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Seafloor litter from the continental shelf and canyons in French Mediterranean Water: Distribution, typologies and trends

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Abstract :

Seafloor litter has been studied both on the continental shelves (by trawling during 24 years) and in canyons (by ROV) of the French Mediterranean sea Water (FMW). On the continental shelf, mean densities range from 49.63 to 289.01 items/km2. The most abundant categories were plastic, glass/ceramics, metals and textiles. Trend analysis shows a significant increase in plastic quantities during the study period. Plastics accumulate at all depths, with heavier items being found in deeper areas, while the continental slope-break appears as a clean area. The spatial distribution of litter revealed the influence of geomorphologic factors, anthropic activities, shipping route, river inputs. All the canyons are affected by debris but coastal canyons (Ligurian Sea and Corsica) were more impacted than offshore canyons in the Gulf of Lion. The FMW appears to be highly polluted with regard to values found in other areas, but lower than those observed in the Eastern Mediterranean.

Highlights

► Time series of 23 years of seafloor litter data collected from bottom trawl surveys. ► Use of three years of litter data collected in canyons from Remotely Operated Vehicle. ► Marine litter assessment for the Gulf of Lion and eastern Corsica areas. ► analyses allowing the identification of hot spots and temporal trends. ► On the continental shelf, annual mean densities range from 49.63 to 289.01 items/km^2. ► The most common litter categories are plastics, glass/ceramic, metals and textiles.

Keywords : Marine litter, Seafloor, Canyon, Mediterranean Sea, Gulf of Lion, Corsica

Introduction

Marine litter is defined as "any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment" (Arcangeli et al., 2018; Galgani et al., 2013b). It is mainly due to anthropogenic activities and ends up in the ocean mainly because of mismanagement. Marine litter can be transported from land, via rivers, thunderstorms, wind and wastewater or can be thrown directly onto beaches and at sea (UNEP/GPA, 2011). Commercial and pleasure-boats, fishing activities, aquaculture, discharges into rivers, urban and industrial areas, legal and illegal shoreline dumps, the recreational use of the coast and harbors are known as important sources of marine litter (Sheavly and Register, 2007). Every year in the world, 8 million of tons of solid plastic debris are introduced into the marine ecosystem (Jambeck et al., 2015; UNEP/MAP, 2015; Villarrubia-Gómez et al., 2018), and their increasing amounts and low degradation rates lead to accumulation in the oceans where they cause a serious threat to the marine environment, human health and the economy (Barnes et al., 2009; Brouwer et al., 2017; Ioakeimidis et al., 2017; Ioakeimidis et al., 2014). Numerous studies have shown the diversity of harm inflicted, which includes in particular the strangling of organisms (Adimey et al., 2014; Anderson and Alford, 2014; Galgani et al., 2018), the ingestion of litter (Fossi et al., 2018; Galgani et al., 2014), the rafting of invasive species (Carlton et al., 2017), and the production of Persistent Organic Pollutants (POP) (Engler, 2012). The problem of marine litter is ubiquitous, concerns all sizes of litter, extending into environmental compartments ranging from shorelines to deeper areas (Thompson et al., 2009).

In Europe, the Marine Strategy Framework Directive (MSFD, 2008/56/EC) has led Member States to take the necessary measures to reduce the impacts of activities on the marine environment in order to achieve or maintain Good Environmental Status (GES) by 2020. The MSFD is based on the monitoring of 11 descriptors of the GES, of which Descriptor 10 corresponds to marine litter. Under the Barcelona Convention, the Mediterranean countries adopted a regional plan in 2013, including research and monitoring, with sea floor litter as an indicator.

Marine litter is found in the different compartments of the marine environment, on beaches, the sea surface (floating litter and microplastics (Palatinus et al., 2019) and on the seafloor and sediments (Renzi et al., 2019). Most of the studies focus on litter quantities, their spatial distribution and the analysis of their various types, providing information on sources that are either land- or ocean-based (*e.g.* commercial shipping, ferries, fishing vessels, offshore installations, aquaculture sites). The level of confidence in source identification can go as far as identifying source activity sectors such as fishing gear, sewage-related debris, sanitary debris and tourist litter (Galgani et al., 2015). Plastics usually account for the major part of marine litter because of their poor degradability and can represent up to 95% of the litter accumulated in the different parts of marine environment (Engler, 2012; Maes et al., 2018; Ryan et al., 2009). Debris from the fishing industry are prevalent in fishing areas (Schlining et al., 2013; Vieira et al., 2015) and may reach 100% in some fishing grounds (Pham et al., 2014).

