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Wright, LS

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Potential microplastic release from beached fishing gear in Great Britain's region of highest fishing litter density

Luka Seamus Wright *, Imogen Ellen Napper, Richard C. Thompson

International Marine Litter Research Unit, School of Biological and Marine Sciences, University of Plymouth, Drake Circus, Plymouth, Devon PL4 8AA, United Kingdom

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A B S T R A C T

While land-based sources of marine plastic pollution have gained widespread attention, marine-based sources are less extensively investigated. Here, we provide the first in-depth description of abandoned, lost or otherwise discarded fishing gear (ALDFG) on northern and southern beaches of the English Southwest Peninsula, Great Britain's region of highest ALDFG density. Three distinct categories were recorded: twisted rope (0.28 ± 0.14 m^{-1}, 17%), braided rope (0.56 ± 0.28 m^{-1}, 33%) and filament (0.84 ± 0.41 m^{-1}, 50%), which likely correspond to fishing rope, net and line. Estimating the disintegration of ALDFG from length and filament number suggests that it has the potential to generate 1277 ± 431 microplastic pieces m^{-1}, with fishing rope (44%) and net (49%) as the largest emitters. Importantly, ALDFG was over five times more abundant on the south coast, which is likely attributable to the three times higher fishing intensity in that area.

1. Introduction

With 4.9 billion tonnes of discarded plastic to date (Geyer et al., 2017), plastic pollution is recognised as a global problem, particularly in the marine environment (Napper and Thompson, 2020). Although marine-based sources have been broadly recognised as an important origin of plastic contamination, major research efforts have primarily focussed on land-based sources. Therefore, there are no reliable global estimates of the kind provided by Jambeck et al. (2015) for sea-based sources (Richardson et al., 2021). This lack of empirical research and reliable estimates is likely due to the difficulty of tracking down marine-based sources of plastic pollution and the widely held misbelief that their annual output is already known (Richardson et al., 2021). Such shortage of research is problematic because sea-based sources contribute much more directly to marine pollution since source and sink are geographically linked.

It is suspected that industrial fishing is the major marine-based source of plastic pollution (Macfadyen et al., 2009; UNEP, 2016; Richardson et al., 2019). Abandoned, lost or otherwise discarded fishing gear (ALDFG) has been present in the marine environment since fishing began (Macfadyen et al., 2009) and has been recognised as a major problem since the 1980s (FAO, 2018). Historically, fishing gear (e.g. nets, ropes and lines) was produced using non-synthetic resources such as cotton, flax or hemp fibres (Sahrhage and Lundbeck, 1992). After the large-scale production of plastic began in the 1950s, synthetic fibres were used as the preferred material as they are less expensive, have higher tensile strength and possess greater resistance to degradation than non-synthetic materials (Deroiné et al., 2019; Terry and Slater, 1998). Now fishing gear consists of various synthetic polymers, including nylon, polyethylene and polypropylene (Nelms et al., 2021), which contribute significantly to plastic waste. Norway's fishing sector alone generates an estimated 4000 t of such waste annually (Deshpande et al., 2020).

Importantly, not all of this fishing waste actually becomes fishing litter in the form of ALDFG. The general aim is for fishing waste to be landfilled, incinerated or recycled, much like other plastic waste (Deshpande et al., 2020). However, Richardson et al. (2019) estimated that 5.7% of all fishing nets and 29% of all fishing lines are abandoned, lost or discarded at sea, wasting the opportunity for sustainable treatment options like recycling. This is a problem of utmost concern because the amount of ALDFG has dramatically increased since the beginning of this century (Ostle et al., 2019; Richardson et al., 2019). Fishing gear is predicted to make up 55% of floating macroplastic in the Northeast (NE) Atlantic (Ostle et al., 2019) and at least 46% in the NE Pacific (Lebreton et al., 2018). On the Mediterranean seafloor, litter can reach densities of 0.79 items m^{-2}, 83% of which is ALDFG with a clear distinction in abundance between fishing lines (68%), nets (18%), ropes (12%) and pots (0.2%) (Enrichetti et al., 2020).

* Corresponding author.
E-mail address: luka@wright.it (L.S. Wright).

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ALDFG is known to harm marine megafauna through ingestion (Jacobsen et al., 2010) and entanglement (Duncan et al., 2017; Jepsen and de Bruyn, 2019), with trawls, fixed and drift nets generally presenting the highest risk (Gilman et al., 2021). Recent research, that categorised and quantified ALDFG in the Ganges river and identified large amounts of fishing rope and net, found several freshwater turtles (*Batagur dhongoka*, *Geoclemys hamiltonii*, *Batagur baska*) and the endangered Ganges river dolphin (*Platanista gangetica gangetica*) at high risk of entanglement (Nelms et al., 2021). ALDFG may also directly damage commercial fish species. For instance, Saturno et al. (2020) examined 216 gastrointestinal tracts of Atlantic cod (*Gadus morhua*) caught by commercial fishers and found 1.4% to contain intact bait bags, used in commercial potting, or polypropylene thread, likely originating from fishing rope.

