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Ghost Gears in the Gulf of Gabès: Alarming Situation and Sustainable Solution Perspectives

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Abstract: This study represents a first step in investigating the prevalence, causes, and spatial distribution of Abandoned, Lost, or Discarded Fishing Gears (ALDFGs) in the Gulf of Gabès, a critical fishing area in Tunisia. Five main fishing gear types—benthic trawls, encircling nets, longlines, gillnets, and trammel nets were analysed for their loss rates and contributing factors. The study involved extensive surveys among local fishermen and the use of geographic information system (GIS) tools for spatial mapping. The findings reveal varying loss rates among different gear types, with longlines experiencing the highest losses (59%), followed by trammel nets (45%), gillnets (40%), trawls (38%), and encircling nets (36%). Causes of gear loss include entanglement on obstructions, conflicts with other fishing gears, entanglement with marine animals, adverse weather conditions, and intentional dumping at sea. The study highlights the challenges posed by the consistent increase in fishing effort in the region. Spatial distribution mapping indicates two significant concentrations of ALDFGs, correlating with specific fishing activities and depths. The study emphasizes the importance of addressing gear losses as a threat to marine biodiversity and ecosystem health. Recommendations for mitigation include improving boat equipment, raising awareness among fishermen, implementing effective waste management, and exploring economic incentives for ALDFG recovery. This research contributes essential insights for fisheries management, environmental conservation, and sustainable practices in the Gulf of Gabès. Collaborative efforts are crucial for developing and implementing strategies that minimize the impact of ALDFGs on the marine environment while supporting the socio-economic interests of fishermen.

Keywords: ALDFG; Gulf of Gabès; interviews; impact; mapping; sustainability

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1. Introduction

The increasing number of fishing fleets around the world reinforces the risk of fishing gear which has become more and more resistant and difficult to degrade. Lost fishing gear consists primarily of gillnets, trawls, longlines, pots, traps, buoys and other types of gear used by the commercial and recreational fishing industries [1,2]. The quantity of plastic released to the world's oceans is in the order of 5.32 to 19.3 million tons per year and will triple by 2025 [2]. Abandoned fishing gear is considered to be a source of plastic pollution (nylon, propylene…) which presents a major problem for marine biodiversity.

The first study on ghost nets was carried out in the 1970s by Smolowitz [3]. In 2009, the FAO declared the ghost net problem of real concern, as its impact and extent had increased dramatically over the past 50 years [4,5]. In fact, every year, 640 tons of fishing gear are thrown away, abandoned or lost in the seas and oceans, thus contributing to the distribution of marine and land debris [6].

Ghost fishing gears remain active for a period ranging from a few days to a few years and continue to capture target and non-target marine species. This phenomenon, known as

ghost fishing, is the heaviest impact of abandoned, lost or otherwise derelict fishing gears (ALDFGs) on marine biodiversity [7] and contributes to a high mortality rate [8–11]. Ghost nets can cause direct damage to marine biodiversity by capturing endangered species and indirect damage by destroying their habitats or when they are degraded into microplastics and ingested by marine organisms. Additionally, ghost fishing poses socio-economic challenges that can impact ocean and human health.

Several causes are the origin of fishing gear loss which can be either environmental, such as storms, currents and sedimentation, or anthropogenic following the intentional rejection of the gear, illegal fishing or vandalism [4,6,7,12].

In Tunisia, there is a notable absence of studies on ghost gears and their impact on biodiversity, to the best of our knowledge. The current study aims to address this gap, shedding light on the issue and serving as a crucial step toward understanding and quantifying its magnitude. This work aims to assess the extent of ghost gear by studying its distribution and nature for conservation purposes. The study is carried out in the Gulf of Gabès, which represents the most important fishing area in Tunisia and a Mediterranean-wide biodiversity hotspot. In the Gulf of Gabès, the number of boats is very high, ranging from traditional coastal sailing boats to the most modern tuna boats and purse seiners. The study of the impacts of ALDFGs in the Gulf, based on interviews with fishermen and sea users, is carried out through a census of ghost gear and the main causes of its loss, as well as a mapping of its spatial distribution. This study represents a first step and a pioneering effort in the region concerning the understanding and management of this growing issue and highlights the urgent need for appropriate mitigation measures.

2. Materials and Methods

2.1. Characterization of the Study Area

The Gulf of Gabès (33°–35° N and 10°–12.5° E) is located in south-eastern Tunisia, stretching from Chebba (Ras Kapoudia) to the Tunisian–Libyan border in the south. It encompasses a vast continental platform [13]. Covering a distance of about 1139 km, the Gulf of Gabès constitutes more than half of Tunisian coasts [14]. In addition to its coastline, the gulf is home to several islands and islets including Kerkennah, Kneiss, and Djerba as well as lagoons like Boughrara and Elbiben (Figure 1). The Gulf of Gabès is a semi-arid climate zone [15,16] and is characterized by a water circulation closely linked to the circulation of Atlantic waters across the Strait of Gibraltar (effects of high-pressure winds and effects of tides). The topography of the bottom of the gulf, as well as the dense vegetation cover, contribute to the complexity of the hydrodynamic nature of the region [17].

The Gulf of Gabès is a hotspot of biodiversity, as the most extensive and continuous meadow of Neptune grass (*Posidonia oceanica*) is found in this area, making it the most important fishing area in Tunisia [18]. However, due to multiple anthropogenic pressures, it has declined drastically since the beginning of the XXth century [19]. The region experiences significant fishing pressure, with the third highest number of active fishing boats in the Mediterranean (FAO Geographical Sub-Area (GSA)), accounting for 8.4% of the total boats [18]. Approximately 52% of the Tunisian fishing fleet, which consists of around 13,000 boats, operates in this gulf and contributes 39.3% of the national fish production [20].

