Marine Pollution Bulletin 201 (2024) 116268

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Retrieval operations of derelict fishing gears give insight on the impact on marine life

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ARTICLE INFO

Keywords:
Marine plastic pollution
ALDFG
Ghost fishing
Retrieval operation
Gillnets
King crab pots

ABSTRACT

Abandoned, lost and discarded fishing gear (ALDFG), significantly impacts marine ecosystems and biodiversity by incidental capture known as ghost fishing. Such impacts were quantified during the Norwegian Directorate of Fisheries' annual ALDFG cleanup operation in September 2023 by examining the characteristics of retrieved ALDFG and recording the taxonomically sorted catch abundance and biomass. A total of 307 specimens equaling 382 kg of biomass were caught in the recovered gillnets and king crab pots. Gillnets exhibited a 27.3 % greater catch abundance and 50.3 % higher biomass per ALDFG unit mass compared to king crab pots. Margalef, Menhinick, Simpson, Shannon, and Pielou diversity indices showed a more pronounced impact on species richness and biodiversity associated with recovered gillnets. This study introduces an approach to assess the impact of ghost fishing on ecosystems and biodiversity through ALDFG retrieval operations, instrumental in developing estimates of the total ghost fishing capture by ALDFG.

1. Introduction

Each year, 1.7 million tons of plastic waste enter the ocean (OECD, 2022). While there is wide geographic variation in the dominance of sources, globally 80 % of the plastic waste found in the marine environment comes from land, while the other 20 % mostly comes from sea-based activities (Andrady, 2015). Sea-based plastic prominently includes abandoned, lost, or otherwise discarded fishing gear (ALDFG) by the commercial fishing industry (Gilman, 2015). Globally, at least 640,000 t of fishing gear are lost or abandoned every year, mainly due to wear and tear, gear failures, gear collisions, human error, dire weather, and intentional dumping (Macfayden et al., 2009; Viool et al., 2018). Due to the materials' inherent capacity to withstand physical, chemical, and biological degradation, this raises concerns regarding impacts on the marine ecosystem and biodiversity (Laist, 1997; Link et al., 2019).

The term ghost fishing characterizes the ongoing entanglement of various taxa by ADLFG. It was first studied in the 1970s, with most published studies originating from the USA, Canada, and Australia (Pecci et al., 1978; Smolowitz, 1978). Since then, available peer reviewed literature has steadily increased, highlighting the detrimental effects on economically significant stocks (Butler and Matthews, 2015), benthic habitats (Consoli et al., 2020), and endangered species (Lively and Good, 2019). From the ghost fishing point of view, set gillnets, driftnets, trammel nets and pots are likely the most problematic type of ALDFG (Kim et al., 2016).

Yet, a substantial knowledge gap persists regarding the impacts of ghost fishing on marine ecosystems and biodiversity. This gap is attributed, in part, to fishermen's hesitance to report lost gear and the time / funds-intensive nature of conducting thorough in situ simulations of ghost fishing (Adey et al., 2008).

Physical removal solutions have been proposed to address ghost fishing in the marine environment. The economic feasibility of small-scale cleanup projects has been demonstrated by the Ocean Cleanup Project (Slat, 2014). Norway is actively working towards retrieving ALDFG from the ocean and beaches through collection and removal plastic material from the coastline, water column, and seabed throughout the year (Jacob, 2016; Falk-Andersson et al., 2019; Norwegian Directorate of Fisheries, 2023a). Annually, approximately 36 tons of ALDFG are removed through registered cleanups in Norway (Hartviksen, 2017), which is still less than 10 % of the estimated lost fishing gear (380 ± 104 tons / year) (De Sadeleer et al., 2021).

The Norwegian Directorate of Fisheries has 40 years of experience in annual ALDFG retrieval operations. Their findings indicate that gillnets and pots present the greatest risk of ghost fishing. The recorded catch

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https://doi.org/10.1016/j.marpolbul.2024.116268
Received 30 January 2024; Received in revised form 3 March 2024; Accepted 12 March 2024
Available online 16 March 2024

upon recovery represents only the quantity at the point of retrieval, which accumulates over time. Additionally, the catch quantity varies with season and different fishing grounds (Norwegian Directorate of Fisheries, 2023a, 2023b, 2023c, personal communication).