Analysis of nationwide beach survey data collected by Marine Conservation Society (MCS) volunteers in the United Kingdom (UK) revealed that ALDFG was at least 79% more abundant along the coast of the Western English Channel and Celtic Sea than any other regional sea (Nelms et al., 2017) (Fig. 1a). This may be due to the high fishing intensity in that region (Witt and Godley, 2007; MMO, 2017) and, more specifically, the prevalent use of nets (Lee et al., 2010). Along part of the north coast of the Southwest (SW) Peninsula, these beach litter accumulations have been analysed in more detail by Watts et al. (2017), who reported that 32% of litter consists of fishing ropes and nets, making up the largest identifiable source of plastic. Furthermore, Welden and Cowie (2017) showed that the degradation of such polymer ropes through abrasion and biofouling in the shallow marine environment can potentially lead to the release of microplastic, fragments and fibres smaller than 5 mm (Galgani et al., 2013; Law and Thompson, 2014).

To our knowledge, the prevalence, characteristics and potential for microplastic release of different types of ALDFG have yet to be described in detail for any part of the NE Atlantic. This surprising lack of information is likely due to important ALDFG metrics, such as size, structure and composition being overshadowed by a focus on mass-based estimates (Richardson et al., 2021). Furthermore, there has been no comparison between the northern and southern coasts of the SW Peninsula, which correspond to the FAO divisions Bristol Channel (27.7.f) and Western English Channel (27.7.e) (Fig. 1b), two areas of markedly different fishing activity in terms of total catch, gear use and target species (Tables 1, S1). Here we aim to fill these knowledge gaps by providing the first assessment of the abundance, composition, structure (length, width, volume, number of filaments) and potential contribution to microplastic pollution of ALDFG in the UK's region of highest ALDFG density (Fig. 1a).

2. Material and methods

2.1. Sampling and categorisation

ALDFG was collected from six beaches on the SW Peninsula (Fig. 1b) in autumn 2019. Apart from being representative of both coasts and therefore different fisheries divisions (Fig. 1b), beaches were chosen to provide a range of sandy and rocky substratum along with high and low wave energy. At each beach, sampling was conducted once over two