2.2. Method of Surveys and Data Analysis

To estimate the number of fishing gears in a fishing area, new researchers have developed a questionnaire-based approach. This is because using underwater observation to count all lost fishing gear involves significant costs and time [12,21–23]. To gather information regarding abandoned, lost, or otherwise derelict fishing gears (ALDFGs) in the Gulf of Gabès for the 2019–2020 fishing season, interviews were conducted among fishermen in 10 fishing ports. Accurately estimating the numbers within each fishing gear becomes challenging due to the diverse array employed by numerous fishing boats each

year. Therefore, this study employed a cluster sampling method, where clusters represent various ports visited and samples are randomly selected fishermen.

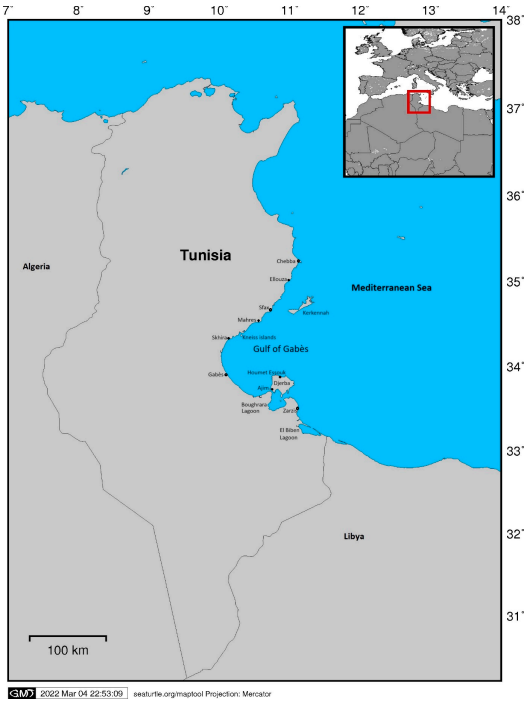

Figure 1. Map of the Tunisian ports where interviews were carried out.

As shown in Table 1, a total number of 540 face-to-face interviews were conducted in different ports of the fishing area. The questionnaires carried out with the fishermen over a period of three months, from September 2020 to November 2020, were not specifically designed for this period, but were carried out throughout the year for all the fishing seasons. Data were collected, including 189 trammel nets, 186 gillnets, 71 trawl nets, 38 encircling nets, and 56 longline cases.

Table 1. Number of surveys carried out by fishing gear type and by site.

Port	Trammel Net	Gillnet	Encircling Net	Trawl Net	Longlines	Total
Chebba	44	48	23	32	16	163
Ellouza	5	11	0	0	1	17
Mahres	3	5	4	0	0	12
Skhira	5	5	2	0	0	12
Sfax	51	49	2	37	20	159
Kerkennah	24	20	0	0	1	45
Gabès	9	6	4	0	0	19
Zarzis	24	18	3	2	14	61
Ajim	6	5	0	0	0	11
Houmet Essouk	18	19	0	0	4	41
Total	189	186	38	71	56	540

The questionnaire includes items addressing the fishing fleet, fishing effort, and fishing gears, with specific attention on quantifying and identifying the causes of losses. Interviewed fishermen provided the GPS coordinates of ALDFGs in the studied area. In most fishing operations, gear losses may involve fractions or smaller components. During interviews, the number of lost nets was defined as the number of fractions of trammel nets, gillnets, trawl nets, and encircling nets, while the number of lost longlines was estimated as the number of lost hooks.

The rate of ALDFG per year per fishing boat in the Gulf of Gabès, serving as the dependent variable, was determined based on independent variables gathered through interviews conducted with fishermen. The independent variables were selected according to the characteristics of the study area.

Eleven independent variables were used to estimate the occurrence and the number of discarded fishing nets from fishing with either trammel nets, gillnets, trawl nets, encircling nets, and longlines, including the number of gear used per fishing boat (1), the depth of fishing activity (in meters) (2), the tonnage of the fishing boat (in tons) (3), the length of the boat (in meters) (4), the average fishing months per year (5), the average number of fishing days per month (6), the annual number of pieces of nets or number of longline hooks used (7), the number of sets per 24 h (8), the haul duration or soak time (in hours) (9), the annual frequency of replacement of the fishing gear (10) and the annual number of parts of fishing gears abandoned per fishing boat (11).

The analyses proceeded in two steps. Firstly, the mean of each variable was calculated by examining the frequencies according to the fishing types (Supplementary Table S1). Secondly, through a multiple regression analysis, this study constructed a regression equation to estimate the number of ALDFGs generated by a fishing boat annually (Supplementary Table S2). To ensure noncollinearity among variables, a multicollinearity test between the independent variables was conducted during the process. In fact, the variance inflation factor (VIF) is a quantification of how much the variance is being inflated. In general, the maximum tolerance for collinearity is 1 with a maximum VIF of 10. A VIF value of 1 indicates that there is no correlation between the predictor and the remaining predictor variables, that there is no multicollinearity and, therefore, the variance is not inflated at all, whereas values greater than 1 indicate increasing multicollinearity. A VIF value above 5 or 10 is typically considered to be high and indicative of severe multicollinearity, while a VIF value above 10 is indicative of severe multicollinearity in need of correction.

The total number of ALDFGs in the Gulf of Gabès was calculated for fishing gear types, for which the total number was provided by the General Directorate of Fisheries and Aquaculture in 2018 [20]. Consequently, the total number of ALDFGs in the Gulf of Gabès was calculated for the trawl benthic and encircling nets by multiplying the gear loss rates by the total number of fleets using these gears in the Gulf of Gabès.

$$T = Y \times N$$

T = the total number of ALDFGs in the Gulf of Gabès

Y = the rate of loss of the fishing boat

N = the total number of boats using this gear in the Gulf of Gabès.