In this study, our primary objective is to introduce an approach to assess the impact of ghost fishing on the marine environment through ALDFG retrieval operations. We aim to establish relationships between ghost fishing catch abundance (number of specimens) / biomass (kg) and the mass (kg) of retrieved ALDFG using data from a retrieval operation led by the Norwegian Directorate of Fisheries in 2023. These are valuable data for developing estimates on the magnitude of biomass caught in ALDFG, even if they are not retrieved. Furthermore, we apply several biological indicators to estimate species richness, dominance, biodiversity, and evenness impacted by recovered ALDFG. Finally, we examined the correlation between the number of retrieved ALDFG units and the total catch biomass (kg) within them. Similarly, we conducted assessments to determine the relationship between the residence time (days) of ALDFG in the marine environment and the total catch biomass (kg) per ALDFG unit retrieved. This provides insights into how catch efficiency is affected by the number of retrieved ALDFG units and the duration of time ALDFG spends in the marine environment.

2. Materials and methods

2.1. ALDFG retrieval

The ALDFG retrieval locations were predetermined by researchers from the Norwegian Directorate of Fisheries before the yearly retrieval operation in 2023. They primarily relied on fishermen's reports of lost fishing gear that were submitted since the last retrieval operation in 2022, either to the coast guard or directly through chart plotters integrated with the Barentswatch system (Barentswatch, 2023). The ALDFG retrieval operation primarily targeted bottom-set gillnets, pots, and longlines, because their strong negative buoyancy restricts current-mediated transport of ALDFG. Fishermen who reported the loss were contacted to gather any additional information that could have improved the effectiveness of the ALDFG cleanup efforts. Additionally, researchers from the Norwegian Directorate of Fisheries assessed whether the lost gear may have been relocated or damaged due to subsequent trawling activities in the area. This was done by checking the available fishing activity database (Norwegian Directorate of Fisheries, 2023a; Norwegian Directorate of Fisheries, 2023b). Priority was given to ALDFG with the lowest likelihood of being relocated by trawling activity, maximizing the efficiency of the yearly retrieval operation.

In the 2023 ALDFG retrieval operation, the 65 m long and 13 m wide commercial seiner "Vikingbank" equipped with winches, net drums, and cranes, was chartered for the retrieval of ALDFG (Norwegian Directorate of Fisheries, 2023c). A modified anchor was attached to a trawl wire with a short chain measuring 1 to 2 m. This assembly, with a total length ranging from 1.3 to 2 times the depth, was then dragged along the seabed at the reported loss location at a speed ranging from 1 to 2 knots (SI, Figs. S1 and S2). Departure took place in Kirkenes on August 28th, 2023, and it ended September 4th, 2023, in Honningsvåg (Fig. 1). The ALDFG retrieval operation ran continuously, 24 h a day, 7 days a week. At each ALDFG retrieval stations, the station number, retrieval date and time, GPS coordinates, and sea depth were recorded.

2.2. Determination of retrieved ALDFG characteristics

During the ALDFG retrieval operation the number of individual gillnets (units) in a fleet and king crab pots (units) in a line were counted. In the context of this study, each retrieved longline was considered as a single longline unit. The stretched gillnet mesh size, gillnet twine diameter, gillnet top / bottom rope diameter, king crab pot line rope diameter, longline diameter, and marker buoy-to-anchor rope diameter, were measured using a vernier caliper (Brinkhof, 2022). The escape mechanism in the retrieved ALD king crab pots was checked to determine if it was open or closed. Due to personnel constraints, data collection between midnight and 6 AM was restricted to the count of gillnet, king crab pot, and longline units, with no measurements recorded for ALDFG characteristics during this period. The gathered data was utilized in conjunction with input from the fishing gear producer Mørenot (SI, Section S2.1.) to estimate the approximate mass (kg) of a gillnet and king crab pot unit. Longline data was not requested due to the

