 Funk Island. 5 Eldey. 6 Karlinn. 7 Mykineshomur. 8 Little Skellig. 9 Great Saltee. 10 Lambay. 11 Grassholm. 12 Ailsa Craig. 13 St. Kilda. 14 Sule Skerry. 15 Noup Head. 16 Foula. 17 Fair Isle. 18 Noss Head. 19 Hermaness. 20 Troup Head. 21 Bass Rock. 22 Bempton Cliffs. 23 Les Étacs. 24 Rouzic. 25 Carry-le-Rouet. 26 Porto Venere. 27 Helgoland. 28 Runde. 29 Syltefjord.

established (Table 1) and the level of fishing activity in the vicinity. The presence or absence of debris within an individual nest was included as the binomial response variable (1 and 0, respectively) with year established since 1900 (earlier established colonies were dated as 1900, the approximate advent of plastic production, Thompson et al. 2009; Hammer et al. 2013), and local fishing intensity, and their interaction, included as fixed effects. To investigate overall similarity in the FO of debris type between the nests and MCS beach debris data we calculated Jaccard's Index (J) of similarity for each of the eight colonies where MCS data was available (Real and Vargas, 1996; Lavers and Bond, 2016; Grant et al. 2018) using the R package *jaccard* (Chung et al. 2018). Jaccard's Index values range from 0 (complete dissimilarity) to 1 (complete similarity), with values of $J > 0.6$ considered significant (Catry et al. 2009; Bond et al. 2012; Grant et al. 2018). To investigate whether observed frequencies of threadlike plastics and debris thought to be from fishing activities differed between the nests and MCS beach debris data we carried out χ^2 tests (Sergio et al. 2011).

To determine whether the size or location of the nest in the colony (within a core or periphery plot) influenced the FO of debris, for the eight Scottish colonies where visual observations were completed, we constructed a generalized linear mixed model (GLMM) with a binomial error structure; colony was included as a random effect to account for multiple plots monitored per colony, and nest size and colony section, and their interaction, as fixed effects. The presence or absence of debris within an individual nest was included as the binomial response variable (1 and 0, respectively). Tukey post-hoc tests were undertaken using the *glht* function in the R package *multcomp* (Hothorn et al. 2008). To check whether the overall FO % was influenced by the number of nests of different sizes that were monitored, we carried out Pearson's product-moment correlations to determine whether the FO of debris in all nest sizes were related to the FO of debris within each size category. To explore among and within colony variation in FO of debris we performed a one-way analysis of variance (ANOVA), to determine the variance within and between groups, with colony as a fixed effect.

3. Results

In total, across all sites, 46% of 7280 monitored Northern Gannet nests across the species range contained debris. In 2018 and 2019, 4991 Northern Gannet nests from twelve colonies were examined in the field for debris (Table 1, Fig. 1). Incorporated debris was detected in nests from all twelve colonies. Among colonies, 40% (2003) of these nests contained debris, however the FO of nests containing debris among these colonies varied (mean FO across colonies = 41 ± 27 SD, Range = 4–100%, Table 1). A further 1840 nests were examined in digital images taken from 14 additional Northern Gannet colonies, between 2014 and 2018, including Grassholm as data from visual observations did not include debris type or potential source (Table 1, Fig. 1). Nest debris was also detected in all these colonies except for the small, recently established colony on Machias Seal Island, Canada. From the digital images, 61% (1123) of all nests contained debris (mean FO across colonies = 64 ± 41 SD, Range = 0–100%, Table 1).

There was significant variation in the FO of nests containing debris among Northern Gannet colonies (Table 1), with slight spatial clustering with respect to FO of debris (Moran's $I = 0.08$, $P = 0.02$). Part of this weak spatial clustering is likely attributed to local fishing intensity. The among colony variation in FO of nests containing debris was significantly related to both the year a colony was established since 1900 and mean fishing effort within 100 km of each gannet colony between 2012 and 2016, with a significant

Table 1
Summary of the most recent studies per colony examining debris in nests of Northern Gannets. Colony numbers refer to location in Fig. 1. For the FO % of nests containing debris, the same letter superscript highlights colonies that have proportions of nests with and without debris that are not significantly different from each other based on Tukey's post-hoc tests.

