Baseline

Submarine canyons along the upper Sardinian slope (Central Western Mediterranean) as repositories for derelict fishing gears

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Abstract

By means of ROV surveys, we assessed the quantity, composition and bathymetric distribution of marine litter in 17 sites along the Sardinian continental margin (Central Western Mediterranean) at depths ranging from 100 to 480 m. None of the investigated sites was litter free, but the mean density of litter (0.0175 ± 0.0022 items m^{-2}) was lower than that reported from other Tyrrhenian regions. The difference in the total litter density among sites was negligible, but the density of Derelict Fishing Gear (DFG) items (most of which ascribable to small scale fishery) in submarine canyons was higher in submarine canyons than in other habitats. Our result suggest that submarine canyons (known to be highly vulnerable ecosystems) act as major repositories of DFGs, and, therefore, we anticipate the need of specific measures aimed at minimizing the loss and abandonement of DFGs in submarine canyons.

Keywords: marine litter; submarine canyons; Derelict Fishing Gear; ROV; plastic

With millions of tons of solid waste entering the marine environment every year, marine litter has become a fast-growing global concern, with alarming evidences coming from all oceanic regions (Jambeck et al., 2015). This global phenomenon has countless input sources and a variety of habitats being affected, with apparently no area of the ocean immune from this threat (Levin and Le Bris, 2015). The Mediterranean Sea, with an estimate of >62 million macro-litter items currently floating on its surface, is one of the world marine regions mostly affected by marine litter (Suaria and Aliani, 2014).

While most of plastic marine litter floats on the sea surface, macro-litter items composed of heavy materials typically descent to the seabed, where, because of their inertia to decomposition, tend to accumulate even in the long term. Regardless of its nature and specific composition, benthic litter alters the receiving habitat in different ways: while at times providing new hard substrata for epibiosis (Melli et al. 2017), it causes physical damage to already settled organisms or even foster chemical contamination. Among benthic litter, a particularly relevant category includes Derelict Fishing Gears (DFGs). DFGs tend to remain entangled on the rocks as well as on habitat structuring species (e.g., corals, sponges, bryozoans). Additionally to the mechanical damage to benthic fauna, DFGs still function for very long times and are able to catch and trap fish and other organisms, so that these abandoned gears cause the so-called ghost fishing (Fernandez-Arcaya et al., 2017). Morever, since these DFGs are made of non-biodegradable compounds, they also represent a persistent contamination source of the marine environment, especially of habitats below the photic zone.

The Marine Strategy Framework Directive (MSFD), developed by the European Commission (Directive 2008/56/EC) represents to date the most important coordinated framework to protect European seas by achieving a 'Good Environmental Status' (GES) by 2020. GES is evaluated through 11 descriptors, the 10th of which is marine litter: for this descriptor GES is achieved once "Properties and quantities of marine litter do not cause harm to the coastal and marine environment". For this reason, the number of monitoring activities and scientific investigations aimed at quantifying and qualifying marine litter in European Seas is continuously increasing. However, the data available on marine litter distribution in deep-sea benthic habitats are still scarce if compared with data from shallower areas (Suaria et al., 2016). Most of the accumulated data on deep-sea litter has been obtained with invasive and semi-quantitative sampling gears (e.g. trawls, dredges; Galgani et al., 1996; Pasquini et al., 2016; Strafella et al., 2015), which, according to the "Guidance on monitoring of Marine Litter in European Seas" (GMML) are preferred for the study of incoherent bottoms (Galgani et al., 2013). More recently, the development and increasing utilization of Remotedly Operated Vehicles (ROVs) has allowed to explore conservatively (i.e. limiting the damage to the benthos), also hard bottoms (Angiolillo et al., 2015; Bo et al., 2014; Cau et al., 2015; Melli et al., 2016).

We investigated the quantity, composition and bathymetric distribution of benthic marine litter in 17 sites located along the Sardinian continental margin (Central Western Mediterranean) at depths ranging from 100 to 460 m (Figure 1). Investigated sites were *a priori* assigned to two categories of habitat: 'canyons' and 'others', according the output of MultiBeam Echo-Sounder (MBES; EM 2040 Kongsberg, 300 kHz frequency) survey conducted prior to ROV dives and to three geographical categories: 'north', 'east' and 'south', according to their location (Figure 1).