The Mediterranean has been described as one of the areas most affected by marine debris (García-Rivera et al., 2017; UNEP/MAP, 2015). The issue of the quantities, natures and sources of seafloor litter remains complex since data remains limited (Ioakeimidis et al., 2017). Studies mainly concern the western and central Mediterranean, Adriatic and Ionian Seas (Consoli et al., 2018; Galgani et al., 1995; Galgani et al., 2000; Ioakeimidis et al., 2014; Melli et al., 2017; Palatinus et al., 2019; Pasquini et al., 2016; Pham et al., 2014; Ramirez-Llodra et al., 2013; Strafella et al., 2015; Vlachogianni et al., 2018) with only a few studies available for the eastern Mediterranean (Ioakeimidis et al., 2014; Pham et al., 2014; Tunca Olguner et al., 2018). Moreover, these studies were all conducted over short periods of time as part of research projects and there is no report on long-term monitoring programs.

Finally, because of the resources required, studies conducted in the deep sea are scarcer (Fabri et al., 2014; Tubau et al., 2015). These different studies indicate that many factors such as hydrodynamic and geomorphologic conditions, the proximity of sources (harbours, rivers, industrial zones), shipping lanes, sedimentation areas and zones of convergence influence their distribution. Debris densities show high variability and the highest quantities (hot spot) are mainly located near large cities, river mouths, and in coastal canyons where currents are slower and heavy sedimentation occurs.

The aim of this paper is to better understand pollution by macro litter on the sea floor in the French Mediterranean Sea and assess temporal trends. It is based on the analysis of data from *(i)* a 24-year series of data collected by trawling on continental shelves (1994-2017), and *(ii)* observations from 201 dives by Remotely Operated Vehicles (ROV) located in canyons, between 800 and 150 m depth (the different dives were carried out between November 2008 and August 2010). This study focuses on the densities, weight and nature of marine debris and their spatial and temporal variability.

II . Material and method

II.1 *Study area: French Mediterranean Waters (FMW) [Gulf of Lion (GoL) and Corsica Island (CI)]*

The French Mediterranean Waters (FMW) are located in the northwestern basin and include two particular areas, first the Gulf of Lion (GoL) and second the Corsica Island (CI). For the continental shelf, the study was performed in the totality of GoL and the eastern part of CI (Figure 1).

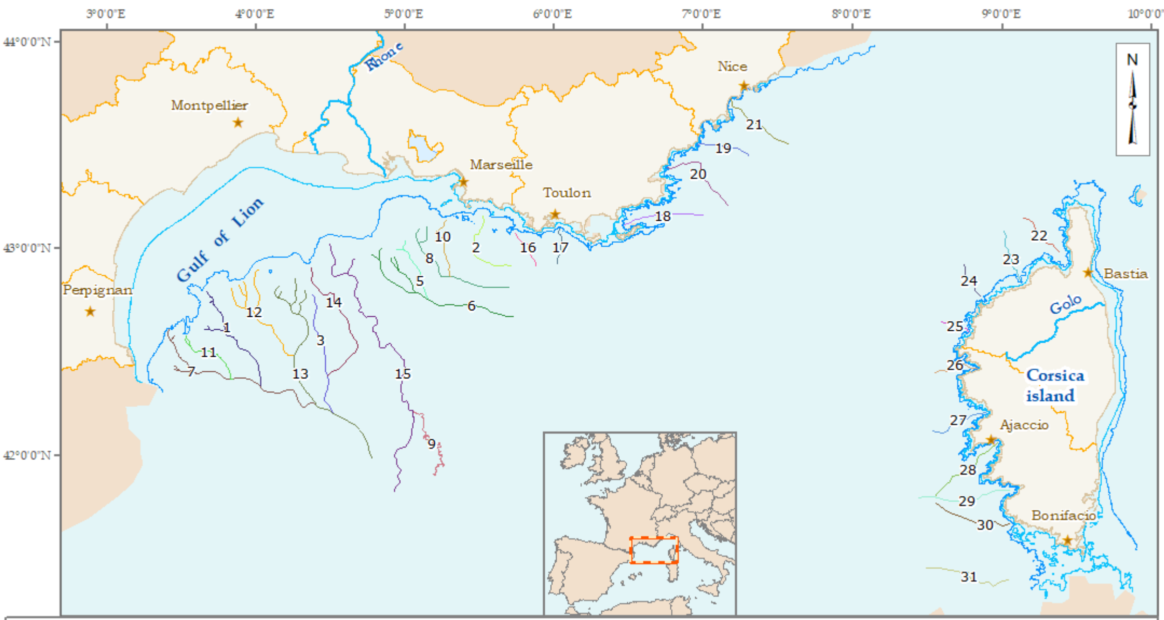
Much of the Mediterranean coast has deep-water bottoms near the shore and the continental shelves are narrow, except close to the outlets of the Rhone river (GoL). They are incised by numerous submarine canyons that are more closely spaced, more dentritic, shorter and steeper than canyons found in other regions of the world (Fabri et al., 2014). Their number is however limited on the eastern part of Corsica with limited depths in the Corsican channel.