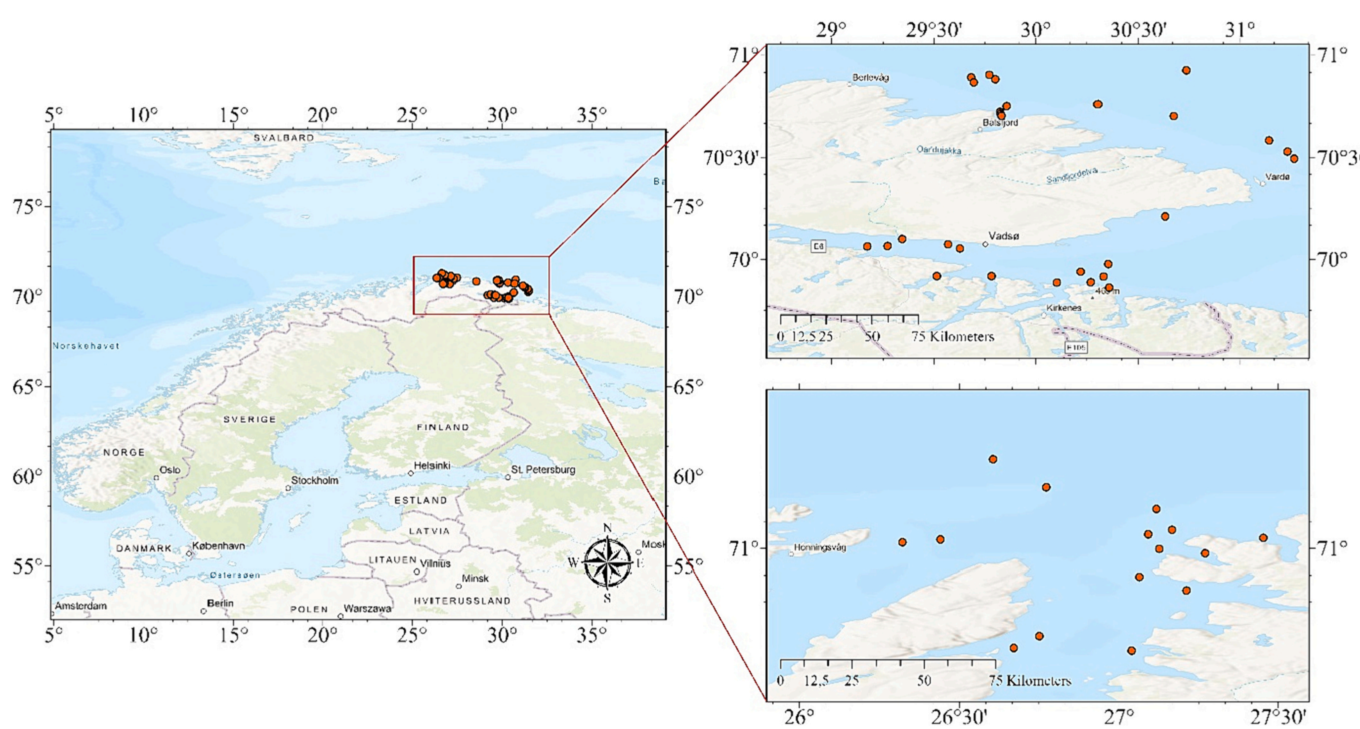

Fig. 1. ALDFG retrieval stations (marked with dots) in northern Norway (Finnmark county) (Arcgis, 2022).

absence of catch within retrieved longlines (Section 3.2).

2.3. Determination of the taxonomically sorted / total catch abundance and biomass in retrieved ALDFG

The catch abundance data for each retrieved ALDFG was recorded and categorized by taxonomy. The total length of fish (cm), from the tip of the snout to the furthest point of the caudal fin when depressed (Silva et al., 2013) and the carapace length (mm) of red king crabs (*Paralithodes camtschaticus*), from the rear of the eye socket, parallel to the center line of the carapace to the posterior edge of the carapace (Stevens and Jewett, 2014), were both gauged with a measuring tape.

The total length of fish and the carapace length of red king crabs were used to estimate the biomass (kg) of the catch. Literature based length-weight relationships for observed species were used (SI, Table S1) (Silva et al., 2013; Stevens and Jewett, 2014). During nights (midnight to 6 AM) only red king crabs were found, and their numbers recorded, though carapace length measurements were not taken. However, an average sample from the literature with a carapace length of 110 mm or a weight of 1.02 kg was used to approximate their biomass (Stevens and Jewett, 2014; Hvingel et al., 2022; Hjertaas, 2023).

The catch abundance and biomass (kg) data collected for each species within an ALDFG unit at every retrieval station were utilized to estimate both the taxonomically sorted and total catch abundance and biomass for each individual and all ALDFG units across all retrieval stations. Species-based proportions of the catch abundance and biomass for each ALDFG unit across all retrieval stations were calculated.

2.4. Estimation of the taxonomically sorted and total catch abundance and biomass per retrieved ALDFG unit

The taxonomically sorted catch abundance and biomass (kg) per ALDFG unit at each retrieval station were calculated by dividing the collected catch abundance and biomass data for each species within an ALDFG unit at every retrieval station by the number of ALDFG units at the retrieval station. We then estimated the average species-specific / total catch abundance and biomass per ALDFG unit across all retrieval stations. This approach facilitated the comparison of ghost fishing catch in distinct ALDFG types, considering variations in the number of ALDFG units and retrieval stations.

The average species-specific / total catch abundance and biomass per ALDFG unit across all retrieval stations were divided by the mass (kg) of the respective ALDFG unit (Section 2.2) to establish the taxonomically sorted / total catch abundance and biomass (kg) per ALDFG unit (gillnet and king crab pot) mass (kg) across all retrieval stations. This enabled the comparison of ghost fishing catch between different ALDFG types on a per-retrieved ALDFG unit mass basis.