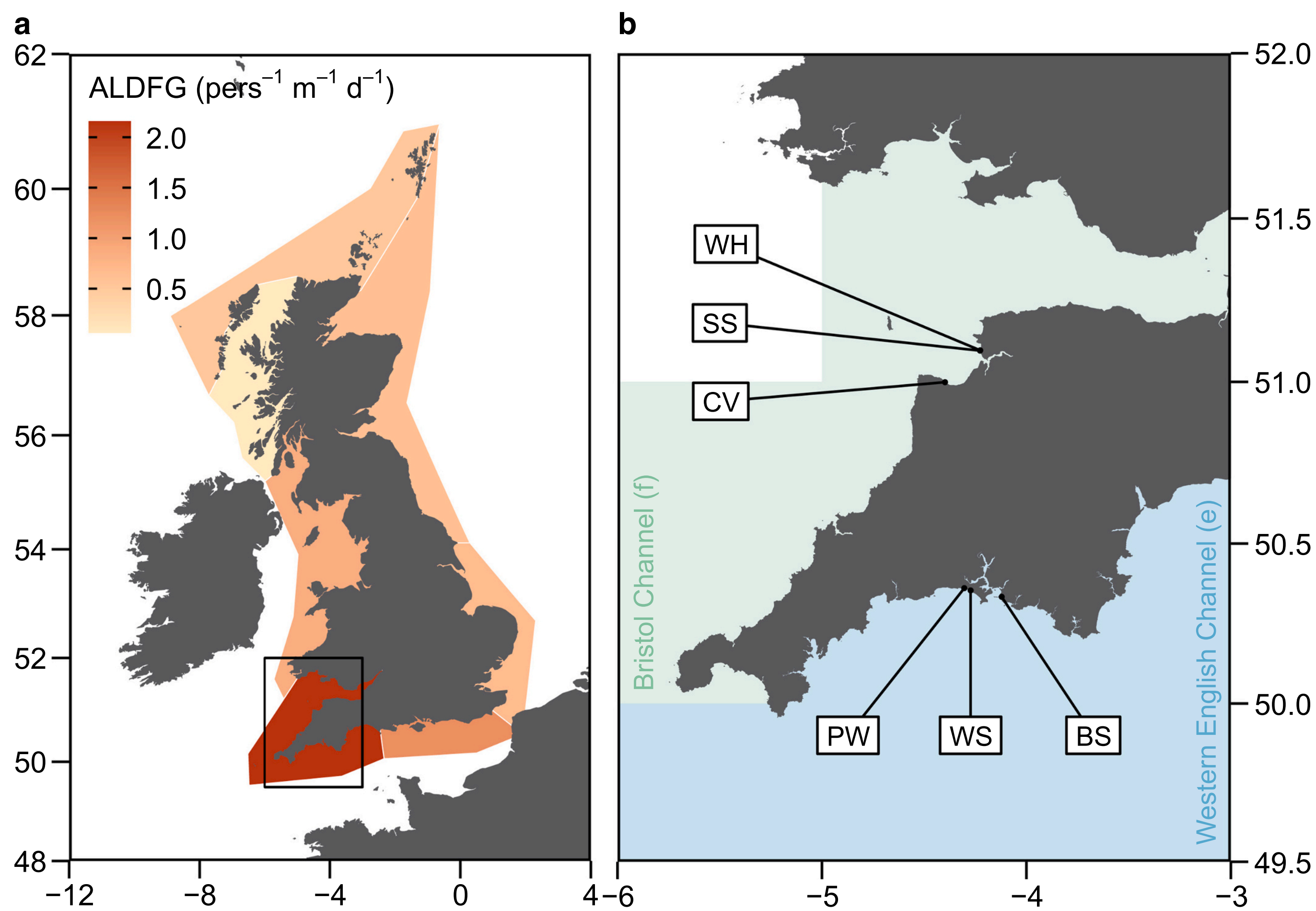

Fig. 1. a, Distribution of ALDFG around Great Britain, according to MCS data (Nelms et al., 2017). b, Location of the six coastal sites surveyed in this study in the geographical context of FAO fisheries divisions (fao.org/fishery/area/Area27): Whitehall (WH), Saunton Sands (SS), Clovelly (CV), Portwrinkle (PW), Whitsand (WS) and Bovisand (BS).

Table 1
Fishing activity in 2018 for divisions e and f within the FAO Major Fishing Area 27 and subarea 7. Divisions e (Western English Channel) and f (Bristol Channel) correspond to the southern and northern coasts of the SW Peninsula. Proportional gear use and target species contribution are calculated from catches over 100 t yr^{-1}. The greater number in each comparison is highlighted in bold. Gear that may potentially contribute to the fishing litter described in this study is underlined. Taxon-specific data are provided in Table S1. Catch data and methods were extracted from publicly available ICES (2020) and MMO (2017) data respectively.

Variable	South (27.7.e)	North (27.7.f)	Absolute Δ	Relative Δ
Total catch	**33,955 t**	9170 t	24,785 t	270%
Target species				
Invertebrates	30%	**43%**	13%	43%
Vertebrates	**70%**	57%	13%	23%
Fishing gear				
Dredge	**15%**	1%	14%	1088%
<u>Beam trawl</u>	**31%**	7%	24%	325%
<u>Demersal trawl/seine</u>	**22%**	5%	17%	314%
<u>Hooked gear</u>	1%	**6%**	5%	293%
<u>Drift and fixed nets</u>	13%	**38%**	25%	199%
Pots and traps	17%	**42%**	25%	148%

hours by a supervised team of three to five (at Whitsand five, otherwise three) volunteers according to MCS (2015) guidelines: all eulittoral ALDFG (between low water and the strandline) was collected along a 100-m stretch of beach. Most eulittoral ALDFG was recorded at the strandline. Since each beach had a different eulittoral area, abundance data are given as eulittoral ALDFG per unit length of beach. Due to time constrains we prioritised sampling multiple beaches once and treating each as a single replicate rather than attempting repeated surveys. Samples were then classified into different categories as described below.

With the exception of fish aggregating devices, pots and traps, ALDFG consists of nets, ropes and lines (Macfadyen et al., 2009). Rope is constructed of strands, that are made of yarns, which in turn consist of several monofilaments (hereafter referred to as filaments) (McKenna et al., 2004). Rope, including that used in the construction of fishing ropes and nets, is generally categorised into two groups: (1) twisted rope, also called laid rope, which is made of strands that are twisted around each other in the same direction and (2) braided rope, also called plaited rope, that consists of interlacing strands (McKenna et al., 2004). Fishing line is simply made of a single unstructured filament. The collected ALDFG was therefore grouped into the three categories twisted rope, braided rope and filament.

2.2. Size metrics

Following separation of different ALDFG categories, the abundance of each category was quantified with a tally counter. The length of individual ropes and filaments and the diameter of ropes were then measured with a ruler (±1 mm). The diameter of filaments was measured to 0.001-mm accuracy with a camera and accompanying imaging software (Retiga, QImaging, Cairn Research Ltd., Faversham, United Kingdom) mounted on a light microscope (M205C, Leica, Wetzlar, Germany). In order to reduce within-rope and -filament variability, three replicate measurements of width were taken at the centre and ends of each sample. Irreversibly entangled filament samples were counted as part of the filament category but were not included in the measurement of length and width. Assuming a cylindrical shape where measured rope width and length are equal to cylindrical diameter and height, sample volume (V, cm^3) was then calculated as

$$V = \pi \times (0.5 \times W)^2 \times L \times 0.001$$

where W is width (mm) and L is length (mm). Finally, using a tally counter, the number of filaments in twisted and braided rope were quantified for a minimum of 48 replicates of each rope category (Fig. 2a).