We carried out participatory mapping using two main approaches. In the first, individual fishermen were asked to mark the main locations of ALDFGs on a map (satellite imagery mosaic with the community at the centre of the 10 km radius). The maps were geo-referenced so that we could later scan and overlay the marked slides for each location; then, a software program counted and displayed the most frequently marked points (sites). In the second method, we carried out the mapping during meetings with a number of fishermen in each community, and produced one map per community, asking fishermen to point out sites or areas where abandoned fishing gear was lost. This approach was more qualitative (only one map) and more focused on relevant sites. Fishermen knew the location of wrecks, rocks and anything that might have caught their gear, and this was recorded on their GPS devices. So, in many cases, we had very precise points.

The spatial distribution of lost fishing gears was achieved by projecting GPS coordinates onto a bathymetric map of the Gulf of Gabès using QGIS 3.32.3, a geographic information system software.

3. Results

3.1. Analysis of Features by Fishing Types

Fishing units used in the Gulf of Gabès exhibit significant variations based on fishing gear types and the depth of fishing activities (Table 2). Trawling operations use boats with a total length ranging from 20 to 45 m with a majority falling within the 20 to 25 m range. The tonnage of trawlers varies between 50 and 350 t, predominantly clustering between 50 and 100 t.

Table 2. Type and sizes of fishing boats.

Fishing Gear Types	Tonnage of Fishing Boats (t)	Length of Fishing Boats (m)
Trawl nets	50–100 (69.57%) 101–151 (27.57%) 152–202 (1.45%) 202–355 (1.45%)	20–25 (84.51%) 25–30 (12.68%) 30–35 (1.41%) 35–40 (1.41%)
Encircling nets	20–40 (68.57%) 40–60 (14.29%) 60–80 (11.34%) 80–100 (5.71%)	10–15 (18.92%) 15–20 (40.54%) 20–25 (35.14%) 25–30 (5.41%)
Coastal fishing gears	1–10 (69.59%) 10–20 (27.04%) 20–30 (4.37%)	4–10 (58.67%) 10–16 (37.77%) 16–22 (3.56%)

For encircling nets, the fishing units used are boats with a total length varying from 10 to 30 m with a prevalent size range of 10 to 20 m. Boat tonnage associated with this type of net fluctuates between 20 and 100 t with a predominant range of 20 to 40 t.

In coastal fishing, the utilized fishing units are boats with total lengths ranging from 4 to 22 m, predominantly measuring between 5 and 10 m. Artisanal boats in this category exhibit tonnages ranging from 1 to 30 t with a majority falling within the 1 to 10 t range.

According to our survey, several boats use different fishing gears in different zones during the year. The fishing sailor is not generally loyal to a specific type of fishing gear, nor a specific fishing area. The distribution of fishing activity in the Gulf of Gabès is, therefore, not homogeneous. The concentration of fishing activities by type of gear in the most important fishing zones of the Gulf of Gabès (Chebba, Sfax, Gabès, Djerba, Zarzis) is illustrated in Figure 2.

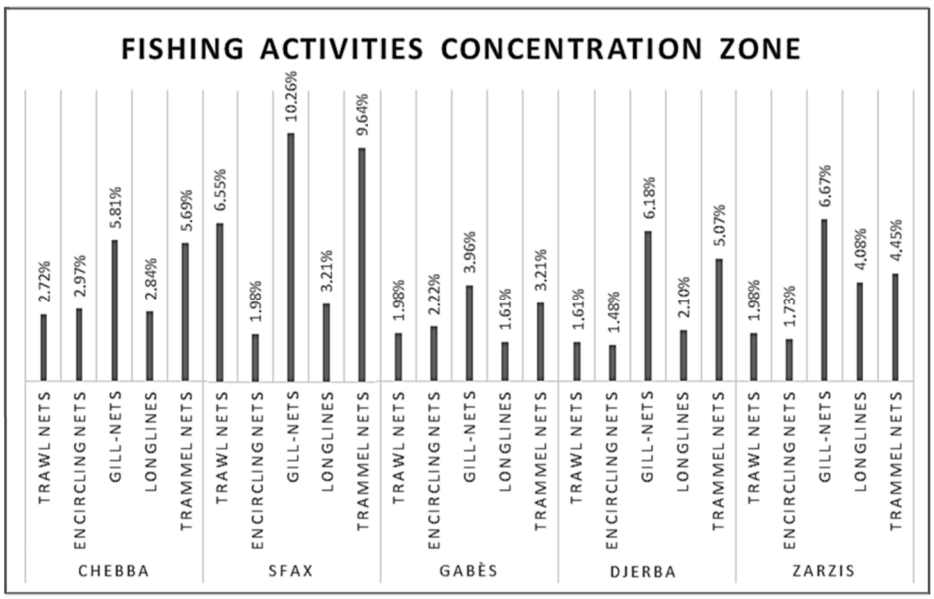

Figure 2. Fishing activities concentration zone in the Gulf of Gabès.

In all of the fishing areas, boats using gillnets are the most numerous, followed by those using trammel nets, so there is a predominance of artisanal fishing. The area of Medenine (Djerba and Zarzis) has the highest concentration of boats using gillnets, while Sfax has the highest concentration of boats using trammel nets. Trawlers, longliners, and boats using encircling nets most often fish in the area of Sfax, Medenine (Djerba and Zarzis), and Chebba, while their fishing activities in the Gabès region are very low.