2.5. Assessing the effects of retrieved ALDFG on species richness, dominance, biodiversity, and evenness

Biodiversity assessments often employ the use of multiple indices to reduce the risk of obtaining partial or biased results (Herrmann et al., 2022). In this study, the commonly used species richness index (Daly et al., 2018), Margalef (1958) index, Menhinick (1964) index, Simpson (1949) index, Shannon (1948) index, and Pielou (1966) index, were utilized to compare the impacts of ALD gillnets and king crab pots on species richness, dominance, biodiversity, and evenness.

The Species Richness Index (SRI) accounts for the absolute number of species in the catch, with all species in the sample given equal weight regardless of species abundance encountered (Maurer and McGill, 2011; Daly et al., 2018). Margalef (MA) and Menhinick (ME) indices were employed to assess the species richness affected while considering the relationship between the number of species and the number of individuals (Herrmann et al., 2022). The Simpson diversity index (D) represents the probability that two individuals randomly taken from the population represent the same species (Simpson, 1949). Elevated Simpson index values suggest a greater dominance of one or a few species, which in turn implies reduced species diversity. The Shannon Diversity Index (H), a widely utilized metric in the study of species biodiversity, enables the simultaneous consideration of both species' richness and the evenness of their abundance (Shannon, 1948). H rises as the number of sampled species and their even distribution increase, yielding a zero index when only one species is observed. Consequently, a lower H indicates a lower species diversity in the sample observed. Pielou evenness index (P) quantifies the degree of evenness in the distribution of individuals among different species in a given community (Pielou, 1966). Thereby, it provides a measure of how balanced or skewed the abundance of species is within a given community.

The values for each of these indices were calculated (equations see, SI, Section S1.3.) using the catch abundance for each species within an ALDFG unit at every retrieval station as core data input. For each type of ALDFG, the average for each index was calculated across all retrieval stations, excluding those with "not a number" results.

2.6. Calculation of the retrieved ALDFG residence time in the marine environment

The spatiotemporal data collected during the ALDFG retrieval operation was cross-referenced with the fishermen's loss reports submitted to the coast guard. This process aimed to establish a connection between the loss / retrieval location and time, ultimately determining the residence time (days) of retrieved ALDFG in the marine environment. With Python (Python, 2023) libraries Pandas (Pandas, 2023) and Geopy (Geopy, 2023), each retrieval location was used as reference point, and the script systematically identified the nearest loss report with the same ALDFG type in the coast guard's database. The distance (m) between associated coordinates was computed, contributing to the validation of the connection and the accuracy in the assessment of the residence time of retrieved ALDFG.

2.7. Linear regression / correlation analysis

Linear regression models (without and with fitting intercepts to 0) and Pearson correlations (Zou et al., 2003) were computed using RStudio (Posit, 2023), to assess the linear correlation between the explanatory variable, number of ALDFG units retrieved, and the dependent variable, total catch biomass (kg) within ALDFG. The use of total catch biomass facilitates the normalization of differences related to specimen and species-specific variations in biomass within the catch.

Additionally, linear regression models and Pearson correlations were employed to evaluate the linear correlation between the residence time (days) of ALDFG in the marine environment and the total catch biomass (kg) per ALDFG unit retrieved. The use of total catch biomass per ALDFG unit allowed for the normalization of differences in the number of ALDFG units between different retrieval stations. Subsequently, linear regression trendlines for retrieved gillnets, king crab pots, and the combination of both fishing gear were plotted using the ggplot2 library (Tidyverse, 2019).

3. Results

3.1. Retrieved ALDFG characteristics

Fifty ALDFG retrieval stations were located between the coordinates 69° 51.644 N - 30° 21.318 E and 71° 01.133 N - 26° 19.270 E (Fig. 1), at depths ranging from 25 to 399 m (SI, Table S2). A total of 60 ALD gillnets (across 4 fleets), 49 king crab pots (from 11 lines), and 9 longlines were successfully retrieved. The escape mechanism (cotton twine, maximum 4 mm in diameter) in 16 out of 21 observed king crab pots was open. One fleet of reported ALD gillnets, 11 lines of king crab pots, 11 longlines, 2 bottom trawls and 1 demersal seine could not be found / retrieved, likely due to being displaced by subsequent fishing activities.

3.2. Taxonomically sorted / total catch abundance and biomass in retrieved ALDFG

A combined mixed catch of 307 specimens, with a total catch biomass of 382 kg, was obtained from 75 % of retrieved gillnet fleets and 64 % of king crab pot lines (Table 1). No catch was found in the remaining ALDFG. Out of the four ALD gillnet fleets retrieved, only one had a mixed catch; in the other three, only red king crabs were found. The one with mixed catch included four different species, namely red king crab, saithe (*Pollachius virens*), cod (*Gadus morhua*), and redfish (*Sebastes* sp.) (SI, Figs. S3 and S4), with catch abundance and biomass decreasing in that order (SI, Table S3). When considering all retrieval stations, the catch abundance and biomass in gillnets predominantly consisted of red king crabs. The proportion of red king crabs was 38.6 % higher when considering abundance, reflecting their lower specimen mass compared to the fish catch (Table 1). In retrieved king crab pots, ghost fishing was limited to just the red king crab. No ghost fishing catch was found in retrieved ALD longlines (Table 1).