2.3. Estimation of microplastic emission

Polymer rope degrades in the marine environment, potentially causing the emission of microplastic fragments and fibres (Welden and Cowie, 2017). Microplastic is generally defined as any piece of plastic that is smaller than 5 mm in length (Fig. 2b; Galgani et al., 2013; Law and Thompson, 2014). Therefore, mean and median potential microplastic release per metre of beach (MP, m^{-1}) for each type of ALDFG were conservatively estimated as

$$MP_{\bar{x}} = \frac{A_{\bar{x}} \times F_{\bar{x}} \times L_{\bar{x}}}{5\ \text{mm}}$$

$$MP_{\tilde{x}} = \frac{A_{\tilde{x}} \times F_{\tilde{x}} \times L_{\tilde{x}}}{5\ \text{mm}}$$

where $A_{\bar{x}}$ is the mean and $A_{\tilde{x}}$ the median eulittoral abundance (m^{-1}), $F_{\bar{x}}$ is the mean and $F_{\tilde{x}}$ the median number of filaments and $L_{\bar{x}}$ is the mean and $L_{\tilde{x}}$ the median length (mm) of the respective litter category. 5 mm refers to the maximum defined length of microplastic (Fig. 2b). Similarly, plastic volume per metre of beach (VE, cm^{-3} m^{-1}) for each type of ALDFG was estimated as

$$VE_{\bar{x}} = A_{\bar{x}} \times V_{\bar{x}}$$

$$VE_{\tilde{x}} = A_{\tilde{x}} \times V_{\tilde{x}}$$

where $A_{\bar{x}}$ is the mean and $A_{\tilde{x}}$ the median eulittoral abundance (m^{-1}) and $V_{\bar{x}}$ is the mean and $V_{\tilde{x}}$ the median volume (cm^3) of the respective ALDFG category. With the lowest number of replicates ($n = 6$), abundance data provided the most conservative estimate of variance around the estimated means and medians. Therefore, the uncertainty of our estimates was calculated by inserting each of the six replicate measures of abundance into the above equations and then calculating s.e.m. (when using means) and interquartile range (when using medians) from the six replicate estimates. The 95% confidence interval was then calculated as the mean ± z × s.e.m.

Total ALDFG volume and microplastic emission were estimated by adding the means or medians of each litter category. Relative contributions of each category to this total were then calculated for means and medians and expressed as the average of the two obtained percentages. Both descriptive statistics and the average of their relative percentages are reported in an attempt to account for the heavy right-skew in our length and filament richness data, since means overestimate the central tendency of right-skewed data. Standard errors for summed estimates were calculated according to the variance sum law, which states that the

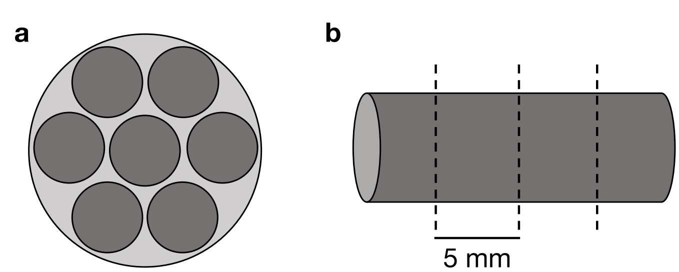

Fig. 2. a, Schematic cross section of a single rope showing an arbitrary number of individual filaments. b, Schematic profile view of a single rope. The length of rope divided by the defined maximal length of microplastic fibres (5 mm, Galgani et al., 2013; Law and Thompson, 2014) multiplied by the number of filaments (a) gives a conservative indication of the number of potential microplastic fibres per rope.

variance of a sum is equal to the square root of the sum of variances of the independent summands.

2.4. Data analysis and visualisation

Data analysis and visualisation were performed in R v4.0.2 (R Core Team, 2020) within the integrated development environment RStudio v1.3.1093 (RStudio Team, 2020). Data exploration revealed that all response variables were clearly right-skewed and therefore did not conform with the assumption of normality (in the case of abundance data the skew was less pronounced). Since transformation of response variables should generally be avoided (Zuur et al., 2009), data were fit to Gaussian and gamma distributions with the *cdfcomp* and *gofstat* functions of the R package fitdistrplus v1.1-3 (Delignette-Muller and Dutang, 2015). The gamma distribution fit the data best in all cases, but it was necessary to remove one extreme outlier in the number of filaments (500), which was identified as cable-laid rope and essentially consisted of multiple twisted ropes (McKenna et al., 2004).

Gamma generalised linear models were built with the *glm* function and fitted with a logarithmic link function. Type II and III sums of squares tests of differences between ALDFG types (first categorical explanatory variable) and coasts (second categorical explanatory variable) were performed with the *Anova* function of car v3.0-10 (Fox and Weisberg, 2019). Pairwise contrast p values and t ratios (effect size ÷ standard error of the effect size) were calculated with emmeans v1.5.3 (Lenth, 2020). Finally, descriptive statistics (means, s.e.m., medians and interquartile ranges) were calculated with psych v1.0.12 (Revelle, 2020) and then visualised with ggplot2 v3.3.3 (Wickham, 2016) and cowplot v1.1.1 (Wilke, 2020). The site map was plotted using vector data from rworldmap v1.3–6 (South, 2011) and gadm.org. Vector editing was performed in Affinity Designer v1.9.1 (Serif Ltd., West Bridgford, UK).