3.2. Fishing Gear Loss Frequencies

Of the fishermen interviewed, 40% reported that they had lost their fishing gear. However, the loss of fishing gear in the Gulf of Gabès is not evenly distributed and shows different proportions. Longlines account for the highest proportion of losses (59%), followed by trammel nets (45%) and gill nets (40%). On the other hand, trawl losses are the lowest with 38%, and encircling nets with 36%. The latter two, trawls and encircling nets, are more resistant in terms of texture and fishers have better control over them than gillnets or trammel nets.

3.3. Estimation of the Number of ALDFGs in the Gulf of Gabès

The results of multiple linear regression analysis, conducted to establish a regression equation estimating the annual rates of ALDFGs in the Gulf of Gabès, are presented in two tables. The first provides descriptive statistics for all variables, both dependent and independent, indicating the sample size and mean for each variable (Table 3) (Supplementary Table S1). In this study, multicollinearity was checked for its possible presence between the independent variables before the multiple regressions were carried out. Generally, the maximum collinearity tolerance is 1 with a maximum variance inflation factor (VIF) of 10. The universal standard for multicollinearity, however, has more stringent criteria with tolerance limits of less than 0.1 and a VIF greater than 10 [23]. The second table displays coefficients that define the multi-collinearity among the independent variables (Table 4) (Supplementary Table S2). This is achieved through VIF, along with the significance tests (*p*-values) for the coefficients. Furthermore, the table includes the parameters of the regression equation such as the regression coefficients for each independent variable and the constant (B). For each fishing gear, an equation is derived, expressing the rate of ALDFG (dependent variable) in relation to the influencing independent variables.

Table 3. Results of descriptive analysis features of fishing gears studied in the Gulf of Gabès.

Variables	Trawl Nets		Encircling Net		Gillnets		Trammel Nets		Longlines	
	Mean	N	Mean	N	Mean	N	Mean	N	Mean	N
1	-	-	-	-	1.77	186	1.69	189	2.30	56
2	44.51	71	34.48	38	16.29	186	25.35	189	34.46	56
3	94.7705	71	28.51	38	10.15	186	10.50	189	12.70	56
4	23.9674	71	17.82	38	9.47	186	9.27	189	10.95	56
5	9.08	71	10.97	38	9.22	186	9.76	189	8.80	56
6	17.23	71	17.90	38	15.03	186	16.21	189	12.80	56
7	-	-	1097	38	35.56	186	74.71	189	2076.79	56
8	8.69	71	2.74	38	3.16	186	1.28	189	1.38	56
9	1.6516	71	1.54	38	3.03	186	10.71	189	8.82	56
10	3.13	71	1.23	38	1.30	186	1.92	189	1.61	56
11	1.56	71	1.097	38	4.30	186	12.20	189	401.96	56

N: number of boats, (1): the number of gear used per fishing boat, (2): the depth of fishing activity (in meters), (3): the tonnage of the fishing boat (in tons), (4): the length of the boat (in meters), (5): the average fishery months per year, (6): the average number of fishing days per month, (7): the annual number of pieces of nets or number of longline hooks used, (8): the number of sets per 24 h, (9): Soak time (in hours), (10): the annual frequency of replacement of the fishing gear and (11): the annual number of parts of fishing gears abandoned per fishing boat.

Table 4. Results of multiple regression analysis of features of fishing gears studied in the Gulf of Gabès.

	Constant	1	2	3	4	5	6	7	8	9	10	11
Trawl nets												
VIF	-	-	1.068	9.86	10	1.208	1.26	-	1.703	1.251	2.327	2.900
Coefficient (B)	−4.390	-	0.032	0.018	0.168	0.084	−0.01	-	0.121	0.324	0.462	0.45
p-value	0.021 *	-	0.003 *	0.022 *	0.108	0.329	0.701	-	0.038 *	0.139	0.000 *	0.000 *
Encircling net												
VIF	-	-	1.729	2.121	1.771	1.755	1.453	9.63	1.188	1.511	1.238	1.981
Coefficient (B)	2.584	-	−0.039	0.001	−0.024	−0.062	−0.053	−0.553	−0.116	0.301	0.016	0.909
p-value	0.237	-	0.042 *	0.962	0.639	0.597	0.186	0.784	0.396	0.346	0.945	0.000 *
Gill-nets												
VIF	-	1.248	1.374	2.019	2329	1.084	1.279	9.89	1.339	1.217	1.137	2.441
Coefficient (B)	−21.934	0.223	−0.043	−0.059	0.313	0.329	0.707	0.292	0.418	0.475	4.567	0.596
p-value	0.000 *	0.775	0.457	0.243	0.126	0.078	0.000 *	0.014 *	0.207	0.005 *	0.000 *	0.000 *
Trammel nets												
VIF	-	1.671	2.868	2.013	2.944	1.151	1.163	4.554	1.779	1.429	1.478	3.052
Coefficient (B)	7.181	−2.899	0.115	0.045	−0.07	−0.013	0.421	0.14	−3.127	−1.047	2.269	1.399
p-value	0.469	0.159	0.541	0.661	0.905	0.976	0.127	0.004 *	0.061	0.001 *	0.125	0.000 *
Longlines												
VIF	-	1.590	1.293	3.893	3.068	1.442	1.28	3.178	2.016	2.494	1.493	2.736
Coefficient (B)	−2000.519	268.385	11.827	12.650	−34.043	−12.971	14.26	0.219	173.692	70.302	242.272	0.941
p-value	0.036 *	0.014 *	0.035 *	0.271	0.35	0.672	0.455	0.029 *	0.321	0.126	0.025 *	0.000 *

N: number of boats, (1): the number of gear used per fishing boat, (2): the depth of fishing activity (in meters), (3): the tonnage of the fishing boat (in tons), (4): the length of the boat (in meters), (5): the average fishery months per year, (6): the average number of fishing days per month, (7): the annual number of pieces of nets or number of longline hooks used, (8): the number of sets per 24 h, (9): Soak time (in hours), (10): the annual frequency of replacement of the fishing gear and (11): the annual number of parts of fishing gears abandoned per fishing boat. * Indicates a *p*-value < 0.05.