Data were acquired during a total of 29 ROV dives onboard the R/V "*Astrea*" in summer 2013, with 1-4 dives per site (Table 1). The software DVDVIDEOSOFT was used to extract high-resolution photo sampling units from ROV footage every 30''. A total of 1.3 km^2 of useful footage of hard bottoms have been acquired during the surveys, which allowed obtaining ca. 4200 independent photo sampling units (*i.e.*, with no overlapping surface among units), across the 17 sites. All frames had a surface comprised between 4 and 7 m^2, allowing the identification of items larger than 10mm. Frames with unclear visibility or too wide area, which would have compromised the resolution of the image, were discarded at the beginning of image processing. The image analysis was performed using the 'CPCe' software (Kohler and Gill, 2006), which estimated each frames' area using a constant scale provided by three laser beams spaced 10 cm apart, mounted on the ROV camera. For each sampling unit, each litter item has been classified according to GMML into 8 macro categories, each with sub-categories (Table 2), with a few simplifications. In particular, plastic bags (sub-category A.1), plastic bottles (A.2) and 'other plastic objects' (A.5) have been pooled together as a unique category (plastic items), whereas A.6, A.7 and A.9 (fishing nets, lines and ropes, respectively) were kept as independent categories. To document the potential impact of benthic litter to organisms, the interaction between litter and benthic fauna was classified according to 3 categories: (i) covering (litter covers the organism); (ii) hanged or snagged to an organism; (iii) litter lying on the seabed, with no impact to fauna.

We report here that none of the sites was litter free, and that the density of litter items does not change with water depth or distance from the nearest coastline (Figure 2). Overall, a total of 234 litter items have been counted and identified as plastic, derelict fishing gears, metal and glass, whereas items belonging to all other GMML categories were absent (Table 2). The average density of litter was 0.0175 ± 0.0022 items m^{-2}. The most abundant category was plastic (ca. 88% of total items), followed by glass (6.4%) and metals (5.6%) (Figure 3A). DFGs included fishing nets, lines and ropes, which accounted for 41.9%, 19.7%, and 16.2% of total plastic items, respectively, followed by other plastic items (Figure 3B). All DFGs were ascribable to local professional small-scale fishery (mostly trammel-nets), whereas no trawls gears were observed. Among all surveyed sites, only three were DFG-free (Table 1).

Differences in the total litter density and composition among regions and between the two habitats were investigated using one-way uni- and multi-variate permutational analyses of variance (PERMANOVA; software PRIMER 6+, Plymouth Marine Laboratory), respectively. Both tests were based on 'Bray-Curtis distance' similarity matrix of non-transformed data, using the habitat typology (canyon *vs*. 'others') and geographical area, separately, as sources of variation.

Overall, the density of total litter does not vary among regions and between habitats (Table 3), whereas we observed significant differences in the litter composition but only between habitats (Table 3). The results of the SIMPER analysis (carried out using the routine included in the PRIMER 6+ software) show that differences in litter composition among the two investigated habitats (overall dissimilarity 74.9%) were mainly explained by variations in the abundance of plastic sub-categories (cumulative contribution to dissimilarity ca. 80%) (Table 4).

Differences in the density of each litter category between the two habitats were investigated separately using Kruskall-Wallis (K-W) non-parametric ANOVA (software PAST 2.17; Hammer et al., 2001). The density of DFGs in canyons is significantly higher (K-W, H= 4.22, $p < 0.05$) than in other sites (Figure 4). Among the different DFGs, nets were about four-folds more abundant in canyons (K-W, H= 7.202, $p < 0.001$; Figure 4)

The totality of the litter-fauna interactions was with large Anthozoans (a total of 114 colonies visually impacted). The remaining portion of litter was observed lying on rocky bottoms (*e.g.*, hanged on outcrops), apparently without any contact with the fauna. The gorgonian *Eunicella cavolinii* (Koch, 1887) was the most frequently impacted species (23% of impacted corals), followed by the corallidae *Corallium rubrum* (Linnaeus, 1758; 18%) and the black coral *Antipathella subpinnata* (Ellis and Solander, 1786; 12%). All other impacted species are reported in Table 4.

Most of the litter observed during the survey lyed on defaunated seafloor (65% of the frames with litter; Figure 5A). In about 24% of the cases, litter was observed in interaction with coral colonies, being trapped or snagged in coral branches, like in the case of fishing lines or nets (Figure 5B). In the remaining 11% of the cases, the litter items lyed on other corals, among which some rare and vulnerable coral species like *Madrepora Oculata*, *Dendrophylla cornigera*, and *Leiopathes glaberrima* (Figure 4C).