3. Results

3.1. Definition and abundance of litter categories

Overall, 1004 individual items of ALDFG from 600 m of coastline were collected and analysed from the six study sites (Fig. 1b). The width of twisted rope (mean ± s.e.m.: 5.01 ± 0.42 mm) and braided rope (5.37 ± 0.22 mm) was similar, albeit more variable in the former. This indicates that in contrast to twisted rope, braided rope was of a standardised diameter, such as is the case with netting. Moreover, these rope types could be clearly distinguished on the basis of their woven structure (Fig. 3a, b). The observed prevalence of knots in the braided rope samples (Fig. 3b) is another indication of their origin as part of fishing nets. Filaments had a relatively large mean diameter of 0.42 ± 0.02 mm (Fig. 3c, d), which indicates that they were mostly fishing line rather than having been a constituent of fishing rope (cf. thin filaments at rope ends in Fig. 3a, b). Hence, twisted rope, braided rope and filament can be seen as proxies for the common ALDFG categories fishing rope, net and line. Degradation into microplastic was observed in all ALDFG categories (Fig. 3a–d). No other ALDFG (e.g. fish aggregation devices, pots and traps) were recorded from any of the beaches.

All generalised linear model results on ALDFG abundance, length, volume and filament number are summarised in Table S2. ALDFG abundance did not differ between litter categories ($X^2_{2,\ 18} = 5.99$, $p = 0.05$) and on average amounted to 0.56 ± 0.17 pieces of plastic per metre of beach. Despite this lack of statistical difference, the p value is only marginally above the α level of 5% and there was a clear tendency towards filaments (0.84 ± 0.41 m^{-1}, 50%) being more abundant than braided rope (0.56 ± 0.28 m^{-1}, 33%), with twisted rope (0.28 ± 0.14 m^{-1}, 17%) being least common (Fig. 4a). Importantly, beaches on the south coast of the SW Peninsula had 5.33 times more ALDFG than those on the north coast ($X^2_{1,\ 18} = 19.41$, $p < 0.001$, Fig. 4a).

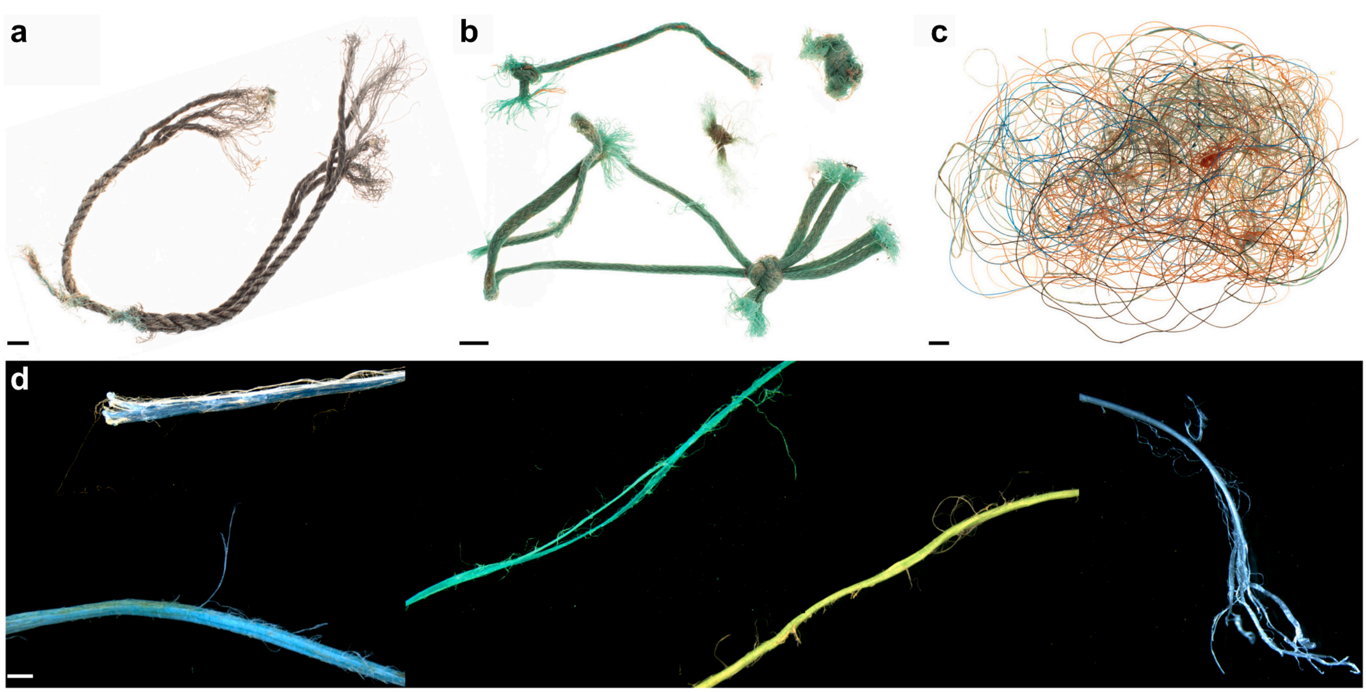

Fig. 3. a, Representative sample of twisted rope. The three levels of construction are clearly distinguishable: yarns < strands < rope (McKenna et al., 2004). b, Representative samples of braided rope. Frequent knots indicate that this rope was once part of a fishing net. Moreover, the abrupt endings despite the intact nature of the rope indicate that these are deliberate offcuts. c, Representative samples of filament. The thickness and texture of the depicted filaments indicate that they were not part of a larger rope. Scale bars = 1 cm. d, Close-up of filament samples from Whitsand, Bovisand and Portwrinkle showing degradation by splitting. Scale bar = 1 mm.