The western current circulation of marine litter in the Mediterranean Sea has been documented (Liubartseva et al., 2018; Ourmieres et al., 2018). The currents are mainly oriented from east to west and have an anti-cyclonic circulation. In the northwestern part, the currents ascend the west coasts of Italy in the Tyrrhenian Sea and, after passing through the Corsica channel, run along the Italian and French coasts.

In the GoL, the convergence of two currents (Eastern Corsican Current - ECC - and Western Corsican Current - WCC) generates the Liguro-Provencal Current which runs from east to west with high seasonal variability and possible anti-cyclonic eddies at the limits of the continental slope (Rubio et al., 2009). Anti-cyclonic circulation schemes also occur in both the northern and western parts of the

GoL (Hu et al., 2011). The mouth of the Rhône river in the GoL also drives circulation and brings debris into the sea. The GoL's continental shelf is particularly wide, reaching lengths of up to 72 km. Its shelf break is well defined at 100-200 m depth with a complex network of adjacent submarine canyons. Due to differences in shelf width along the continental margin, some of these canyons can be found relatively close to the shore (*e.g.* Cap de Creus canyon), while others appear relatively far offshore [Grand and Petit-Rhône canyons (UNEP-MAP-RAC/SPA, 2013)]. The GoL is an area subject to strong anthropogenic impact (Micheli et al., 2013), with the presence of numerous activities: industries, tourism, harbours, fisheries, aquaculture, maritime traffic and large cities, including the city of Marseille (France's second largest city) which has a commercial port, an industrial zone and strong seasonal touristic activity.

Around Corsica, two currents are identified: the East Corsica Current and West Corsican Current (Millot and Taupier-Letage, 2005). The eastern coast of Corsica is under the influence of Tyrrhenian sea current, which runs along the Italian coast and passes through the Corsica channel. Off the coast of the town of Bastia, the presence of eddies divides the current into two branches, the first oriented northward and the second oriented southward (Faure et al., 2012; Gerigny, 2012). On the west coast, the current flows northward, merging with the eastern current at Cape Corsica to generate the Ligurian current.



Canyon name

Name	Num	Name	Num	Name	Num	Name	Num	Name	Num
Bourcart	1	Marseille	8	Montpellier	14	Saint-Tropez	20	Porto	26
Cassidaigne	2	Petit Rhône	9	Petit Rhône	15	Var	21	Sagone	27
Catherine Laurence	3	Planier	10	La Ciotat	16	Saint Florent	22	Ajaccio	28
Estaque	5	Pruvost	11	Toulon	17	Ile Rousse	23	Valincu	29
Grand Rhône	6	Marti	12	Stoechades	18	Calvi	24	Des Moines	30
Lacaze-Duthiers	7	Sète	13	Cannes	19	Galéria	25	Castelsardo	31

Figure 1: Map of French Waters in the Mediterranean Sea with the localization of the Gulf of Lion (GoL), Corsica Island (CI), canyons and main rivers.