Colony [a]	Country	First known breeding	AOS/AON [b] (Year counted)	Sampling year	Sampling Period	Number of nests monitored (% of colony monitored) [c]	Number of colony subplots	FO % of nests containing debris	Source of data
1. Machias Seal Is.	Canada	2012 [d]	2 (2018) [d]	2018	Incubation	2 (100.0)	NA	0[a]	Photographs (this study)
2. Bonaventure Is.	Canada	<1860 [e]	59 586 (2009) [p]	2018	Incubation	181 (0.3)	1	4[b]	Visual obs. (this study)
3. Cape St. Mary's	Canada	1879 [e]	14 789 (2009) [p]	2007	Throughout	300 (2.0)	NA	68[ijk]	Bond et al. (2012)
4. Funk Island	Canada	<1534 [e]	9987 (2009) [p]	2007	Throughout	230 (2.3)	NA	47[gh]	Bond et al. (2012)
5. Eldey	Iceland	<1764 [e]	14 810 (2014) [q]	2018	Incubation	175 (8.7)	NA	65[hij]	Photographs (this study)
6. Karlinn	Iceland	<1959 [f]	656 (2014) [q]	2017	Incubation	367 (56.0)	NA	20[cdef]	UAV images (this study)
7. Mykinesholmur	Faroe Is.	<1500 [g]	2350 (2004) [r]	2019	Incubation	417 (17.9)	NA	74[jkl]	Visual obs. (this study)
8. Little Skellig	Ireland	1856 [e]	35 294 (2014) [h]	2017	Chick rearing	293 (0.8)	NA	72[ijk]	Photographs (this study)
9. Great Saltee	Ireland	1929 [e]	4722 (2013) [h]	2017	Incubation	97 (2.05)	NA	4[bc]	Photographs (this study)
10. Lambay	Ireland	2007 [h]	728 (2013) [h]	2017	Incubation	101 (13.9)	NA	8[bcde]	Photographs (this study)
11. Grassholm	Wales	1820 [e]	39 011 (2009) [i]	2018	Chick rearing	100 (0.3)	1	100[n]	Visual obs. (this study)
12. Ailsa Craig	Scotland	1526 [e]	33 226 (2014) [i]	2018	Chick rearing	234 (0.70)	1	12[bcd]	Visual obs. (this study)
13. St Kilda	Scotland	1549 [e]	60 290 (2013) [i]	2018	Incubation	66 (0.1)	NA	82[ijklm]	Photographs (this study)
14. Sule Skerry	Scotland	2003 [i]	1870 (2013) [i]	2018	Chick rearing	171 (9.1)	2	25[def]	Visual obs. (this study)
15. Noup Head	Scotland	2003 [i]	751 (2014) [i]	2018	Incubation	296 (39.4)	4	26[ef]	Visual obs. (this study)
16. Foula	Scotland	1980 [i]	1226 (2013) [i]	2018	Incubation	115 (9.4)	1	54[ghi]	Visual obs. (this study)
17. Fair Isle	Scotland	1974 [i]	3591 (2014) [i]	2018	Incubation	365 (10.2)	6	53[gh]	Visual obs. (this study)
18. Noss	Scotland	1914 [e]	11 786 (2014) [i]	2018	Incubation	558 (4.7)	8	46[g]	Visual obs. (this study)
19. Hermaness	Scotland	1917 [e]	25 580 (2014) [i]	2018	Incubation	1281 (5.0)	12	47[g]	Visual obs. (this study)
20. Troup Head	Scotland	1987 [i]	6456 (2014) [i]	2018	Incubation	609 (9.4)	8	19[cde]	Visual obs. (this study)
21. Bass Rock	Scotland	1447 [e]	75 259 (2014) [i]	2014	Chick rearing	88 (0.1)	NA	22[cdef]	Aerial images (this study)
22. Bempton	England	1937 [e]	12 494 (2014) [s]	2018	Incubation	664 (5.3)	8	31[f]	Visual obs. (this study)
23. Les Étacs	Channel Is.	1940 [k]	5765 (2011) [s]	2017	Chick rearing	140 (2.4)	NA	100[n]	Photographs (this study)
24. Rouzic Island	France	1939 [j]	21 545 (2014) [i]	2017	After breeding	116 (0.5)	NA	100[n]	Photographs (this study)
25. Carry-le-Rouet	France	2006 [m]	2 (2013) [m]	2013	Incubation	2 (100.0)	NA	100[n]	Photographs (this study)
26. Porto Venere	Italy	2013 [o]	1 (2017) [o]	2017	Incubation	1 (100.0)	NA	100[n]	Merlino et al. (2018)
27. Helgoland	Germany	1991 [n]	780 (2016) [n]	2018	Chick rearing	72 (9.2)	NA	92[klm]	Photographs (this study)
28. Runde	Norway	1940 [l]	3600 (2016) [l]	2017	Incubation	79 (2.2)	NA	97[lm]	Photographs (this study)
29. Syltefjord	Norway	1967 [l]	563 (2016) [l]	2016	Incubation	160 (28.4)	NA	98[m]	Photographs (this study)

[a] Number refers to the colony number in Fig. 1.
[b] Apparently occupied site (AOS)/apparently occupied nest (AON).
[c] Based on the AOS/AON stated in this table.
[d] Tony Diamond & Angelika Aleksieva pers. Comm.
[e] Fisher and Vevers (1944).
[f] Sunna Björk Ragnarsdóttir pers. Comm.
[g] Salomonsen (1935).
[h] Newton et al. (2015).
[i] Murray et al. (2014).
[j] Siorat and Rocamora (1995).
[k] Veron and Lawlor (2009).
[l] Barrett et al. (2017).
[m] Deideri et al. (2014).
[n] Störmer (2017).
[o] Merlino et al. (2018).
[p] Chardine et al. (2013).
[q] Skarphéðinsson et al. (2016).
[r] Jensen et al. (2005), similar to the present colony size (Jóhannis Danielson pers. comm.).
[s] JNCC (2016) http://jncc.defra.gov.uk/page-2875. Data available from previous years for these colonies are listed in Table S1.

interaction between the two factors ($X^2_1 = 67.3$, $P < 0.001$; Fig. 2). Colonies located in areas of higher fishing effort within 100 km of the colony had a higher occurrence of nests containing debris than those in areas of lower fishing effort, with more recently established colonies containing fewer nests with incorporated debris than older colonies.