The epibiontic colonization of litter items was also high: 65% of the observed items showed high fouling levels, with epibionts covering almost 100% of the available surface. Derelict nets and entangled longlines were mostly colonized by the serpulid policheate *Filograna implexa*, ramified hydroids *(Sertulariidae*), encusting sponges, colonial tunicate, bryozoans and zoanthids. About 28% of the litter items showed a surface coverage by fouling of ca. 50% and just 7% of the observed items were free of epibionts. Ghost fishing was documented only in one of the investigated sites (GOc, submarine canyon) (Figure 5D).

Data on marine litter accumulated on the continental shelf do often derive from opportunistic investigations, because of the high costs of research surveys devoted specifically to litter. In fact, to date, such kind of litter-focused research has traditionally shared ship time with fishery-related trawl surveys (or similar). Despite the increasing number of studies on this topic, this limitation has led to spatially dispersed, temporally fragmented and potentially biased information towards a documentation mostly focused on fishing grounds. This, unavoidably weakens our knowledge and understanding of the threats deriving from marine litter. In this regard, it is noticeable that the MSFD technical subgroup on marine litter pointed out how complex seabed geomorphology may enhance the accumulation of litter in the seafloor, with vast-area techniques such as trawl surveys being un-practicable in these environments. Our study, as part of a larger investigation focused on the coral habitats in the

Sardinian upper slope, has proved that not destructive surveys conducted with ROV can provide reliable information on litter quantity and composition over relatively large areas.

We showed that the Sardinian upper slope is characterized by a density of litter items lower than that reported from other Mediterrranean regions (Angiolillo et al., 2015; Cau et al., 2017b, 2015). Since the Sardinia coasts are characterized by relatively small human resident populations (with exception during the summer season), our data are consistent with the assumption by which the smaller the human population on the coast, the lower the abundance of litter (Galgani et al., 1996; Mordecai et al., 2011).

Previous analyses conducted in European seas showed that submarine canyons typically accumulate benthic litter, mostly land sourced (Pham et al., 2014). This pattern is expected because submarine canyons with heads very close to the coasts, such as those under scrutiny in our study, can act as conduits of material towards the deep sea (Canals et al., 2006; Pusceddu et al., 2013).

Our results only partially confirm this analysis. In fact, while we report here that the total density of litter in canyons is not significantly different from that in other geomorphological settings, the density of DFGs within Sardinian submarine canyons is about three times higher than that in other geomorphological settings. The discrepancy between our results and those from previous reports can be ascribed to the relatively low abundance of litter along the Sardinian upper slope, when compared with other Mediterranean regions (Table 6), as well as by the close position of investigated canyons to the coast, wich make these habitats more accessible to small scale fishery vessels, widely distributed all around the island of Sardinia (Follesa et al., 2011).

At the same time, our data are also in contrast to those reported from studies conducted in other oceanic regions and at larger spatial scales, which generally have identified marine litter as mainly land-sourced (Ramirez-Llodra et al., 2011). In fact, we show here that the Sardinian upper slope is mostly affected by litter derived from small-scale professional fisheries, whose density is about three times higher than that of any other litter class. This result pinpoints the peculiar origin of benthic litter around Sardinia. Moreover, given the prohibitive costs of DFGs removal from the deep-sea, which in addition could possibly increase the risk of further impacts on benthic fauna such as deep coral forests or essential fishing habitats, among others (Bo et al., 2015, 2014; Cau et al., 2017a; Taviani et al., 2015). We anticipate the need of specific measures aimed at abating incorrect practices of small-scale professional fisheries within submarine canyons.

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Table 1. Location, depth, distance from the coast and typology of morphological settings for each of the 17 sites investigated along the upper Sardinian slope. + = DFGs present; - = DFGs absent.