3.3. Taxonomically sorted / total catch abundance and biomass per retrieved ALDFG unit / unit mass

The minimum catch abundance and biomass (kg) of species were both zero for retrieved gillnets and king crab pots, while the maximum values were 7.14 specimens / 7.26 kg per gillnet unit, and 15 specimens / 15.24 kg per king crab pot unit (SI, Table S3). On a per retrieved ALDFG unit basis, king crab pots captured 35.7 % more abundance and 14.4 % more biomass compared to gillnets (Table 2).

The total catch abundance and biomass per kg of retrieved gillnet exceeded those of king crab pots by 27.3 % and 50.5 %, respectively (Fig. 2).

3.4. Effects of retrieved ALDFG on species richness, dominance, biodiversity, and evenness

The highest overall impact on species richness and biodiversity was observed in the recovered fleet of gillnets with mixed catch (SI, Table S4). Nevertheless, at the same retrieval station (118), the lowest species dominance (D) was observed. The lack of a mixed catch at other stations prevented the measurement of catch evenness (P).

Across all retrieval stations, salvaged gillnets had a more pronounced impact on species richness and biodiversity, when compared to king crab pots (Table 3). Additionally, a higher species dominance was observed in ALD king crab pots as opposed to ALD gillnets.

3.5. Retrieved ALDFG residence time in the marine environment

The residence times for retrieved gillnets ranged from 116 to 335 days, for retrieved king crab pots from 2 to 382 days, and for retrieved long lines from 84 to 409 days (SI, Table S5). The distances between cross-referenced coordinates for retrieved gillnets ranged from 0 to 2 m, for retrieved king crab pots from 0 to 754 m, and for retrieved long lines from 0 to 335 m.

Across all retrieval stations, recovered king crab pots exhibited the lowest average residence time, followed by gillnets and longlines, respectively (Table 4). With the highest geolocating precision observed in ALD gillnets, succeeded by longlines and king crab pots.

Table 2
Average species-specific / total catch abundance and biomass (kg) per ALDFG unit across all retrieval stations.

Type of ALDFG unit	Common species name	Average catch abundance of species per ALDFG unit across all retrieval stations	Total	Average catch biomass of species per ALDFG unit across all retrieval stations	Total
Gillnet	red king crab	2.01	2.27	2.09	2.85
	saithe	0.20		0.63	
	cod	0.05		0.13	
	redfish	8.3e-03		4.6e-04	
King crab pot	red king crab	3.08	3.08	3.26	3.26

3.6. Linear regression / correlation analysis

Linear regression models (without fitting intercepts to 0) were computed between the number of retrieved ALDFG units and the total catch biomass (kg) within ALDFG (SI, Fig. S5). Statistical significance was observed only when considering both retrieved gillnets and king crab pots. When intercepts were set to 0 (as no catch biomass is expected in 0 ALDFG units), statistically significant linear regression models with higher R^2 values and lower standard errors were observed for retrieved gillnets, king crab pots, and the combination of both fishing gear. Pearson correlation was found to be statistically significant only when both retrieved gillnets and king crab pots were considered.

While negative trends were identified in the linear regression models and Pearson correlation analyses assessing the relationship between the residence time (days) of ALDFG in the marine environment and the total catch biomass (kg) per number of ALDFG units retrieved, statistical significance couldn't be determined (SI, Fig. S6).

4. Discussion

Three types of ALDFG were recovered during the retrieval operation: bottom-set gillnets, king crab pots, and longlines, the last of which did not yield any catch. Once the bait from longlines is gone the chance of ghost fishing substantially drops (Matsuoka et al., 2005). However, ALD longlines still pose a significant entanglement threat to marine organisms, such as cetaceans (Garrison, 2005; Caitlin, 2017; Marks et al., 2020), pinnipeds (Butterworth, 2016), sharks (Afonso et al., 2012),

Table 1
Summary of catch abundance and biomass (kg) in ALDFG units across all retrieval stations.