For the colonies in Scotland where visual observations were conducted, we found a significant interaction between nest size and location in the colony (core or periphery) on the FO of incorporated debris ($X^2_5 = 1197.6$, $P < 0.001$, $R^2 = 0.38$). This interaction was attributed to more large nests being located in the core areas of colonies (mean number of large nests = 33.0 ± 31.5 SD) than on the periphery (mean number of large nests = 9.2 ± 19.0 SD). Nests that were classified as small (FO = 16% ± 0.1 SD) contained significantly less debris than those classified as medium (FO = 35% ± 0.2 SD) or large (FO = 67% ± 0.3 SD), with medium nests also having a lower FO than large nests (all post-hoc tests $P < 0.001$; Table S2). Therefore, plots in the core of colonies had a significantly higher FO of debris than periphery plots (core: FO = 52.1% ± 27.6 SD; periphery: FO = 11.2% ± 9.4 SD. Table S2). Among colonies, the FO of debris in all nests was significantly correlated to the FO of debris within each size category (Small: $t_{25} = 5.83$, $P < 0.001$, $R_p = 0.76$. Medium: $t_{33} = 6.84$, $P < 0.001$, $R_p = 0.77$. Large: $t_{28} = 6.52$, $P < 0.001$, $R_p = 0.78$). Variation in the FO of incorporated debris among colonies (r = 0.16) was greater than that within colonies (r = 0.08).

Data on the type and potential source of debris recorded in nests were available for 5842 nests, across 23 colonies, of which 2642 (45%) contained debris (Table 2). Threadlike plastics, most likely

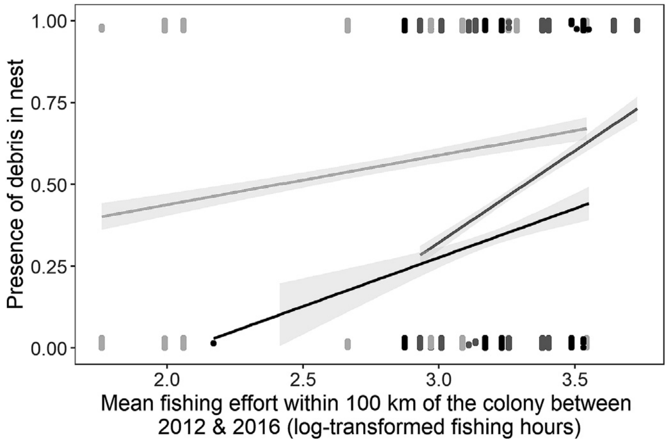

Fig. 2. The presence of debris in Northern Gannet nests was positively related to the mean fishing effort between 2012 and 2016 within 100 km of the colony, measured as log-transformed fishing hours, which was influenced by the year the colony was established. Colonies established more recently contained a lower proportion of nests containing debris than older colonies. Each point at 0.00 (no incorporated debris) and 1.00 (incorporated debris) represents a nest. Solid lines indicates the trend lines with 95% confidence intervals (shaded area) predicted from a generalized linear model (GLM) with a binomial error structure. To visualise the significant interaction between local fishery effort and year established, the data for year established was split into three groups based on the mean and one standard deviation above and below the mean: Light grey – the oldest colonies established before 1900; dark grey – colonies established between 1937 and 1967; black – the newest colonies, established since 1974.

from fishing activities, were the most frequent debris type, recorded in 45% of all nests (mean FO across colonies: 52% ± 35 SD), and so present in every nest that contained debris. Most of this threadlike fishing debris was rope or net, however 448 nests (8% of all 5842 nests) contained packaging straps, also thought to originate from fishing activities. The remaining debris types contributed only a small amount to the debris recorded. For ten colonies, we obtained data on the estimated percentage surface area of individual nests comprised of debris, by type and potential source (Table 3). Combining all debris types, the majority of the visible surface area of nests were comprised of 0–10% of debris as nesting material (Fig. 3).

For the eight colonies where MCS beach debris data were available within 20 km, the composition of debris observed in nests was found to be dissimilar to that found on nearby beaches ($J < 0.13$, $N = 8$. Table S3). The FO of nests containing threadlike plastics was significantly greater than the proportion of threadlike items on beaches ($\chi^2_1 = 64.0$, $P < 0.001$, $N = 8$), as was the proportion of items categorised as being from fishing activities ($\chi^2_1 = 46.0$, $P < 0.001$, $N = 8$), indicating active selection by gannets for these debris types as nest material (see Table 4).

4. Discussion

Northern Gannets commonly incorporate debris into their nests, with debris recorded in 28 of the 29 colonies monitored. Most debris identified in nests was threadlike plastics, as found previously (e.g., rope and net fragments originating from fishing activities; Votier et al. 2011; Bond et al. 2012). The remainder of the

Table 2
The frequency of occurrence (FO) of debris categorised by type and potential source, as a percentage of all monitored nests. Colony numbers refer to location in Fig. 1.

Colony [a]	Number of nests examined	Number of nests containing debris (%)	FO of debris by type (%) [b]				FO by potential source (%)		
			Thread	Sheet	Hard	Other	Fishing	Consumer	Unknown
Data from visual observations									
2. Bonaventure	181	7 (4)	3	0	0	1	2	1	1
7. Mykineshomur	418	310 (74)	74	1	0	0	74	1	0
12. Ailsa Craig	234	28 (12)	12	0	0	0	11	0	1
13. Sule Skerry	171	43 (25)	25	0	0	0	25	4	0
14. Noup Head	296	77 (26)	25	1	0	0	24	3	0
15. Foula	115	62 (54)	54	1	0	0	53	1	1
16. Fair Isle	364	193 (53)	53	0	0	0	48	15	1
17. Noss	558	256 (46)	45	1	0	0	44	1	1
18. Hermaness	1281	605 (47)	47	2	0	0	43	10	0
20. Troup Head	609	118 (19)	19	0	0	0	19	0	0
22. Bempton [c]	197	132 (67)	65	3	1	1	60	12	2
Data from digital images									
1. Machias Seal Island	2	2 (0)	0	0	0	0	0	0	0
5. Eldey	175	114 (65)	65	0	0	0	65	0	0
6. Karlinn	367	75 (20)	20	0	0	0	20	0	0
8. Little Skellig	293	210 (72)	72	1	0	0	72	1	0
9. Great Saltee	97	4 (4)	4	0	0	0	4	0	0
10. Lambay	101	8 (8)	7	1	0	0	7	1	0
11. Grassholm [d]	82	82 (100)	99	1	2	0	98	0	7
13. St. Kilda	66	54 (82)	82	0	0	0	82	0	0
21. Bass Rock	88	19 (22)	22	0	0	0	22	0	0
23. Les Étacs	140	140 (100)	100	0	0	0	100	0	0
24. Rouzic	116	116 (100)	100	0	0	0	100	8	0
25. Carry-le-Rouet	2	2 (100)	100	0	0	0	100	0	0
26. Porto Venere	1	1 (100)	100	0	0	0	100	0	0
27. Helgoland	72	66 (92)	92	0	0	0	92	21	0
28. Runde	79	77 (97)	97	0	0	0	97	13	0
29. Syltefjord	160	156 (98)	98	1	0	0	97	53	0