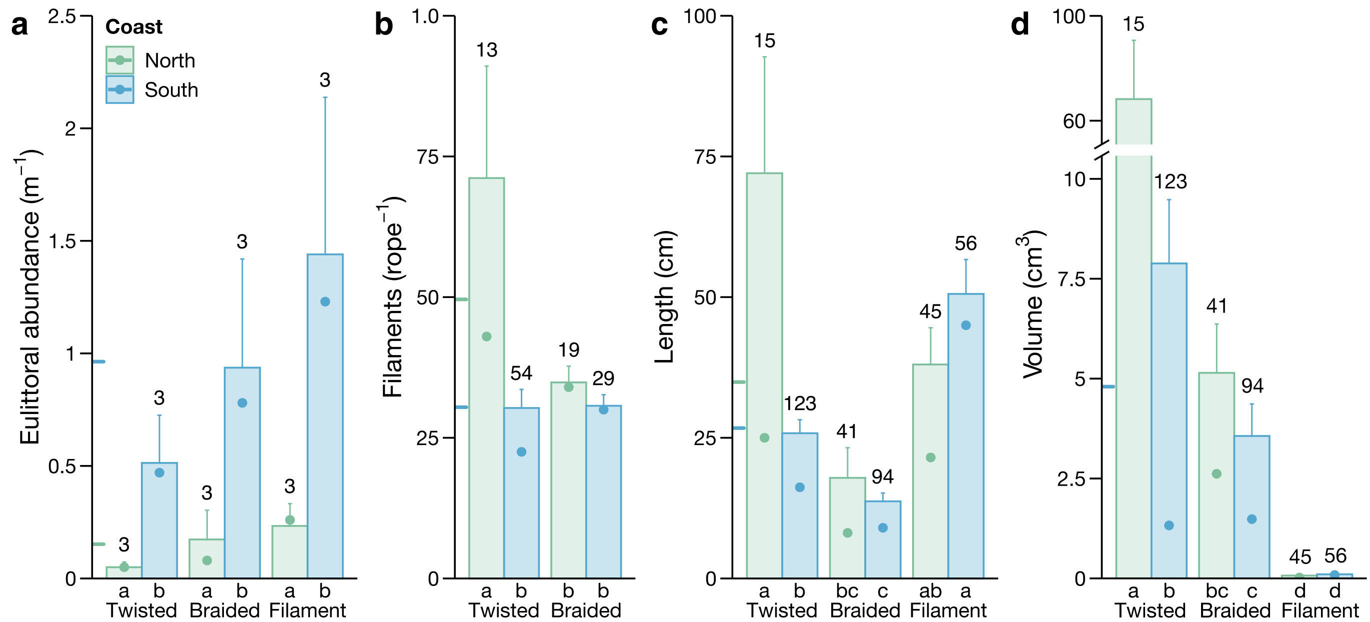

Fig. 4. Density (a), number of filaments (b), length (c) and volume (d) of different types of ALDFG. Bars with error bars represent means + s.e.m., points indicate medians, numbers above bars are sample sizes and letters designate groups of statistical similarity. The median volume of twisted rope on the north coast and mean volume of all ALDFG on the north coast, both masked by the scale break, are 18.98 cm^3 and 12.25 cm^3 respectively. Filaments always consist of a single filament and are therefore not shown in b.

3.2. Size metrics

The number of filaments per rope ranged between 2 and 500, the maximum being an extreme outlier that was removed during analysis, and was more variable in twisted rope than braided rope (Fig. 4b). This result is directly comparable to the lower variability in the diameter of braided rope mentioned in 3.1, further supporting the identification of braided rope as fishing net. Mean filament richness was 1.04 times greater for twisted than for braided rope on the north coast ($X^2_{1,\ 115}$ = 8.63, $p = 0.003$) but did not vary between ropes in the south ($X^2_{1,\ 115}$ = 0.007, $p = 0.93$) (Fig. 4b). Moreover, twisted rope contained 1.35 times more filaments on the north coast than on the south coast ($X^2_{1,\ 115}$ = 19.16, $p < 0.001$), while braided rope contained a similar number of filaments on both coasts ($X^2_{1,\ 115} = 0.4$, $p = 0.53$) (Fig. 4b).