Ten independent variables were utilized in the multiple regression analysis to estimate the annual number of trawl net pieces lost per fishing boat.

The VIF is below 10 (Table 4), indicating the absence of collinearity among them. Consequently, these variables are deemed independent of each other. In formulating the regression equation, we considered the coefficients of regression for independent variables with a significance level of $p < 0.05$ (Table 4). The number of abandoned, lost, or discarded trawl nets is affected by 5 independent variables, including the depth of fishing activities (X1), the tonnage of the boats (X2), the number of sets per 24 h (X3), the number of trawl net parts abandoned per year (X4), and the frequency of net replacement per year (X5).

Using these variables, the regression equation is expressed as follows:

$$Y \text{ (the total number of trawl nets loss)} = a \text{ (constant)} + (b \times X1) + (c \times X2) + (d \times X3) + (e \times X4) + (f \times X5)$$

b, c, d, e, and f: the regression coefficients of each independent variable.

The loss rates of trawl net pieces were calculated using the following means: the average depth of fishing activities (44.51 m), the average trawler tonnages (94.77 t), the average number of sets per 24 h (8.69), the average number of abandoned parts (1.56) and the average frequency of net replacement per year (3.13) (Table 3).

The annual number of discarded trawl net pieces (Y) can be estimated as follows:

$$Y = -4.390 + 0.032 \times 44.51 + 0.018 \times 94.7705 + 0.121 \times 8.69 + 0.450 \times 1.56 + 0.462 \times 3.13 = 1.939 \approx 2$$

This implies that approximately 2 pieces of benthic trawl net are lost in the study area per year by a trawler with an average tonnage of 94.77 operating in an average depth of 44.51 m and conducting an average of 8.69 sets per 24 h.

The total number of active trawlers in the Gulf of Gabès is 263 [20]. Based on this information, the total number of abandoned, discarded, or lost trawl nets by the entire trawl fleet in the Gulf of Gabès can be estimated as follows:

$$T = Y \times 263$$

$$T = 263 \times 1.939 = 509.957$$

Rounding up, approximately 510 pieces of trawl nets are discarded annually in the Gulf of Gabès.

Multiple regression analysis of encircling nets presents a VIF strictly less than 10 (Table 4). These variables are, therefore, not collinear and independent of each other. Two independent variables with a $p < 0.05$ are used to formulate the equation for estimating the rate of encircling nets abandoned, discarded, or lost annually, including the depth of fishing activities (X1) and the annual number of abandoned encircling net pieces (X2).

The regression equation is written as follows:

$$Y \text{ (the total number of lost encircling nets)} = a \text{ (constant)} + (b \times X1) + (c \times X2)$$

b and c: regression coefficients of each independent variable.

The average depth of fishing activities is 34.5 m and the average number of abandoned parts is 1.097 (Table 4). Using these means, the annual rate of discarded encircling net pieces (Y) can be estimated as follows:

$$Y = 2.584 + (-0.039) \times 34.5 + 0.909 \times 1.097 = 2.23$$

About 2 pieces of encircling nets are lost annually and by a boat operating in an average depth of 34.5 m in the Gulf of Gabès.

The total number of active purse seiners in the Gulf of Gabès stands at 184 [20]. The total number of pieces of encircling nets abandoned, rejected, or lost by the whole encircling nets fleet in the Gulf of Gabès is determined by the following equation:

$$T = Y \times 184$$

Y being the total number of abandoned, discarded, or lost encircling net pieces per year in the Gulf of Gabès.

$$T = 184 \times 2.23 = 410.32$$

Around 410 pieces of encircling nets are rejected each year in the Gulf of Gabès.

Regarding the coastal fishing gears, all variance inflation factors (VIF) are consistently less than ten (Table 4). The 11 variables used to estimate the rate of abandoned, lost, or otherwise discarded gillnets, trammel nets, and longline hooks, exhibit non-collinearity.

Three independent variables, each with a significant level of $p < 0.05$, were used to produce the regression equation for the rate of abandoned, rejected, or lost trammel nets. These are the number of pieces of net used (X1), the soak time (X2), and the number of pieces of net left in the sea (X3).

Using these variables, the regression equation is written as follows:

$$Y \text{ (the total number of lost trammel nets)} = a \text{ (constant)} + (b \times X1) + (c \times X2) + (d \times X3)$$

b, c and d being the regression coefficients of each independent variable.

The loss rates of pieces of trammel net were calculated using the following descriptive statistics: the average number of pieces of net used (74.71), the soak time (10.7147), and the average number of pieces of abandoned nets (12.2) (Table 5).

Table 5. Causes of fishing gear loss.

Causes	Trawl Net	Encircling Net	Gillnet	Trammel-Net	Longline
Bottom structure	82%	17%	23%	25%	38%
Gear conflicts	10%	20%	35%	34%	22%
Entanglement with animals	6%	49%	30%	29%	13%
Weather conditions	2%	14%	12%	12%	27%

The annual number of rejected trammel nets (Y) can be estimated as follows:

$$Y = 7.181 + 0.140 \times 74.71 + (-1.047) \times 10.7147 + 1.399 \times 12.20 = 23.48$$

About 23 pieces of trammel nets are lost in the Gulf of Gabès annually by a fishing boat using an average number of net pieces of 74.71 with an average soak time of 10.71 h.