[a] Number refers to the colony number in Fig. 1.
[b] Standardised debris categories as recommended by Provencher et al. (2017). Foamed plastics was not detected in any nests. Values do not sum to 100% as some nests contained more than one debris type or potential source.
[c] 204 of 664 nests contained debris at Bempton, however detailed data on incorporated debris was only available for 196 nests, 132 of which contained debris.
[d] Only overall frequency of occurrence data was available for the 100 Grassholm nests from visual observations, therefore digital images were used for frequency of occurrence by debris category and potential source of 82 nests.

Table 3
The mean (±SD) estimate of individual surface area content comprised of each debris type and potential source, of nests containing debris, where visual observations were completed across monitoring plots. Colony numbers refer to location in Fig. 1.

Colony	Mean (±SD) estimate of individual nest surface area by debris category (%)								Mean (±SD) estimate of individual nest surface area by potential source (%)					
	Thread		Sheet		Hard		Misc.		Fishing		Consumer		Unknown	
2. Bonaventure	8.3	±8.0	0.0		0.0		5.0		11.8	±7.7	5.0		1.5	±0.7
12. Ailsa Craig	2	±1.9	0.0		1.0		0.0		2	±1.9	0.0		1.5	±0.7
14. Sule Skerry	3.1	±2.5	0.0		0.0		0.0		3.1	±2.5	0.0		0.0	
15. Noup Head	4.6	±6.0	5.5	±6.4	0.0		1.0		4.7	±6.0	4.3	±5.2	0.0	
16. Foula	14.9	±15.1	5.0		0.0		0.0		14.9	±15.2	5.0		15.0	
17. Fair Isle	13.1	±13.7	0.0		0.0		30.0		13.3	±13.8	1.0		8.8	±14.2
18. Noss	12.2	±12.1	3.6	±1.5	0.0		0.0		12.3	±12.2	3.6	±1.5	1.7	±0.6
19. Hermaness	12.9	±11.9	4.4	±3.5	1.5	±0.7	4	±1.7	12.6	±11.9	11.2	±10.7	3	±1.9
20. Troup Head	7.6	±6.7	0.0		0.0		0.0		7.6	±6.8	0.0		2.0	
22. Bempton	22.7	±21.2	4.4	±1.3	1.0		5.0		22.6	±21.3	6.5	±3.6	4.3	±1.5

observed threadlike plastic was packaging straps, often used to wrap boxes of fish and bait. We found that the FO of nests containing debris at the colony level was related to the year that colony was established and local fishing effort. For the eight colonies with adjacent beach surveys, the proportion of debris that was classified as threadlike plastics was higher in the gannet nests than that collected from beaches, indicating that gannets selected for threadlike debris (Votier et al. 2011), given its similarities to natural nesting material such as seaweed and grass (Montevecchi, 1991; Nelson, 2002).

We found considerable variation in the proportion of nests containing debris among colonies with part of this variation related to the spatial structure of the colony locations. Specifically, our results indicate that part of this variation among colonies was influenced by the intensity of local fishing activities. As found by Bond et al. (2012), we observed a positive relationship between FO and fishing intensity, measured as mean fishery effort between 2012 and 2016 within 100 km of a colony. Colonies located in areas of high fishing effort had a greater proportion of nests with incorporated debris. This suggests that areas of higher fishing activity are also those that have greater levels of fishing related marine debris (Walker et al. 1997; Ribic et al. 2012; Unger and Harrison, 2016), which was reflected by the gannets in these locations using threadlike plastics more often as nesting material. The variation in FO of nests containing debris among colonies was also related to the age of the colony. Colonies established after 1974 had fewer nests containing debris with those established before this date, likely because newer colonies contained more small nests, and had less time for debris to accumulate. Colonies established before 1900 had a greater occurrence of nests containing debris as they have had many years to accumulate debris. Additional factors that we did not account for may also have influenced the FO of nests containing debris in colonies. For example, prevailing winds and currents, which can accumulate debris in certain locations (Barnes et al. 2009; Critchell and Lambrechts, 2016), and local levels of aquaculture, which can also be a source of threadlike debris (Hinojosa and Thiel, 2009; Merlino et al. 2018). Unfortunately, data were not available to explore these factors. Furthermore, the fishery effort data we used in our analysis included all gear types, so some of the methods used to catch these species may contribute little to the debris Northern Gannets incorporate into their nests, and catch of different target species does vary spatially.