Dive	Site	Lat (N)	Long (E)	Depth range (m)	Sites	Code	Distance from the coast (Km)	Morphology	DFGs
1	1	40°18'912	9°40'495	120	Gonone canyon	GOc	0.91	canyon	+
2	2	40°21'825	9°53'670	120	Orosei canyon	ORc	11.6	canyon	+
3	2	40°21'767	9°53'657	120	Orosei canyon	ORc	11.5	canyon	+
4	2	40°21'692	9°53'950	186	Orosei canyon	ORc	11.6	canyon	+
5	3	40°25’400	10°19’120	350	Baronie seamount	BAs	43.2	seamount	-
6	4	40°43'080	9°49'933	145	Mortorio canyon	MOc	8	canyon	+
7	5	40°55'169	9°54'140	190	Tavlolara canyon	TAc	18.8	canyon	+
8	6	41°17'427	9°37'481	220	Caprera canyon	CAc	17.9	canyon	+
9	6	41°18'357	9°38'021	190	Caprera canyon	CAc	19.6	canyon	+
10	7	41°04'217	9°47'899	120	Mortorio canyon	MOc	16.8	canyon	+
11	7	41°04'152	9°47'845	145	Mortorio canyon	MOc	16.8	canyon	+
12	7	41°04'200	9°48'224	140	Mortorio canyon	MOc	16.8	canyon	+
13	6	41°20'433	9°38'121	160	Caprera canyon	CAc	22.5	canyon	+
14	5	40°54'860	9°54'041	170	Tavola canyon	TAc	17.6	canyon	+
15	5	40°54'768	9°54'908	290	Tavolara canyon	TAc	17.6	canyon	+
16	8	40°47'340	9°51'615	460	Capo Coda Cavallo canyon	CCCc	1.4	canyon	-
17	1	40°17'544	9°40'252	215	Gonone outcrop	GOc	1.65	rocky outcrop	+
18	9	39°58'136	9°43'734	147	Arbatax canyon	ARc	3.7	canyon	+
19	9	39°58'080	9°43'770	180	Arbatax canyon	ARc	3.8	canyon	+
20	10	39°46'789	9°49'369	460	Corallo nero outcrop	CNs	12.9	rocky outcrop	+
21	11	39°03'646	9°32'946	190	Cavoli canyon	CVc	2.3	canyon	+
22	11	39°04'780	9°33'760	170	Cavoli canyon	CVc	2.4	canyon	+
23	12	38°52'843	9°16'413	210	Bancotto outcrop	BCp	25.3	rocky outcrop	-
24	13	38°42'527	8°54'642	420	Nora canyon	NOc	19	canyon	+
25	13	38°42'162	8°54'783	463	Nora canyon	NOc	19.4	canyon	+
26	14	38°35'773	8°30'301	330	Teulada outcrop	STp	33.3	rocky outcrop	+
27	15	38°44'425	8°29'025	140	Bancotto outcrop	BTp	19.5	rocky outcrop	+
28	16	38° 45’ 470	8°12’333	400	Buco through	BUh	29	trough	+
29	17	39°10'122	8°06'133	140	Secca outcrop	SEp	10.4	rocky outcrop	+

Table 2. Abundance, frequency (% of total items), and density (± standard error) of litter items along the upper Sardinian slope.

Category	N items	Frequency (%)	Density n m^{-2} (± S.E.)
Plastic items (A.1; A.2; A.5)	24	10.3	0.0036 ± 0.0015
Fishing Nets (A.6)	98	41.9	0.0058 ± 0.0013
Fishing Lines (A.7)	46	19.7	0.0026 ± 0.0009
Fishing Ropes (A.9)	38	16.2	0.0023 ± 0.0006
Metals (C)	13	5.6	0.0013 ± 0.0005
Glass (D)	15	6.4	0.0016 ± 0.0005

Table 3. Results of the PERMANOVA tests carried out to ascertain differences in the density and composition of benthic litter among regions and between the two habitats (i.e., canyons vs. 'others'); df = degrees of freedom, MS = mean square; Pseudo-F = permutational F; P(MC) = probability level with Monte Carlo tests. Multivariate test (composition of litter) has been carried out including in the analysis all litter items listed in Table 2. Significant p-values are reported in bold.

Density of litter items

Source	df	MS	Pseudo-F	P(MC)
Area	2	190.71	0.2384	0.893
Residual	14	799.95		
Total	16			

Source	df	MS	Pseudo-F	P(MC)
Habitat	1	1801.5	2.7632	0.1
Residual	15	651.95		
Total	16			

Composition of litter

Source	df	MS	Pseudo-F	P(MC)
Area	2	1422.1	1.0328	0.417
Residual	14	1376.9		
Total	16			

Source	df	MS	Pseudo-F	P(MC)
Habitat	1	5754.1	5.2739	**0.014**
Residual	15	1091.1		
Total	16			

Table 4. Results of the SIMPER analysis indicating the percentage of dissimilarity between canyons and other geomorphological settings explained by the different litter categories.

Contrast	Dissimilarity (%)	Litter category	Contribution (%)	Cumulative (%)
Canyon *vs.* Others	74.86	*Nets (A.6)*	34.05	34.05
		Other plastic (A.1,2,5)	20.75	54.80
		Lines (A.7)	14.73	69.53
		Glass (C)	11.39	80.92
		Ropes (A.9)	10.63	91.55

Table 5. Species and number of individuals encountered in contact with benthic litter along the Sardinian upper slope.

	n. of impacted ind.	%
Dendrophylla cornigera	8	7
Corallium rubrum	21	18
Eunicella cavolini	26	23
Callogorgia verticillata	10	9
Paramuricea clavata	8	7
Antipathella subpinnata	14	12
Antipathes dichotoma	2	2
Acanthogorgia hirsuta	1	1
Viminella flagellum	1	1
Parantipathes larix	7	6
Madrepora oculata	8	7
Leiopahtes glaberrima	8	7

Table 6. Density of benthic litter in different regions of the Mediterranean Sea. * = Abundance reported as linear measurement (items/100 m).