Type of ALDFG	Number of ALDFG	Common species name	Catch abundance	Catch biomass	Total catch abundance	Proportion of the total catch abundance	Total catch biomass	Proportion of the total catch biomass	Total catch abundance of all ALDFG	Total catch biomass of all ALDFG
Gillnet	60	red king crab	116	123	147	0.79	214	0.57	307	382
		saithe	24	76		0.16		0.35		
		cod	6	16		0.04		0.07		
		redfish	1	0.06		0.01		3e-03		
King crab pot	43	red king crab	160	167	160	1	167	1		
Longline	9	–	–	–	–	–	–	–		

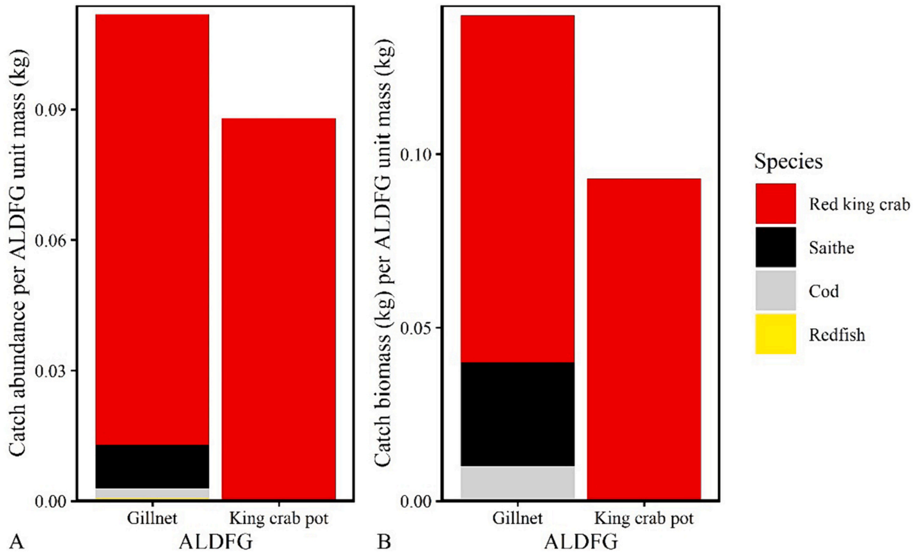

Fig. 2. Taxonomically sorted catch abundance (A) and biomass (kg) (B) per ALDFG unit mass (kg) across all retrieval stations.

Table 3
Average indices result for ALDFG unit across all retrieval stations.

Type of ALDFG unit	Species richness index	Margalef index	Menhinick index	Simpson index	Shannon index	Pielou index
Gillnet	1.50	0.28	0.36	0.82	0.32	0.70
King crab pot	1	0	0.33	1	0	–

Table 4
Average residence time (days) of ALDFG unit across all retrieval stations, along with corresponding average distance (m) between cross-referenced coordinates from the ALDFG retrieval operation and fishermen's loss reports.

Type of ALDFG unit	Average residence time	Average distance
Gillnet	201	1
King crab pot	185	197
Longline	287	38

seabirds (Collins et al., 2021), and sea turtles (Gless et al., 2008). The available entanglement data in ALDFG is limited and likely underestimated (Stelfox et al., 2016). While ALDFG retrieval operations may not be a suitable methodology for assessing entanglement in longlines, observation of live entanglements within species populations and the analysis of stranding records may be employed to assess the entanglement impacts of longlines on marine ecosystems and biodiversity (Høiberg et al., 2022). Ghost fishing catch was observed in 75 % of the retrieved ALD gillnet fleets and 64 % of the recovered king crab pot lines. Consistent with existing literature (Gilman et al., 2016; Lively and Good, 2019), regarding the potential ghost fishing impact of ALD gillnets and king crab pots. One possible explanation for the lower catch probability in retrieved ALD king crab pots is the absence of bait, attributed to the extended residence time of the pots in the marine environment (Cerbule et al., 2023). In contrast, gillnets do not depend on bait to sustain catch efficiency over time. Moreover, in the Norwegian king crab fishery, pots have been outfitted with a biodegradable cotton string (maximum 4 mm in diameter) integrated into the pot's netting, with the aim to reduce the effects of ghost fishing (Norwegian Directorate of Fisheries, 2019). In case the king crab pot is lost, the degradation of the cotton string creates a permanent opening, allowing captured crabs to escape. The estimated time to failure for a 96-thread cotton string (5 mm, 115.2 kg initial breaking strength) is 182 days (Winger et al., 2015). Twisted cotton strings (2.5–5.0 mm thickness, 16.6 kg - 39.3 kg initial breaking strength) demonstrated a degradation time ranging from 68 to 234 days, while braided cotton strings (2.0–5.2 mm thickness, 11.8 kg - 42.4 kg initial breaking strength) exhibited a span of 108 to 205 days (Araya Schmidt and Queirolo, 2019). According to Kimker (1990), the mean time to failure falls between 89 and 107 days, depending on the thread count. Additionally, data from a commercial golden king crab fishery suggests a mean time to failure of 44 days for 30-thread strings (Barnard, 2008). On the other hand, when abandoned snow crab pots were recovered after spending approximately 1.5 years at sea, none of the 5 mm diameter cotton strings used had deteriorated, maintaining a mean breaking strength of 17 kg (Humborstad et al., 2021). Thereby, the effectiveness of this mechanism highly varies depending on cotton thread count, diameter, presence of a core, manufacturing processes, cotton quality / blends, braiding method, usage / storage before the pot is lost, pot type and environmental conditions (Winger et al., 2015). During this ALDFG retrieval operation, the escape mechanism was found to be open in 16 out of the 21 observed king crab pots with an average residence time of 196 days. The average residence time of king crab pots with the escape mechanism closed was 147 days, while for pots with the escape mechanism open, the average residence time was 228 days. It remains uncertain whether the forces generated during the retrieval process might have influenced the escape mechanisms.