During this study, we encountered a number of challenges in collecting data on nest incorporation of debris by Northern

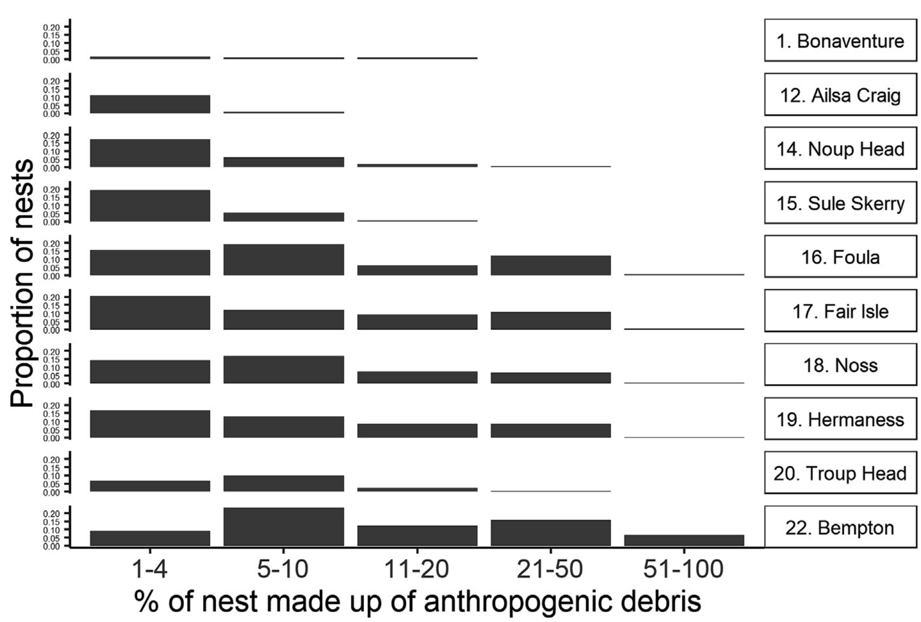

Fig. 3. For each colony where visual observations were carried out, the distribution of gannet nests for each percentage category of individual nests containing anthropogenic debris. Highlighting that for the majority of these nests, the surface area was comprised of 1–10% of debris as nesting material.

Table 4
Marine Conservation Society (MCS) beach clean data within 20 km of Northern Gannet colonies, with the frequency of occurrence (FO) of debris collected, by type from all debris collected, and the FO of Northern Gannet nests containing debris by type (of all nests that contained debris). Colony numbers refer to location in Fig. 1.

Colony	No. of MCS beach cleans within 20 km of the colony [a]	FO of threadlike plastics (%)			FO of fishing related (%)			FO of consumer related (%)			FO of unknown source (%)		
		Beach (mean ± SD)		Nests	Beach (mean ± SD)		Nests	Beach (mean ± SD)		Nests	Beach (mean ± SD)		Nests
11. Grassholm	14	37.98	±19.85	100	31.68	±16.97	100	24.45	±13.00	0	43.87	±16.01	0
12. Ailsa Craig	6	27.57	±10.81	96	3.77	±2.43	89	51.97	±12.86	4	44.26	±13.96	7
13. St. Kilda	1	16.77		100	7.72		100	61.28		0	31.01		0
15. Noup Head	2	59.68	±8.60	96	16.89	±5.41	92	25.03	±14.28	12	58.07	±19.70	1
20. Troup Head	16	15.3	±12.54	100	8.46	±4.74	99	46.94	±22.56	0	44.6	±19.75	1
21. Bass Rock	41	6.91	±5.60	100	3.21	±3.38	100	60.23	±15.43	0	36.56	±14.97	0
22. Bempton	121	13.45	±11.80	98	8.56	±8.74	91	44.76	±18.09	17	46.69	±16.61	3
23. Les Étacs	6	15.47	±7.30	100	5.55	±3.62	100	58.63	±11.10	0	35.81	±11.48	0

[a] Number of beach cleans between 2012 and 2017 from beaches within 20 km of each colony.

Gannets. Firstly, we found variability in the FO of debris in nests among plots within a colony, most likely attributed to differences in the size of nests among plots. In sheltered parts of a colony, gannets can add new material onto existing nests annually, creating large pedestals up to 100 cm in height (Nelson, 2002). These large nests may contain debris incorporated over many years, with anthropogenic debris likely to persist longer than natural nesting material. Conversely, small nests will likely only contain debris collected during that year. Within this study fewer small nests contained debris than large nests, in contrast to Montevecchi (1991) who found no difference in FO between large Northern Gannet nests (>12 cm in height) and more recent nests (<10 cm in height). Furthermore, plots in core areas of the colonies contained more nests with incorporated debris than on the periphery plots, attributed to periphery plots likely being the more recently colonised areas (Nelson, 2002) and therefore generally containing a higher proportion of small, newer nests. It is important to take this variability in nest size and location within a colony into consideration if comparing FO among colonies and years and ideally monitor the same plots in subsequent years. The exact location of vantage points where monitoring or photographs are taken should therefore be recorded to assist temporal monitoring at the same locations in the future. The sample size of nests monitored are also important. To detect change in FO, the sample size of nests will vary depending on the level of prevalence and the level of detectable change required. Provencher et al. (2015) calculated that to detect a 20% change in prevalence, 187 and 42 nests would need to be surveyed annually at Funk Island and Cape Saint Mary's, respectively, reflecting colonies containing a medium and high FO of nests containing debris, which is less than the mean sample size of nests in our field study (245; Table 1). We therefore have higher confidence in the values of FO from colonies where a higher proportion of nests were checked. Visually checking nests from a distance will also underestimate the actual prevalence of incorporated debris, with the distance from the nest where monitoring takes place affecting the detectability of debris, with smaller items likely be missed. Unless a colony can be accessed, we recommend that a telescope is used to increase the likelihood that small debris items are detected. From a sample of 182 nests observed from a vantage point on Fair Isle, we recorded a lower FO using binoculars (49%) than a telescope (65%). Images taken with an UAV or from an aeroplane may particularly underestimate the FO of nests containing debris depending on the height images are taken, and therefore we have lower confidence in the values of FO from Bass Rock, England, and Karlinn, Iceland. On Mykinesholmer we had the opportunity to estimate the FO of nests containing debris with both an UAV and telescope from a vantage point. The FO of nests containing debris using the UAV was 62% compared to 74% from the vantage points. Identifying and classifying the potential type and source of debris incorporated into nests can also be challenging, especially at a distance and for smaller items. However, identifying the debris type, and where possible the potential source of incorporated debris, can be useful to raise awareness and inform actions to reduce marine debris. For the most part, the threadlike plastics observed in gannet nests, in the field and from photographs, could be readily identified as rope or packaging straps due to the size and distinctiveness of these items, even at a distance. However, it is important to acknowledge that there will be uncertainties when classifying items from a distance.