II.2 Sampling cruises: MEDITS program

Seafloor litter data were collected from annual bottom trawl surveys performed in May-July since 1994 over the continental shelf (10 m to 200 m depth) and the continental slope (200 to 800 m) of the Mediterranean Sea as part of the MEDiterranean International Trawl Survey (MEDITS) scientific program. This project is dedicated to the evaluation of fishery resources, using a standardized common protocol (Bertrand et al., 2002a; Bertrand et al., 2002b; MEDITS Working Group, 2017). The data used in this paper (partly published in separate reviews for the years 1994-1997, 2009 and 2014) were acquired from 1994 to 2017, without a survey in 2007, using bottom trawls with otter boards, and the same net with a 20 mm mesh in the codend. The duration of the tows was standardized to 3 knots and 30 min for shelf stations, and 60 min for the continental slope [see Bertrand et al. (2002b) for full details].

In France, the MEDITS cruises cover the GoL and Eastern Corsica, with 65 and 23 stations respectively. The samples are taken from the bottom from 10 to 800 m depth, divided into five depth strata (*i.e.* 10-50 m, 51-100 m, 101-200 m, 201-500 m and 501-800 m). This horizontal and vertical sampling stratification method of the area makes it possible to optimize the sampling and obtain a wide distribution of the samples both at the spatial level and at depth.

Before 2014, a specific protocol for marine litter derived from the MEDITS standardized protocol for trawling (Bertrand et al., 2002a) was used and distinguished 7 different litter categories. Since 2014, a new specific protocol for marine debris (Fiorentino et al., 2013) has been used following MSFD recommendations (Galgani et al., 2013b).This protocol now identifies 34 different typologies included in 9 main categories related to litter material and 25 sub-categories related to sources. For long term analysis, in order to not create bias due to protocol change, each litter was associated with a specific "category" of marine litter (plastic, glass and ceramics, metal, clothes (textile) and natural fiber, unspecified, paper and cardboard, various, recycled wood and sanitary litter). Typologies are only looked at for short-term analysis. On board, the seafloor debris are counted, weighed (only since 2013) and their typologies identified. The general characteristics of the haul are also recorded (*e.g.* haul code, date, geographic coordinates, depth zone, trawled length, opening of the trawl) and of the standardized density indices (and surface mass indices) are then calculated for total litter and by category, dividing the number of items collected by the surface of trawled area:

$$D_t = \frac{N_t}{L_t \times O_t}$$

with:

- D_t = litter density in items/km² for the trawl t,
- N_t = litter number counted in the trawl t,
- L_t = trawled length in km recorded for trawl t,
- O_t = opening of the trawl in km recorded for trawl t.

II.3 Remotely Operated Vehicle (ROV) data: MEDSEACAN and CORSEACAN cruises

The canyon heads were explored during the MEDSEACAN and CORSEACAN campaigns (Fourt et al., 2013), between November 2008 and August 2010 (http://cartographie.aires-marines.fr/?q=node/47), using 'Super Achille' ROV from Comex (www.comex.com). The MEDSEACAN campaign was conducted in seventeen French canyons of the Mediterranean Sea located near the continental slope and the open slope between the Toulon and Stoechades canyons, through 101 dives. The CORSEACAN campaign was conducted in thirteen canyons located on the western part of CI, through an additional 100 dives. Details of the two campaigns are given in Fabri et al. (2014); Goujard and Fourt (2014). The submersible was used to collect underwater images. On each image, the individual debris were identified, categorized and georeferenced. Marine litter was classified in various types: plastic, fishing gear, metal, glass and ceramic, and "other" when unsure about the type. The total sum of litter, as well as types, was calculated for all the dives carried out in each canyon and the results were normalized to a linear distance of one kilometer. To ensure comparability, only dives below 150 m were selected. Part of the data collected in the submarine region between Toulon canyon and Stoechades canyon was studied at depths under 180 m by Fabri et al. (2014) and includes data from the continental shelf deeper than 150 m for the present study.

II.4 Data base summary

Table 1 summarizes, for each region and each dataset, the type of data, data standardisation, the years available in the dataset and the classification used for marine litter For data on continental shelf and slope from trawling activities, FMW data correspond to the combination of GoL and CI data. Concerning the canyon data, they take into account the canyons of the GoL, the Ligurian Sea and the eastern part of Corsica. No trawling data are available in the French Ligurian Sea because of the continental shelf is almost nonexistent at this location. The merger of trawl and ROV data was not possible because they have different measure unit and as a result they have been treated separately.