Long-term trials have shown that the escape rates of king crabs can be significant even in the absence of escape mechanisms (High and Worlund, 1979; Godøy et al., 2003; Stiansen et al., 2008). Hence, further investigation is warranted, particularly through long-term simulations of the ghost fishing catch in king crab pots with and without escape mechanisms.

Red king crabs were the only species caught in ALD king crab pots and constituted the primary catch in ALD gillnets. These results align with the existing literature for Norway, where the ghost fishing catch in ALD king crab pots was dominated by red king crabs (Godøy et al., 2003; Long et al., 2014; Starbatty, 2016). In ALD gillnets, there is a temporal shift in catch composition, wherein scavenging crustaceans progressively become the dominant component, gradually replacing fish catch

(Brown and Macfadyen, 2007). Given the retrieved ALD gillnets' average residence time (201 days) in the marine environment, the ghost fishing catch was skewed towards scavenging invertebrates. This aligns with findings from a prior ALDFG retrieval operation (Cho, 2005) and in situ ghost fishing simulations (Kaiser et al., 1996; FANTARED 2, 2003; Pawson, 2003). Saithe, cod, and redfish were captured in one retrieved gillnet fleet, providing further evidence that the fish species selectivity of ALD gillnets doesn't change drastically when the gillnet becomes lost (Erzini et al., 1997; Humborstad et al., 2003; Sancho et al., 2003; Tschernij and Larsson, 2003).

Results of this study offer only a momentary snapshot of the total ghost fishing impact of ALDFG on the Norwegian marine environment. The lethal time for 100 % (LT_{100}) of cod caught in gillnets is approximately 93 h (Jensen, 2022). Due to the rapid post-mortem degradation rates of fish, averaging 3.6 kg / day, as observed in Norwegian fjords (Sweetman et al., 2014; Dunlop et al., 2021), the absence or low ghost fishing catch at the time of retrieval does not necessarily imply that fish landings were low or absent throughout the entire deployment period. This hypothesis gains further support when considering longer residence times of ALD gillnets in the marine environment, are associated with a catch bias towards scavenging invertebrates (Brown and Macfadyen, 2007). The same logic may be applied, albeit to a lesser extent than for fish species, to the catch of red king crabs within retrieved ALD gillnets and king crab pots. Red king crabs can endure live holding periods of up to 92 days without feeding (Lorentzen et al., 2019). Furthermore, the LT_{100} and degradation rates may be affected in ALD king crab pots by the cannibalistic / scavenging behavior exhibited by red king crabs (Godøy et al., 2003; Long and Whitefleet-Smith, 2013).

On a per-retrieved ALDFG unit basis, ALD king crab pots exhibited an increased catch abundance and biomass compared to the mixed catch observed in ALD gillnets. However, it is essential to validate that the red king crab catch in hauled pots was not only temporary due to significant escape rates (Stiansen et al., 2008). This is crucial for corroborating or refuting the conclusion drawn by Starbatty, 2016, who asserted that ghost fishing catch resulting from king crab pots does not significantly impact unaccounted king crab mortality rates in Norway. Conversely, In Womens Bay (Kodiak island, Alaska, USA) king crab ghost fishing mortality rates varied, ranging from 16 % to 37 % per year (Long et al., 2014), while in long-term trials in northern Norway reported mortality rates spanned from 0 % to 16.7 % (Godøy et al., 2003). Deceased crabs may serve as a potential food source for other individuals, resulting in a reduction of dead crab remnants within retrieved pots (Long and Whitefleet-Smith, 2013). This could lead to an underestimation of the mortality rates (Godøy et al., 2003). The ghost fishing biomass caught per kilogram of gillnet was higher compared to that caught per kilogram of king crab pot, which may be attributed to the lower mass of a gillnet unit. As a result, on a per ALDFG unit mass basis, gillnets have a greater ghost fishing impact on the marine environment than king crab pots.