To derive the estimation equation for the rate of abandoned, discarded, or lost gill nets, five independent variables with a significance level of $p < 0.05$ were incorporated. These variables comprise the number of net pieces abandoned per year (X1), the sets in 24 h (X2), the replacement frequency of the gear per year (X3), the number of gillnet pieces used (X4), and the number of fishing days per month (X5).

The regression equation is written as follows:

$$Y \text{ (the total number of lost gill nets)} = a \text{ (constant)} + (b \times X1) + (c \times X2) + (d \times X3) + (e \times X4) + (f \times X5)$$

b, c, d, e and f being the regression coefficients of each independent variable.

The loss rate of gill net pieces was calculated using the following values: the average number of pieces of net discarded per year (4.3), the average soak time in hours (3.026), the average frequency of gear replacement per year (1.3), the average number of gillnet pieces used (35.56), and the average number of fishing days per month (15.03) (Table 4).

The estimation of the annual number of discarded gillnets by fishing boat (Y) can be determined as follows:

$$Y = -21.934 + 0.596 \times 4.3 + 0.475 \times 3.026 + 4.567 \times 1.3 + 0.292 \times 35.56 + 0.707 \times 15.03 = 9.013$$

About 9 pieces of gillnets are lost in the Gulf of Gabès annually by a fishing boat using about 35 pieces of nets, replacing its nets about 1.3 times per year and operating about 15 days per month, with an average soak time of 3.026 h.

To estimate the rate of abandoned, rejected, or lost hooks, five independent variables with a significant level of $p < 0.05$ were retained. These variables include the annual number of abandoned hooks (X1), the yearly frequency of gear replacement (X2), the number of hooks used (X3), the depth of fishing activities (X4), and the annual number of gears used per boat (X5).

The resulting regression equation is estimated as follows:

$$Y \text{ (the total number of lost longline hooks)} = a \text{ (constant)} + (b \times X1) + (c \times X2) + (d \times X3) + (e \times X4) + (f \times X5)$$

b, c, d, e and f being the regression coefficients of each independent variable.

The longline hook loss rates were calculated using the following descriptive statistics: the average number of discarded hooks per boat (401.69), the average gear replacement frequency per year (1.61), the average number of hooks used (2076.79), the average depth of fishing activities (34.46 m), and the average number of gears used per year per boat (2.304) (Table 5).

The total number of discarded hooks (Y) can be estimated as follows:

$$Y = -2000.519 + 0.941 \times 401.96 + 242.272 \times 1.61 + 0.219 \times 2076.79 + 11.827 \times 34.4643 + 268.385 \times 2.304 = 248.568$$

About 249 hooks are lost annually in the Gulf of Gabès per boat with an average of 2.304 gears used annually and around 2076.79 hooks used at an average depth of 34.46 m.

3.4. Causes of Loss

Surveys conducted with fishermen provide insights into the causes of ALDFGs categorized by the type of fishing gear, as outlined in Table 5. The primary cause of loss of trawls is getting entangled with obstructions such as wrecks, rocky seabed and artificial reefs, accounting for 82% of responses. Similarly, for longlines, entanglement with obstructions is a significant cause, representing 42% of responses.

Conflicts with other fishing gears emerge as the predominant cause of loss of gillnets (35% of responses) and trammel nets (34% of responses). In the case of encircling nets, the primary cause of gear loss is entanglement with marine animals, constituting 49% of responses. This factor is also noteworthy for gillnets and trammel nets, contributing to 30% and 29% of losses, respectively. Furthermore, according to 27% of respondents, unfavourable weather conditions are a significant factor in the loss of longline hooks.

3.5. Spatial Distribution of ALDFGs in the Gulf of Gabès

The surveys conducted with fishermen in various ports of the Gulf of Gabès have allowed us to gather the GPS positions of wrecks and abandoned fishing gears in the region. While this information may not be exhaustive, the spatial distribution mapping has provided us with insight into the extent of ALDFGs in the area. The map (Figure 3) reveals two significant concentration zones. The first is located at depths around 30 m south of Sfax and north of Djerba, while the second deepest lies at depths between 40 and more than 100 m along the Gulf of Gabès coasts. Nevertheless, a more comprehensive and long-term study involving other types of gears is essential, particularly along the Kerkennah island coasts, which appear to be heavily impacted by plastic traps posing a significant threat to the entire area [24].