As we obtained data through visual observations and photographs in this study, we have no information on the size and/or mass of incorporated debris, and therefore on the amount of debris within individual nests. Our biggest challenge was estimating the amount of visible debris at the nest surface. It is valuable to collect quantitative data on the amount and type of visible debris incorporated into nests to establish whether this influences the likelihood of entanglement. For most nests containing debris, the visible surface comprised an estimate of 1–10% of anthropogenic nesting material, although in several colonies, a small number of nests had a visible surface area of over 50% comprised of debris. In our field study, one observer (NJOH) estimated the amount of debris at the nest surface, with the exception of Bempton Cliffs, which involved several different observers. Using digital images of Northern Gannet nests from Syltefjord, the repeatability of two observers recording the percentage of visible debris at the surface of individual nests was low, although the values were significantly correlated ($t = 10.459$, $P < 0.001$, $R_p = 0.73$), attributed to the estimates of one observer being consistently higher. Estimating the contribution of different debris types to the nest material is therefore unlikely to be repeatable among observers, and may have influenced the higher values recorded at Bempton Cliffs. It is therefore important to establish a standardised method of more accurately assessing the amount of visible debris in nests from visual observation and photographs, which is repeatable among observers; for example using a modified Coral Point Count approach (Kohler and Gill, 2006) to extract information from photographs similar to that used for Brown Booby (*Sula leucogaster*) nests (Verlis et al. 2014).

To determine any affects that incorporating debris into nests might have on individuals and populations it is also important to record information on entangled individuals. During 2018, 2019 for Mykinesholmur, 112 entangled individuals were observed (Table S4). However, entangled Northern Gannets were only encountered *ad hoc* during nest monitoring as most visits were made during incubation, with the exception of Grassholm and Rouzic, where data were obtained from researchers making targeted visits at the end of the breeding season to free entangled individuals. From examining images of entangled chicks and adults, all identified debris was threadlike plastics, with individuals entangled via their head, legs or wings. There were also several reports of other species entangled in debris incorporated within gannet nests, specifically Common Guillemots (*Uria aalge*) that breed sympatrically at several sites. Although there is unlikely to be a population level effect of entanglement at the nests at current mortality levels (Votier et al. 2011), there are very few quantitative data, and so we do not have a full understanding of its potential demographic consequences. It is therefore vital to systematically record entanglement, especially to establish how this mortality may potentially affect species in combination with the many other threats that seabirds face (Avery-Gomm et al. 2018).

As most nesting material is thought to be collected by seabirds locally, monitoring debris incorporated into nests may be useful to monitor the extent and magnitude of debris in the marine environment (Lavers et al. 2013; Tavares et al. 2016; Grant et al. 2018; Jagiello et al. 2019). Monitoring debris in seabird nests compliments other useful methods of monitoring debris in the marine environment, such as that found on beaches (Nelms et al. 2016; OSPAR, 2010; Ribic et al. 2012; Battisti et al. 2019). It also incorporates an extra aspect by highlighting that species actively interact with debris, with the potential to cause harm, and with consequences for conservation (Tavares et al. 2016; Avery-Gomm et al. 2018). Monitoring debris incorporated into nests is a largely non-invasive and straightforward way to identify and record temporal or spatial changes in debris parameters, especially compared to debris ingestion. Furthermore, many seabird colonies are already monitored by researchers and rangers, as well as being frequented by tourists, and photographers, therefore data and digital images can be collated to monitor debris in nests (Wang et al. 2016; Ryan, 2018). To ensure future comparisons can be made among studies, it is vital that data is collected in a standardised way. At present there are no standardised approaches for recording or reporting nest incorporation of debris, therefore where appropriate, we recommend following those for debris ingestion studies, for example classifying debris types (Provencher et al. 2017). To complement data collected by standardised methods, we have created a website to collate images of nest incorporation, and incidences of entanglement, taken *ad hoc* by researchers and members of the public (www.birdsanddebris.com). Ideally, annual monitoring of debris should occur to accurately detect changes in prevalence over time (Provencher et al. 2015). However, for species such as the Northern Gannet, which can build large nests with debris incorporated over a number of years, it may be difficult to detect changes over short time periods, and it therefore may be more effective to monitor such species over longer time periods, for example over decades (Bond et al. 2012). Although, there is the potential for small gannet nests, which are likely built entirely in a single breeding season, to be used to monitor changes over short-time periods; for example, the small, ephemeral nests of Brown Boobies are used to monitor changes in debris over short- as well as long-time periods (Verlis et al. 2014; Grant et al. 2018).