Length of ALDFG differed between litter categories on the north ($X^2_{2,\ 374} = 18.69$, $p < 0.001$) and south ($X^2_{2,\ 374} = 46.1$, $p < 0.001$) coasts. On the north coast, twisted rope and filament were of similar length (t = 1.84, $p = 0.44$) but 3.03 times ($t = 3.96$, $p = 0.001$) and 1.13 times ($t = 3$, $p = 0.03$) longer than braided rope respectively (Fig. 4c). On the south coast, filament was 96% longer than twisted rope ($t = 3.58$, $p = 0.005$), which in turn was 88% longer than braided rope ($t = 3.97$, $p = 0.001$) (Fig. 4c). Moreover, length was more variable in twisted rope (s.e.m.: 3.29 cm) and filament (s.e.m.: 4.49 cm) than braided rope (s.e.m.: 1.92 cm) (Fig. 4c). Length did not differ between coasts within ALDFG categories, except for twisted rope, which was 1.79 times longer on the north coast ($X^2_{1,\ 374} = 13.47$, $p < 0.001$) (Fig. 4c).

Volume varied greatly between types of ALDFG on the north ($X^2_{2,\ 374}$ = 134.16, $p < 0.001$) and south ($X^2_{2,\ 374} = 100.69$, $p < 0.001$) coasts. On north coast beaches, twisted rope had 12.26 times more volume than braided rope ($t = 4.51$, $p < 0.001$), which in turn was 73 times more voluminous than filament ($t = 10.48$, $p < 0.001$) (Fig. 4d). Similarly, twisted rope was 1.21 times more voluminous than braided rope (t = 3.05, $p = 0.03$), which in turn had 33.58 times more volume than filament ($t = 11.04$, $p < 0.001$) on the south coast. Volume did not differ between coasts within ALDFG categories, except for twisted rope, which was 7.66 times more voluminous on the north coast ($X^2_{1,\ 374} = 28.31$, p < 0.001) (Fig. 4d).

3.3. Estimation of microplastic emission

Twisted rope, braided rope and filament together made up between 0.78 (median) and 6.39 ± 2.33 (mean ± s.e.m.) cm^3 of estimated plastic volume per metre of beach, contributing 47%, 52%, and 2% respectively (absolute estimates are given in Table S3). Similarly, twisted rope, braided rope and filament potentially emit between 300 (median) and 1277 ± 431 (mean ± s.e.m.) microplastic fragments per metre of beach, contributing an estimated 44%, 49% and 7% respectively (Table S3). Consequently, our conservative estimates indicate that twisted and braided rope have the potential to produce more microplastic fragments than filament, suggesting that ALDFG structure may be more important than abundance. Moreover, with 1737 ± 529 potential microplastic pieces m^{-1} on the south coast and 746 ± 287 m^{-1} on the north coast, the amount of potentially released microplastic from beached fishing litter mirrored the geographical trend of ALDFG abundance. However, the estimated 95% confidence intervals and interquartile ranges are too large to make a definite statement (Table S3), necessitating further data collection for more precise estimates of microplastic emission from ALDFG.

4. Discussion

To our knowledge, this study represents the first detailed description and analysis of the prevalence and characteristics of different ALDFG types on NE Atlantic coasts. Moreover, we provide the first comparison of ALDFG between two areas of very different fishing activity in terms of total catch, gear use and target species (Fig. 1b, Tables 1, S1). We found that in the area of highest fishing litter abundance in Great Britain (Fig. 1a), beached ALDFG exclusively consists of ropes (17%), nets (33%) and lines (50%). These findings agree with global estimates of gear loss (Richardson et al., 2019) and observed relative abundance of different fishing litter on the Mediterranean seafloor: 12% ropes, 18% nets and 68% lines (Enrichetti et al., 2020). While the predominance of fishing lines is beyond question, our results suggest that they may still contribute least to potential microplastic emission. This is primarily attributable to the obviously larger number of filaments in twisted and braided rope. When adjusted to units standardised by person and time (cf. Nelms et al., 2017), our mean ALDFG abundance of 1.74 ± 0.44 $pers.^{-1}$ m^{-1} d^{-1} is somewhat lower than the previously reported 2.16 $pers.^{-1}$ m^{-1} d^{-1} for the entire region (Fig. 1a). Therefore, our estimate of 1277 ± 431 potentially emitted microplastic pieces per metre of beach is likely conservative.

In addition to the degradation of ALDFG, which has been empirically evidenced (Welden and Cowie, 2017) and which we have documented (Fig. 3d) and estimated to cause substantial amounts of microplastic emission, direct use on board fishing vessels can release even more microplastic (Napper et al., 2021). Fibres have long been reported to be the most common form of microplastic in the NE Atlantic (Thompson et al., 2004) and are known to reduce the energy budget of marine macrofauna upon ingestion (Watts et al., 2015). Perhaps a large proportion of such secondary microplastic fibres (Fig. 3d), as well as potentially misidentified fragments (Napper et al., 2021), originate from degradation of ALDFG and abrasion of actively used fishing gear. Like the impact of fishing-related macroplastic outlined in the introduction, this release of microplastics may have consequences for the fishing industry. For instance, commercial fish are attracted to the odour of biofouled microplastic (Savoca et al., 2017), which reduces their reproduction, growth and survival when ingested (Lönnstedt and Eklöv, 2016).