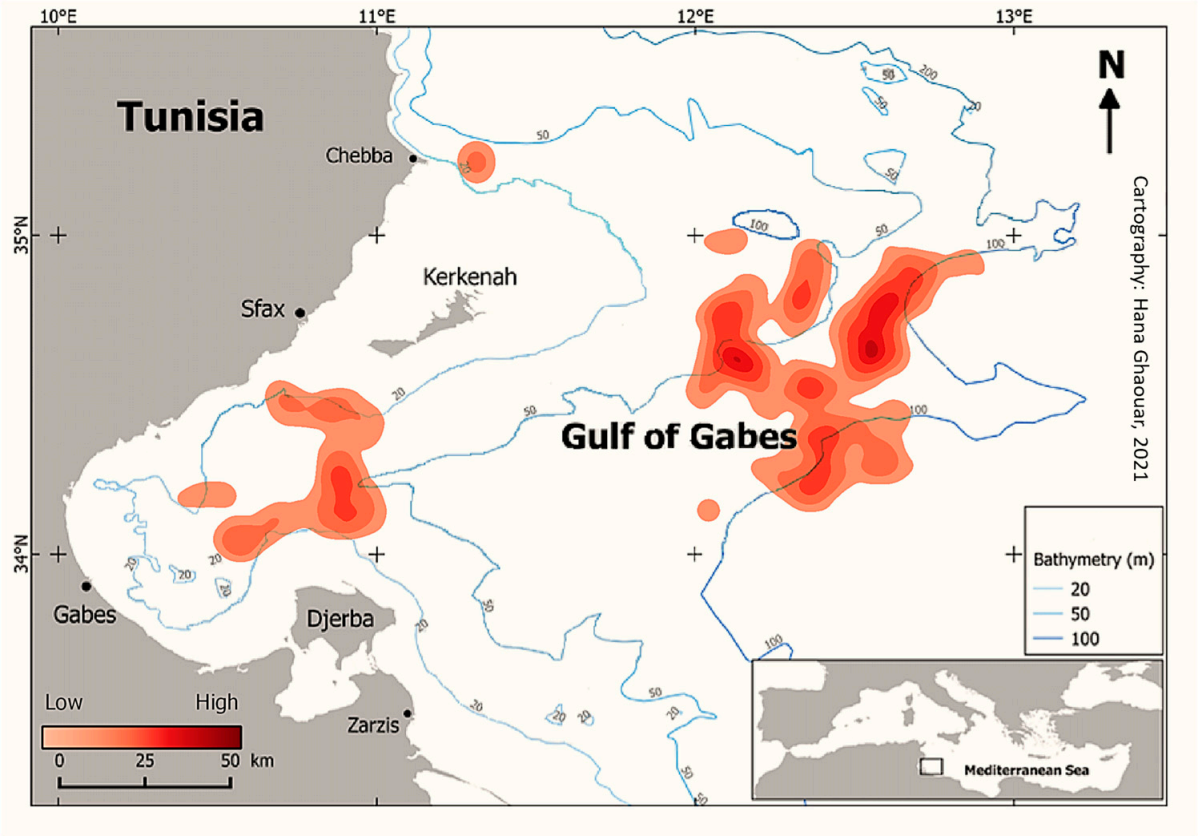

Figure 3. ALDFGs distribution in the Gulf of Gabès.

4. Discussion

4.1. Fishing Gear Loss

Ghost fishing is a potentially serious threat because of the very large quantities of fishing gear used [12]. Our results on gear loss rates are consistent with those of the Global Ghost Gears Initiative [25] on the probability of loss of longlines, gillnets, encircling nets and trawls. According to a study carried out by [6], the loss percentage of gillnets in the European Union is less than 1%, whereas in the Gulf of Gabès, this type of gear can experience a loss percentage as high as 40%. The lower incidence of ALDFGs in European

Union countries would be linked to the high recovery rates facilitated by well-equipped fishing boats using GPS technology [26].

Research conducted in Istanbul by [12] indicated that the loss rates of encircling net pieces per fishing boat per year are approximately 1.03, resulting in a total of 113 pieces lost annually. Our investigations in the Gulf of Gabès reveal higher estimates, with a loss rate of 2 pieces per boat per year and a total number of approximately 368 pieces lost annually.

Furthermore, a study conducted in South Korea by [23], reveals that the loss rates of gillnet pieces per boat per year are approximately 9.64. This agrees with our own results, where we found a similar rate of around 9 gillnets lost per boat per year. The high loss rates of ALDFGs in the gulf may stem from fishermen's negligence. Indeed, 18% of fishermen discard non-reusable nets into the sea and 45% of them abandon their damaged gear at sea. Furthermore, a significant number of boats lack GPS equipment, making it difficult to locate lost or damaged gear and almost impossible to recover it.

According to our knowledge and surveys, inshore fishermen generally show a lack of loyalty to both fishing gear and fishing areas. They tend to move frequently between gears or fishing areas, making it difficult to estimate the total number of ALDFG. Addressing this issue requires broader spatio-temporal studies to comprehensively assess and resolve the problem. Such studies are crucial, as the issue poses a threat to the marine environment with its potential physical, chemical, and biological impacts.

4.2. Causes of Fishing Gear Loss

In the Gulf of Gabès, fishing activity has consistently risen over the years, primarily driven by artisanal fishing, constituting approximately 94% of the total fleet [20]. The expansion of the fishing fleet could be an important factor in the increased loss of fishing gear, increasing the risk of conflict, a major factor in the ALDFG phenomenon. Other influencing factors include entanglement with obstructions, entanglement with marine animals and adverse weather conditions, all of which collectively contribute to this hazardous occurrence within the marine environment. According to the statements of the fishermen interviewed, and especially those using trammel nets and gillnets, one of the main factors in the loss of fishing nets is entanglement with animals, particularly the blue crab (*Portunus segnis*). This phenomenon is consistent with the findings of [27], who identified it as an important factor contributing to the loss of fishing gear in the Gulf of Gabès.

Houssine et al. [28] confirmed that approximately 81% of fishers in Oman identified wildlife interactions as a significant factor contributing to gear loss, which continues to entrap animals, including birds, turtles, whales, sharks, and dolphins, for years.

4.3. Spatial Distribution of ALDFGs

The mapping of the ALDFG reveals two concentration areas within the Gulf. The first concentration is situated at depths of around 30 m, which corresponds to the average depth of fishing activity for longliners (34.26 m) and trammel nets, which were identified as the most frequently lost gear in this study. The second concentration zone of ALDFGs extends from depths of 40 to more than 100 m, corresponding to the depth of trawl fishing activities, which also exhibits a notable percentage of loss (38%).

Distribution maps depicting wrecks and bottom obstructions containing ALDFG provide insights into the scope of the ghost gear phenomenon and could explain the fact that the major cause of all types of gear losses would be attachment to obstructions. The areas in front of Chebba and Kerkennah, as well as the eastern area of Djerba and Zarzis, seem less affected. It is possible that this large number of fishing gears is an indication that this area has been intensively fished for many years. As a result, these areas are more exposed to boat traffic and this can greatly affect the frequency of gear loss, increasing the potential for gear conflicts and the potential for the cutting off of markers, one of the main sources of gear loss [29,30].