To be a useful indicator a species should be abundant, widely distributed, affected by the pollutant of concern and reflect the levels of this pollutant in the environment (Furness and Camphuysen, 1997). The Northern Gannet meets the first three of these criteria, but as they show selectivity for threadlike plastics as nesting material, Northern Gannets are not a suitable indicator species to monitor marine debris in general. However, they could be useful in monitoring fishing related debris. Approximately 18% of the total debris in the marine environment originates from fishing activities (Andrady, 2011), but it may contribute 50–90% of debris in areas of high activity or away from human development (Hammer et al. 2013; Unger and Harrison, 2016; Lebreton et al. 2018). The majority of entanglement incidents involving bird species are also attributed to fishing related debris (Ryan, 2018). Data obtained from monitoring nest incorporation of debris by gannets could be used to explore reduction measures with fishing industry stakeholders. Several actions have been proposed by the European Commission to tackle sea-based sources of debris, from fishing as well as aquaculture, which include a legislative proposal on port reception facilities for vessel waste, Extended Producers Responsibility schemes, recycling targets, and deposit schemes (European Commission, 2018). There are also a number of local and national incentives to reduce abandoned, lost and discarded fishing gear, although there are issues with low compliance and enforcement, as well as monitoring of their success (Gilman, 2015). Therefore, data on nest incorporation of debris could be used to evaluate the effectiveness of these actions on reducing debris associated with fishing activities (Xanthos and Walker, 2017; Willis et al., 2018; Tavares et al. 2019). There was a significant, and detectable, decline in the FO of nests containing fishing gear at two Northern Gannet colonies in Newfoundland after a ground-fishery closure (Bond et al. 2012). Although the range of the Northern Gannet is predominantly confined to the northern hemisphere, the Australasian Gannet (*Morus serrator*) and Cape Gannet (*Morus capensis*) could be monitored in the southern hemisphere given that they also build substantial surface nests similar to Northern Gannets, and also incorporate debris (Norman et al. 1995; Ryan, 2018).

5. Conclusion

Anthropogenic debris was found in all but one Northern Gannet colony monitored since 2007 across this species' range, with the vast majority of debris being threadlike plastics, likely from fishing activities. The FO of threadlike debris in nests was related to local fishing effort in the vicinity of the colony and the age of the colony. Northern Gannets showed selectivity for threadlike debris, therefore although they are not suitable for monitoring marine debris in general, they could be useful to monitor the effectiveness of actions brought in to reduce fishery-related debris in the wider environment. Monitoring debris incorporated in gannet nests is a relatively straight-forward and non-invasive method. Furthermore, recording the FO of debris in nests, and entanglement of chicks and adults, may provide further details on the potential risk to birds of incorporating debris in to their nests.

Conflict/declarations of interest

None.

Acknowledgements

This work was funded by the ERDF Interreg VB Northern Periphery and Arctic (NPA) Programme through the Circular Ocean and Blue Circular Economy projects. We thank all who provided data and digital images on nest incorporation in Northern Gannets: SMRU and Maggie Sheddan (Bass Rock); RPSB International Research Team and Mike Babcock (Bempton Cliffs); David Pelletier (Bonaventure Island); Sunna Björk Ragnarsdóttir (Eldey); Beth Clarke, Lisa Morgan and Greg Morgan (Grassholm); Winnie Courtene-Jones (Helgoland); Andrew Power (Lambay and Great Saltee); Yann Kolbeinsson (Karlinn); Alderney Rangers (Les Étac and Ortac); Vincent Hyland (Little Skellig); Angelika Aleksieva (Machias Seal Island); Arild Hareide and Nils Roar Hareide (Runde); Michael Chalmers (Boreray, St. Kilda) and Rob Barrett (Syltefjord). We also thank all who provided access permissions and assistance in the field: Fair Isle Bird Observatory, RSPB (Noup Head, Troup Head); Jóhannis Danielsen (Mykinesholmur); Shelia Gear (Foula); Scottish Natural Heritage especially Andy Denton, Jennifer Clark and Mike Pennington (Noss and Hermaness); and Sule Skerry Ringing Group. We thank Rob Hughes for help with fieldwork on Shetland and Orkney, and Anika Groβe for help with the digital images. Comments from Davi Castro Tavares and an anonymous reviewer improved this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2019.113152.

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Monitoring nest incorporation of anthropogenic debris by Northern Gannets across their range

Supplementary material

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Table S1. Summary of previous studies examining anthropogenic debris in Northern Gannets nests.

Colony [1]	Country	Sampling year	Number of nests monitored	FO % of nests containing debris	Reference
2. Bonaventure	Canada	2007	550	2	Bond *et al*. 2012
3. Cape St. Mary's	Canada	1989	117	95	Montevecchi 1991
		2007	300	68	Bond *et al*. 2012
4. Funk Island	Canada	1989	624	98	Montevecchi 1991
		2007	230	47	Bond *et al*. 2012
11. Grassholm [2]	Wales	< 1978	Unknown	49	Nelson 2002
		2006	6	100	Votier et al. 2011
12. Aisla Craig	Scotland	< 1978	Unknown	1	Nelson 2002
18. Noss	Scotland	1990	159	88	Camphuysen 1990
19. Hermaness	Scotland	1990	344	95	Camphuysen 1990
21. Bass Rock	Scotland	< 1978	Unknown	25-80	Nelson 2002
22. Bempton	England	< 1978	Unknown	75	Nelson 2002

[1] Number refers to the colony number in Figure 1.

[2] Estimated that 80% of the nests in the colony contained debris.

Table S2. Frequency of occurrence of debris within nests of different sizes (small < 10 cm in height, medium 10 – 30 cm, large > 30 cm) for each plot of the eight Northern Gannet colonies monitored from vantage points during the 2018 breeding season. Nest size was not recorded at Bempton Cliffs, Bonaventure Island or Grassholm. No. – number.