Region	Substrate	Depth (m)	Density (n. items 100 m^{-2})	Reference
South Tyrrhenian Sea	Rocky banks	30-300	2.0-16	Angiolillo et al., 2015
South Sardinian seas	Rocky banks	30-300	1.0-9	Angiolillo et al., 2015
Sicily	Rocky banks	30-300	0-30	Angiolillo et al., 2015
Adriatic Sea	Rocky banks	21-23	1.23-8.29	Melli et al., 2016
Ligurian Sea	Submarine canyon	180-700	0-1.2*	Fabri et al., 2014
Gulf of Lion	Submarine canyon	180-700	0-0.5*	Fabri et al., 2014
NW Mediterranean	Submarine canyon	40-1448	0.30–11.23*	Galgani et al., 1996
Sardinia	Submarine canyons	145-460	1.01.-3.06	*This study*
Sardinia	Others	140-460	0.38-3.88	*This study*

Figures' captions

Figure 1. Location of the sampling area and the ROV dives along the Sardinian upper slope.

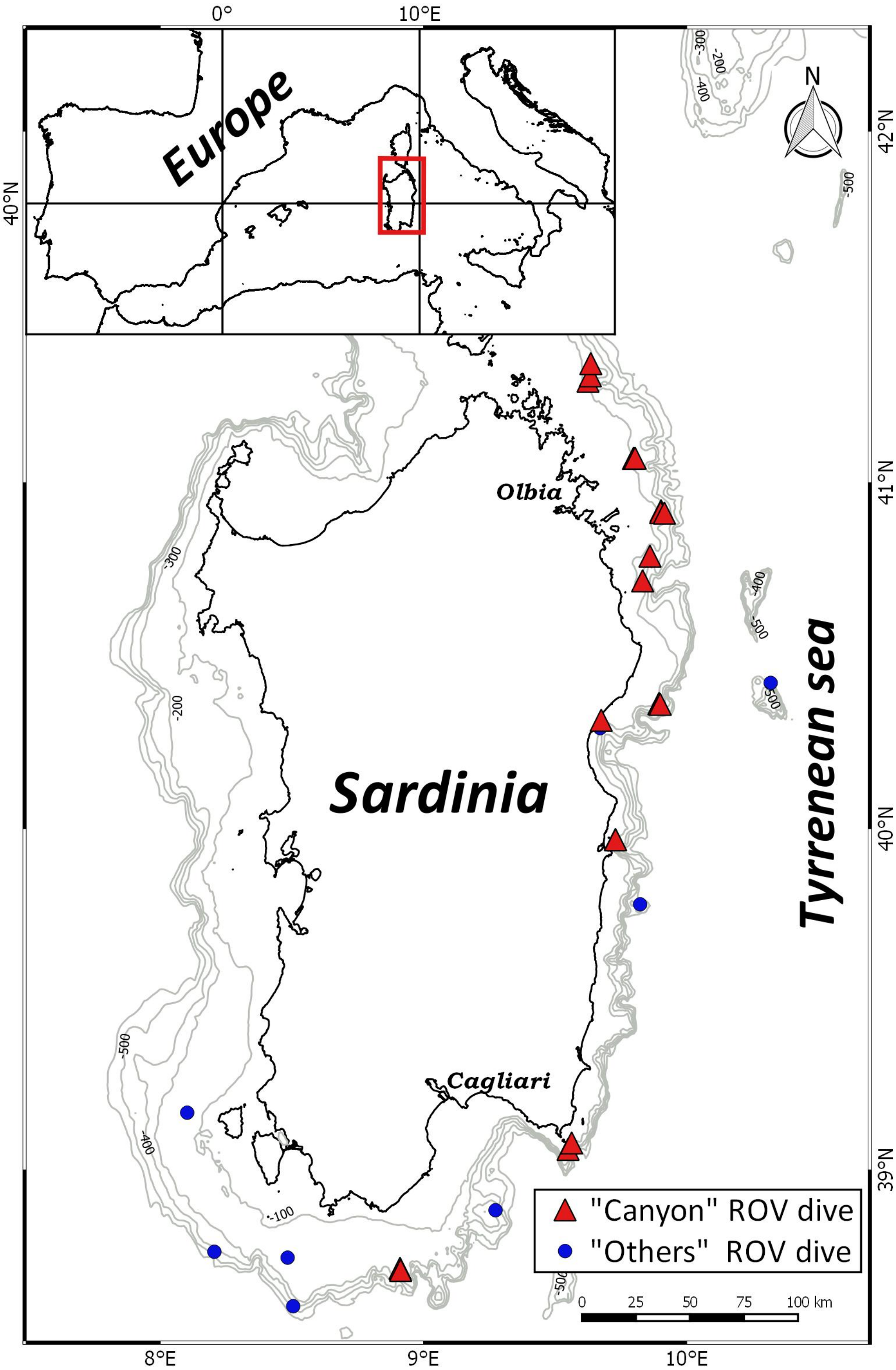
Figure 2. Variation of litter density with water depth (A) and distance from the nearset coastline (B) along the Sardinian upper slope.