Indicators were used to evaluate how ALD gillnets and king crab pots influenced species richness, dominance, biodiversity, and evenness. Due to the lower catch selectivity of gillnets compared to king crab pots, as observed in literature (Starbatty, 2016; Brinkhof, 2022), retrieved ALD gillnets had a more pronounced impact on species richness and biodiversity than ALD king crab pots. Accordingly, a higher species dominance was observed in the retrieved ALD king crab pots as opposed to ALD gillnets. Due to the substantial residence time of retrieved ALD gillnets in the marine environment and ghost fishing catch being skewed towards scavenging invertebrates, the impact on species richness and biodiversity was limited (Herrmann et al., 2022). Results may also have been influenced by the fact that only four ALD gillnets were recovered, indicating a limitation in the sample size.

While ghost fishing prevention measures are being adopted in Norway for pot fisheries (Norwegian Directorate of Fisheries, 2019), similar initiatives are yet to be implemented for gillnets. The typical lifespan of a traditional gillnet ranges from 1.5 to 2 years (Ziegler et al., 2002; Deshpande et al., 2020). ALD gillnets degrade exceptionally slowly in the marine environment, particularly in the deep and cold ocean waters of Norway, located below the photic zone (Krause et al., 2020). This slow degradation leads to high persistence once gillnets are released into the marine environment, ultimately leading to long term ghost fishing environmental impacts (Welden and Cowie, 2017). Environmentally friendlier biodegradable alternatives have been tested in the Norwegian gillnet fishery for cod (*Gadus morhua*), saithe (*Pollachius virens*), halibut (*Reinhardtius hippoglossoides*) and European plaice (*Pleuronectes platessa*) (Grimaldo et al., 2018a, 2018b; Cerbule et al., 2022). However, biodegradable gillnets are currently more expensive (due to low production volumes) and often less efficient than traditional options (Grimaldo et al., 2019; Grimaldo et al., 2020; Cerbule et al., 2022). Thus, due to a lack of economic incentives, Norwegian fishermen are unwilling to switch to biodegradable alternatives (Standal et al., 2020). By gaining a deeper understanding of ALD gillnets ghost fishing impacts on the marine ecosystems and biodiversity through ALDFG retrieval operations, economic incentives factoring in the deferred environmental and economic losses resulting from ghost fishing may be adopted via collaborative efforts involving gear distributors, fishery stakeholders and government institutions. Fishermen could receive bonus quota, to offset the lower catch efficiency and higher costs associated with biodegradable fishing gear alternatives. Sustainability attributes associated with ALDFG may be integrated into MSC Fisheries Standards, establishing a ghost fishing-free MSC certification (MSC, 2023). Granting stakeholders employing biodegradable gillnets access to the best available market opportunities (Standal et al., 2020). Further research will contribute to the development of critically needed assessment methods (Ruiz-Salmón et al., 2021), accounting for the effects of ghost fishing on benthic boundary layer, benthic and pelagic species. These sustainable decision-making tools could then also be integrated into the subsidy system.

Overall, study results underscore a significant level of concern regarding the potential ghost fishing impact of ALD gillnets and king crab pots on Norwegian marine ecosystems and biodiversity. Assessing the full extent of ghost fishing effects caused by these types of ALDFG on an annual basis remains challenging. Uncertainties arise from the annual ALDFG mass lost, and the abundance / biomass caught. Additional complexity arises from factors such as the degradation of the catch and the residence time of ALDFG, both influencing the overall yearly catch.

The Directorate of Fisheries conducted a retrieval cruise in 2023 covering approximately 1800 km of Norwegian coastline. However, the data presented in this publication focuses on a specific region of this coastline, namely Finnmark. This area experiences lower gillnet fishing activity but is characterized by an intensive king crab fishery. The survey leader noted a comparatively low quantity of recorded catch, attributed to the reduced prevalence of gillnets in this geographical area. Additionally, regulations have been implemented mandating escape holes (biodegradable tread) in king crab pots, contributing to the observed catch dynamics.

CRediT authorship contribution statement

Dorian Vodopia: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francesca Verones:** Writing – review & editing, Supervision, Methodology. **Cecilia Askham:** Writing – review & editing, Supervision, Methodology. **Roger B. Larsen:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The published material was gathered during the Norwegian Directorate of Fisheries' ALDFG retrieval expedition in 2023. This data, obtained from ALDFG retrieval activities in close coastal and fjord areas in Finnmark, represents only a limited portion of the expedition's broader scope of work. We express our gratitude to the editor and reviewers for their insightful comments.

Funding

Dorian Vodopia's participation in the Norwegian Directorate of Fisheries' retrieval operation was funded by the Norwegian Research Council through the Dsolve project, grant number 310008. Francesca Verones' contribution has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 850717).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2024.116268.

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