Furthermore, gear lost due to unskilled handling by recreational fishermen has been reported in Santa Catarina, Brazil [31]. In order to better understand the extent and

distribution of gear loss along the Tunisian coast, these theories require further investigation. However, a more comprehensive study over time, including other gears, is necessary. This is particularly crucial for the Kerkennah region, which appears to be significantly impacted by plastic traps [24]. These traps represent a scourge and a proven danger for the whole region. Initiatives have been planned through the Life MedTurtles project to remove ghost fishing gear from the two hotspots reported during our study in the Gulf of Gabès, but continued vigilance is essential to protect marine ecosystems.

Finally, the development of acoustic sonar technology used to locate and combat the environmental threat of ghost gear should be deployed in various regions. In 2022, WWF France and WWF Germany started actively combating ghost gear in the Mediterranean Sea using this innovative and efficient method. They completed the first test in October 2022 in Corsica, where the team used sonar technology to help locate lost nets targeting crayfish. They searched 900 hectares, where they identified 90 net/line targets, which represent, at minimum, tens of kilometres of ghost gear [32].

5. Conclusions

This study on Abandoned, Lost, or Discarded Fishing Gears (ALDFGs) in the Gulf of Gabès, the most important fishing area in Tunisia and a biodiversity hotspot in the Mediterranean, provides a comprehensive insight into an alarming environmental issue in the region.

Key findings reveal concerning rates of fishing gear losses, with significant variations among different gear types. Benthic trawls, encircling nets, longlines, gillnets and trammel nets were the 5 main fishing gears studied in the Gulf of Gabès. Indeed, our results show that approximately 2 pieces of trawl and encircling net are lost per year per fishing vessel; a total of 526 pieces of trawl and 410 pieces of encircling net are lost per year in the Gulf of Gabès. Longlines are lost at a rate of approximately 249 hooks per vessel per year. Gillnets are lost at a rate of around 9 pieces per vessel per year, and, for trammel nets, we found that around 23 pieces of net could be lost annually by a fishing vessel operating in this area. Longlines are the most commonly lost gear (59%), followed by trammel nets (45%), gillnets (40%), trawls (38%) and encircling nets (36%).

There are many different factors that contribute to these losses, such as unfavourable weather patterns, natural barriers, and confrontations between fishing gear. The results showed a clear tendency for ghost catch rates to vary according to gear type and environmental factors. The interactions also suggest that the reasons for this may be multifactorial. Since ghost fishing is a major threat to fisheries, fish stocks and marine ecosystems, it is important for fisheries management to understand the extent of gear loss and the problem of ghost fishing.

One important element raising the likelihood of gear loss is the area's steady increase in fishing effort. The results also underscore limited awareness among fishermen regarding the negative impact of ALDFGs on the ecosystem and biodiversity.

The spatial distribution of ALDFGs reveals significant concentrations, emphasizing specific areas where management and prevention efforts could be intensified.

Additionally, the mapping of loss sites aligns with the presence of marine debris, highlighting the importance of waste management in fishing activities.

Several factors can influence the concentrated accumulation of this debris. These include size (e.g., length of rope), bottom type, physical processes (e.g., tides, circulation patterns), weather conditions, fishing effort and levels of boat traffic. A higher proportion of lost gear due to gear conflicts is expected in areas with higher levels of boat traffic and fishing intensity. It is important to note that the regional 'hotspots' of gear accumulation presented here can only be an indicator of the differences in effort levels between the fishermen surveyed. For these reasons, estimates of extent and geographical distribution should be cautious. It is also important to note that the true geographical pattern of lost gear may not be accurate as gear may be dispersed from adjacent habitats by prevailing environmental conditions (e.g., storms, currents, wind).

To mitigate these issues, measures such as enhancing boat equipment, increasing fishermen awareness, collecting and recycling lost gear, and providing economic incentives for ALDFG recovery could be considered. These actions aim to reduce the impact of ALDFGs on the marine ecosystem while supporting the livelihoods of local fishermen. Several studies reveal that over 90% of the species caught in ghost gear are of commercial value [6,25]. This undermines the sustainability and economic returns from fisheries by reducing or eliminating harvests. Ghost gear also damages valuable marine habitats such as coral reefs and mangroves. Plastic gear can take decades to break down, persistently entangling and harming marine life. Finally, ghost gear also poses a danger to navigation and threatens the safety of mariners; and, like other marine debris, ghost gear affects tourism by spoiling the natural beauty of coastal areas. A collaborative approach involving local stakeholders, fisheries management authorities, and environmental organizations is crucial for implementing sustainable solutions to this complex problem. Furthermore, it is important to note that this study represents a pioneering effort in the region concerning the understanding of the extent of ALDFGs. By addressing this critical issue and providing actionable recommendations, this research contributes significantly to the ongoing efforts for fisheries management, environmental conservation, and sustainable practices in the Gulf of Gabès and beyond. Collaboration among various stakeholders will be essential for the effective implementation of these recommendations and the long-term protection of marine ecosystems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16072632/s1, Table S1: Descriptive analysis results for all fishing gear studied using SPSS software IBM SPSS Statistics for Windows, Version 28.0. Armonk, NY, USA: IBM Corp. A: Trawl net; B: Encircling net; C: Gill net; D: Trammel net; E: Longlines. Table S2: Multiple regression analysis results for all fishing gear studied using SPSS software. A: Trawl net; B: Encircling net; C: Gill net; D: Trammel net; E: Longlines.

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