Figure 3. Relative importance of categories of total litter (A), plastic litter (B) and derelict fishing gears (C) along the upper Sardinian slope.

Figure 4. Density of each category of benthic litter in canyons and other geomorphological settings along the Sardinian upper slope. Black dots represent outliers. The top and bottom lines of the rectangle are the 3rd and 1st quartiles, respectively. The line in the middle of the rectangle represents the median. The top whisker denotes the maximum value, while bottom whisker the minimum value.

Figure 5. Different typologies of interaction between benthic litter and fauna along the Sardinian upper slope: A) litter with no interaction with benthic fauna; B) fishing net trapped in coral branches and colonized by spiecement of *Filograna implexa*; C) plastic bags covering coral colonies; D) lost trammel net, ghost fishing a spiny lobster.

Figure 1



0°
10°E
40°N
Europe
42°N
41°N
40°N
39°N
N
Olbia
Sardinia
Tyrrenean sea
Cagliari
-300
-200
-400
-500
-100
"Canyon" ROV dive
"Others" ROV dive
0
25
50
75
100 km
8°E
9°E
10°E

Figure 2

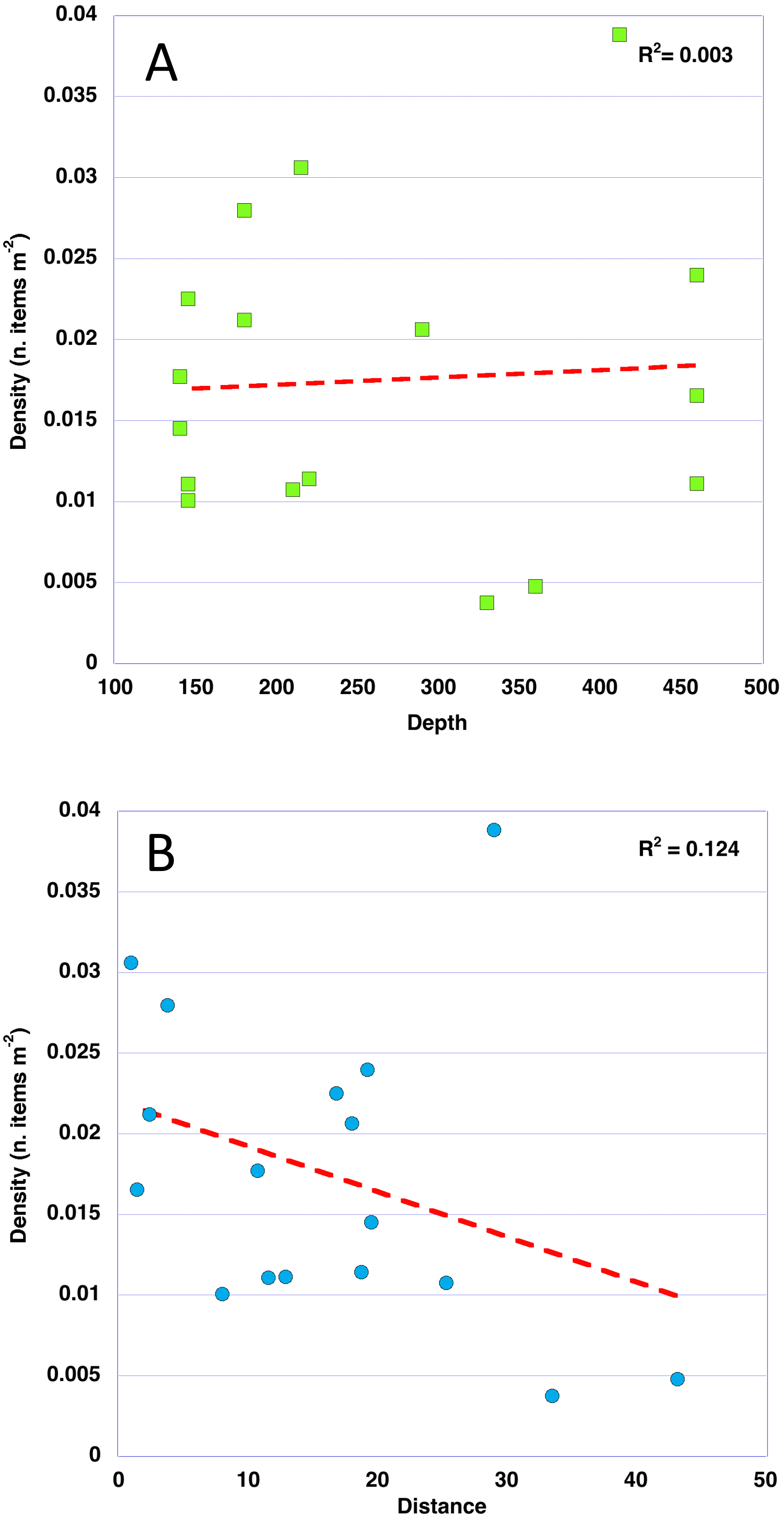

A
R^2= 0.003
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Density (n. items m^{-2})
100
150
200
250
300
350
400
450
500
Depth
B
R^2 = 0.124
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Density (n. items m^{-2})
0
10
20
30
40
50
Distance

Figure 3

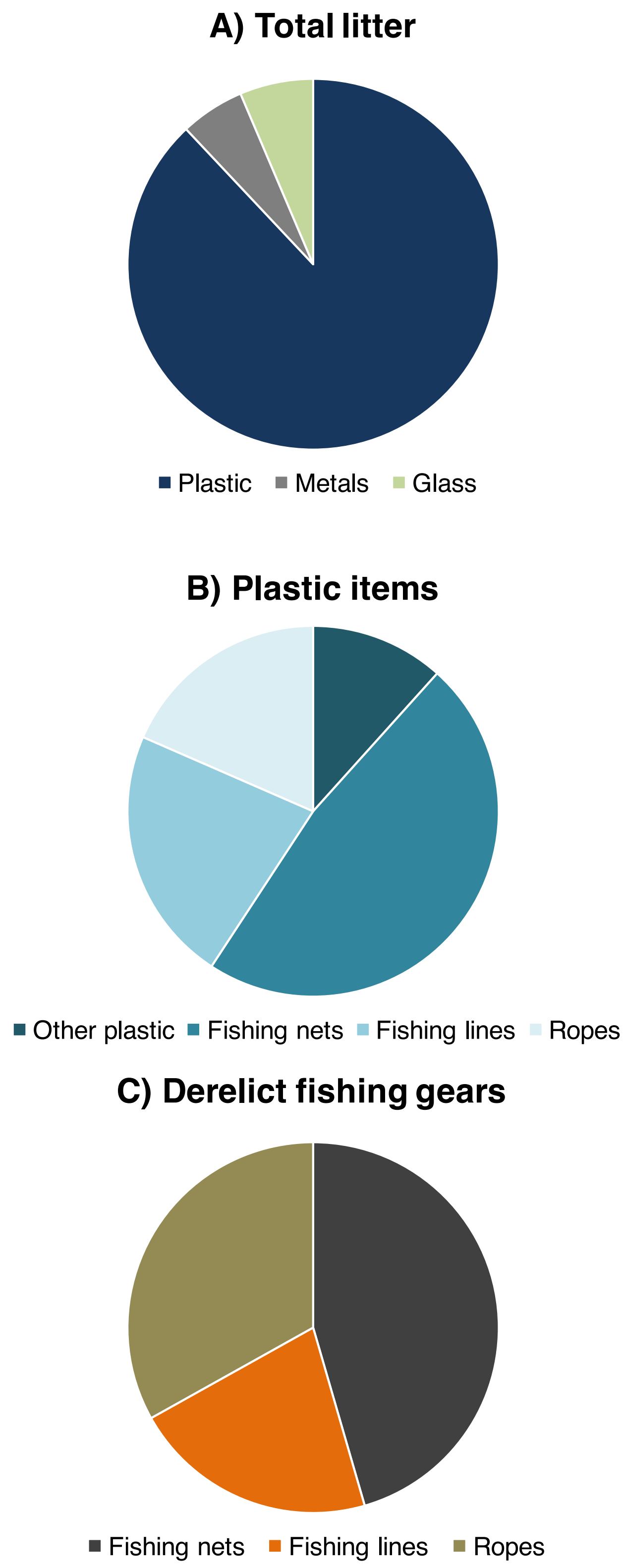

A) Total litter
Plastic
Metals
Glass
B) Plastic items
Other plastic
Fishing nets
Fishing lines
Ropes
C) Derelict fishing gears
Fishing nets
Fishing lines
Ropes