We found that the south coast had 5.33 times more ALDFG items than the north coast of the SW Peninsula (Fig. 4a). This fact is adequately explained by higher fishing activity (Table 1). With some of the UK's largest fishing ports (Newlyn, Plymouth and Brixham), 1339 fishing vessels and 2272 fishermen, the south coast has all of the large fishing ports on the SW Peninsula (MMO, 2017). In contrast, the only large fishing port near the north coast (Milford Haven in Wales) only has 451 vessels and 753 fishermen (MMO, 2017). Moreover, 2.7 times more seafood biomass and 34% more taxa are extracted in the Western English Channel (27.7.e) off the south coast than in the Bristol Channel (27.7.f) off the north coast (ICES, 2020; Table 1). Interestingly, gear that may contribute to the ALDFG we found (beam trawls, demersal trawls/ seines, hooked gears, drift and fixed nets) was used to fish 67% of yield above 100 t yr^{-1} in 27.7.e, while in 27.7.f such gear is only used for 56% of catch (MMO, 2017; Table 1). Most notably, we did not find any pots or traps among beached ALDFG, which are the predominant gear used off the north coast (Table 1). This geographic comparison suggests that regional fishing activity is directly linked to the amount of ALDFG and subsequent potential for microplastic release during its disintegration.

Another potential explanation for the observed geographical trends is the prevalent winds and their corresponding wind-driven currents and swells. In the southwestern part of Great Britain, the predominant winds are southwesters (Met Office, 2016). By driving surface currents in the same direction, these may cause floating macroplastic to mostly accumulate on the south coast of the SW Peninsula. Additionally, the south coast receives consistently stronger swells. For instance, Whitsand Bay, one of our study sites on the south coast, has wind or ground swell with over 91-cm wave height and over 7-s period for 46% of the year, while at Saunton Sands, one of our study sites on the north coast, such powerful swells are never observed (magicseaweed.com). Nonetheless, we believe differences in fishing intensity are the most parsimonious explanation for the observed geographical contrast in fishing litter abundance. If winds and their accompanying currents and swells were the main driver of beached fishing litter abundance, we would observe abundant ALDFG on the coasts of western England and Wales and wind-exposed northern and western Scotland, which evidently is not the case (Fig. 1a).

It is somewhat more difficult to explain why, unlike braided rope, twisted rope was richer in filaments, longer and more voluminous on the north coast (Fig. 4b–d). A potential explanation may be the 1.99 times more common use of drift and fixed nets in FAO division 27.7.f than 27.7.e (Table 1). These nets, which are also called gillnets and are classed as static or passive gear (MMO, 2017), are connected to buoys and sometimes also anchored to the seafloor with long rope. Twisted ropes are the most commonly used ropes for anchoring and net hauling in the maritime industry (McKenna et al., 2004). Therefore, it seems likely that the long ropes used in gillnetting mostly have a twisted structure. Furthermore, it is possible that the observed large filament number and volume of these twisted ropes provides them with additional strength to withstand biofouling, wave energy and currents during longer periods of submersion.

It is important to recognise that some degree of gear loss from fishing and other maritime activity is inevitable. This can be as a consequence of fishing effort, gear conflicts, extreme weather and operator error (FAO, 2016). However, some ALDFG could be intentional, such as offcuts from nets. For instance, the low variability in length and width of braided rope reported here suggest that it was a constituent of net and intentionally discarded. Current solutions, like the non-governmental organisations and clean-up initiatives MCS and Fishing for Litter (Wyles et al., 2019), target the symptoms rather than the root of the problem. In addition, and contrary to popular narrative, consumers cannot affect change in this form of plastic pollution because they are not informed of the ALDFG associated with each seafood choice. Therefore, government intervention may be the most promising solution. Examples of such top-down regulation are gear markings to improve traceability of perpetrators (Macfadyen et al., 2009; FAO, 2016; He and Suuronen, 2018) or stronger enforcement of the guidelines defined by the International Convention for the Prevention of Pollution from Ships (MARPOL) (Haward, 2018). Even if ALDFG is disposed of on land in accordance with MARPOL, most fishing litter ends up in landfills and there is certainly scope for the expansion of recycling in this sector (Deshpande et al., 2020; Nelms et al., 2021).

In conclusion, this study is the first to characterise beached ALDFG down to its detailed filament structure and link its abundance and thus potential microplastic emission to fishing activity. Our results suggest that fishing nets and ropes have a higher microplastic emission potential than fishing lines. We believe that further research into the structure of various fishing gear alongside its microplastic release due to degradation after disposal at sea and abrasion during use will help to focus regulation efforts. We hope that our study inspires future research into ocean-based plastic pollution more broadly and informs policy development in this field.

Data and code availability

All data and code are available at github.com/lukaseamus/marine-microplastic. We place no restrictions on data and code availability.

CRediT authorship contribution statement

Luka Seamus Wright: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Imogen Ellen Napper:** Funding acquisition, Conceptualization, Methodology, Investigation, Writing – review & editing. **Richard Charles Thompson:** Funding acquisition, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Some of the content of this paper are part of a much larger project which was funded by the UK Government, Department for Environment, Food and Rural Affairs (Defra). This manuscript has been prepared specifically for the purposes of *Marine Pollution Bulletin*. We have a long history of government funded research with Defra directly leading to scientific publications in a range of journals. Defra are well aware of our submission and fully support our publication of this manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2021.113115.

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