Colony	Vantage Point location (latitude, longitude)	Plot	Colony section	Total Nests	No. of small nests	% of small nests with debris	No. of medium nests	% of medium nests with debris	No. of large nests	% of large nests with debris
12. Ailsa Craig	NA [1]	1	Edge	234	61	3	106	15	67	15
14. Sule Skerry	NA [2]	1	Centre	116	0	0	116	21	0	0
	59.083757,-4.4083723	2	Centre	55	10	10	26	35	19	47
15. Noup Head	59.3304077,-3.0726743	1	Edge	9	7	0	2	0	0	0
	59.3289627,-3.0721384	2	Centre	125	87	28	34	38	4	100
	59.3293977,-3.0726577	3	Centre	143	90	12	41	32	12	50
	59.3312137,-3.0729839	4	Centre	19	8	13	11	45	0	0
16. Foula	60.1377317,-2.1125557	1	Centre	115	50	34	49	63	16	88
17. Fair Isle	59.551396,-1.6324093	1	Centre	124	50	22	61	28	13	69
	59.550763,-1.6384335	2	Centre	26	4	0	8	25	14	43
	59.550763,-1.6384335	3	Centre	33	2	0	11	64	20	100
	59.543599,-1.6405417	4	Centre	54	9	56	24	71	21	90
	59.543599,-1.6405417	5	Centre	81	24	13	40	40	17	100
	59.550735,-1.6310708	6	Centre	47	6	83	8	75	33	100
18. Noss	60.1344867,-1.0116697	1	Centre	69	27	26	15	53	27	96
	60.1328707,-1.0149147	2	Edge	106	91	8	15	33	0	0
	60.1344867,-1.0116697	3	Edge	26	21	14	5	80	0	0
	60.1344867,-1.0116697	4	Edge	12	9	11	3	0	0	0
	60.1360817,-1.0126077	5	Centre	61	26	15	14	50	21	90
	60.1344867,-1.0116697	6	Centre	23	9	11	11	82	3	100
	60.1384387,-1.0129886	7	Centre	177	89	31	58	45	30	93
	60.1384387,-1.0129886	8	Centre	84	23	57	14	79	47	98
19. Hermaness	60.8229816,-0.9081767	1	Centre	84	2	0	12	50	70	89
	60.82206,-0.905414	2	Edge	54	35	6	19	11	0	0
	60.834932,-0.896744	3	Centre	176	14	36	40	73	122	98
	60.820045,-0.905527	4	Centre	73	6	17	13	38	54	94
	60.82206,-0.905414	5	Centre	70	5	40	7	71	58	100
	60.8229816,-0.9081767	6	Centre	77	9	22	15	40	53	100
	60.834159,-0.895991	7	Edge	90	90	17	0	0	0	0
	60.834714,-0.89646	8	Edge	239	37	5	199	17	3	100
	60.8229816,-0.9081767	9	Edge	77	33	0	40	8	4	25
	60.834932,-0.896744	10	Centre	61	4	0	7	57	50	98
	60.8229816,-0.9081767	11	Edge	64	20	0	32	9	12	8
	60.8229816,-0.9081767	12	Centre	216	26	27	83	17	107	57
20. Troup Head	57.694273,-2.30057	1	Edge	56	41	0	6	17	9	56
	57.694288,-2.30007	2	Edge	29	29	0	0	0	0	0
	57.694672,-2.298389	3	Edge	82	82	7	0	0	0	0
	57.694273,-2.30057	4	Centre	51	47	0	3	0	1	0
	57.694658,-2.297986	5	Centre	93	72	0	10	30	11	9
	57.694273,-2.30057	6	Edge	66	14	0	18	28	34	50
	57.694273,-2.30057	7	Centre	157	37	0	52	21	68	68
	57.6945218,-2.3017217	8	Centre	75	NA	NA	NA	NA	NA	NA

[1] Gannet nests were monitored from several points on the beach looking up at the colony at different angles to maximize the number of nests included for this colony. [2] Gannet nests were monitored from several points at the edge of the colony during ringing activates.

Table S3. Values (J) of Jaccard's Index of Similarity for comparing debris type composition between Northern Gannet nests and Marine Conservation Society beach debris data collected within in the vicinity of each colony. Values of J > 0.6 are considered significant.

Colony	J
11. Grassholm	0.006
12. Ailsa Craig	0.013
13. St. Kilda	0.006
15. Noup Head	0.011
20. Troup Head	0.010
21. Bass Rock	0.006
22. Bempton	0.013
23. Les Étacs	0.006

Table S4. Summary of entangled Northern Gannets recorded during 2018, and for Mykinesholmur in 2019.

Colony	Count	Age	How entangled	Debris type	Debris potential source
5. Eldey	1	Adult	Unknown	Threadlike	Fishing
7. Mykinesholmur	2	Adult	Unknown	Threadlike	Fishing
11. Grassholm	19	Adult	-	-	-
	45	Chick	-	-	-
18. Noss	1	Adult	Unknown	Unknown	Unknown
19. Hermaness	1	Adult	Wing	Threadlike	Fishing
	1	Adult	Unknown	Unknown	Unknown
20. Troup Head	1	Adult	Head	Threadlike	Fishing
21. Bass Rock	1	Adult	Legs	Threadlike	Fishing
	1	Chick	Unknown	Threadlike	Fishing
24. Rouzic	26	Adult	-	-	-
	10	Chick	-	-	-
27. Helgoland	1	Adult	Head	Threadlike	Fishing
28. Runde	2	Adult	Legs	Threadlike	Fishing