Figure 4

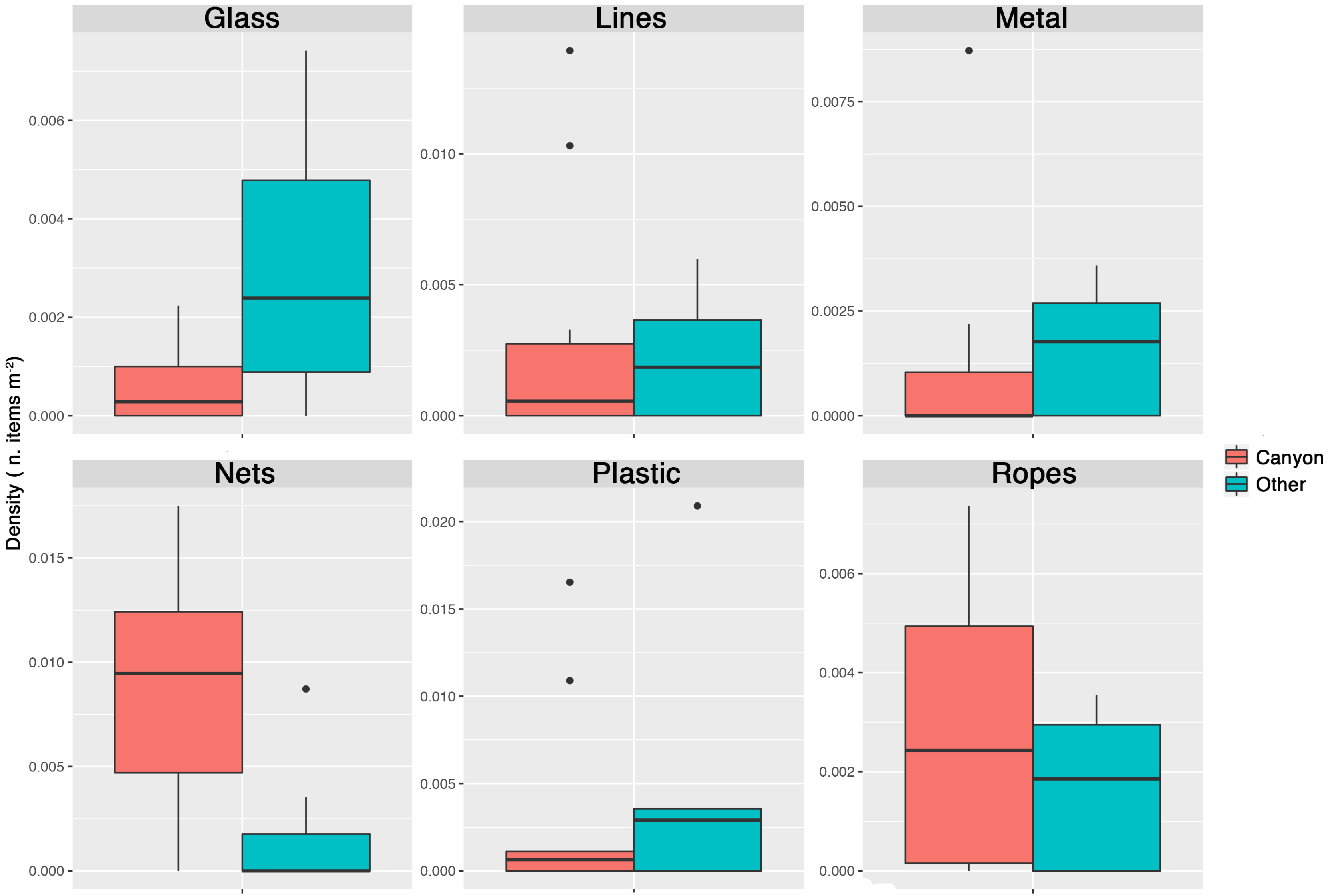

Glass
Lines
Metal
Nets
Plastic
Ropes
Density (n. items m-2)
0.000
0.002
0.004
0.006
0.005
0.010
0.0000
0.0025
0.0050
0.0075
0.015
0.020
Canyon
Other

Figure 5