Table 1: data base and processing data summary

Region	Sampling method	Localisation	Deep location	Data	Data standardization	Unit	Time period	Missing years	Number of years	Protocol used for classification of marine litter	
										until 2014	after 2014
FMW	trawling	GoL + eastern CI	continental shelf and slope	Number and weight of litter	normalized to a distance of one square kilometer	item(s)/km² and Kg/km²	1994-2017	2007	23	7 marine litter categories (Bertrand et al., 2002a)	9 marine litter categories (Galgani et al., 2013b)
	ROV	GoL + Ligurian + Western CI	canyon / continental slope	number of litter	normalized to a linear distance of one kilometer	item(s)/km	2008-2010	-	-	7 marine litter categories (Bertrand et al., 2002a)	
GoL	trawling	GoL	continental shelf and slope	Number and weight of litter	normalized to a distance of one square kilometer	item(s)/km² and Kg/km²	1994-2017	2007	23	7 marine litter categories (Bertrand et al., 2002a)	9 marine litter categories (Galgani et al., 2013b)
	ROV		canyon / continental slope	number of litter	normalized to a linear distance of one kilometer	item(s)/km	2008-2010	-	-	7 marine litter categories (Bertrand et al., 2002a)	
CI	trawling	Eastern coast	continental shelf and slope	Number and weight of litter	normalized to a distance of one square kilometer	item(s)/km² and Kg/km²	1995-2017	1998 / 2002 /2007	20	7 marine litter categories (Bertrand et al., 2002a)	9 marine litter categories (Galgani et al., 2013b)
	ROV	Western Coast	canyon / continental slope	number of litter	normalized to a linear distance of one kilometer	item(s)/km	2010	-	-	7 marine litter categories (Bertrand et al., 2002a)	
Ligurian Sea	No trawling data available in this area because the continental shelf is almost nonexistent										
	ROV	French part of Ligurian Sea	canyon / continental slope	number of litter	normalized to a linear distance of one kilometer	item(s)/km	2010	-	-	7 marine litter categories (Bertrand et al., 2002a)	

II.5 Statistical processing

The MEDITS data set was analyzed for trends, focusing on total debris, plastics and fishing gear. Since the data are not distributed according to a normal distribution, the non-parametric Mann-Kendall test (based on ranks rather than values) was used. The Kendall correlation coefficient was calculated from the density data of the whole dataset, in order to evaluate the presence of a trend over the 24 years. The direction of the trend was then determined by the sign of the correlation coefficient. As this test only detects monotonic trends, it was also applied over rolling six-year periods, in order to detect shorter trends in the time series. The calculation was carried out with the software R© (V3.2.5) with the Kendall function of the "Kendall" (V2.2) package.

II.6 Identification of accumulation areas considered as priority areas

In order to obtain a summary of litter spatial distribution over the large set of data and help locate areas with a high concentration of debris, the study area was delimited by cells of three square-nautical miles and a weighted average of densities was calculated in each cell, relying in part on the method performed by García-Rivera et al. (2017). The choice of cell size was considered as a good balance between the resolution of the data and the size of the study area. First, the track of each haul was defined by the start and end coordinates of the haul, then cut into segments when the haul overlapped several cells. The standardized marine litter density of the haul was assigned to each segment. As cells may be crossed by several hauls, the weighted means of marine debris densities were calculated using the length of the segments included in the cell as weighting factor:

$$\bar{d}_c = \frac{\left(\left(l_{c,1} * D_1\right) + \left(l_{c,2} * D_2\right) + \ldots + \left(l_{c,n} * D_n\right)\right)}{\sum_{t=1}^{n} l_{c,t}}$$

where:

- $\bar{d}_c$ = weighted mean of marine debris density in items/km²in cell *c*,
- $l_{c,t}$ = length in km of trawl *t* segment in cell *c*,
- D_t = litter density in items/km² for the trawl *t*,
- *n* = total number of trawls.

III. Results

III.1 Litter quantities and trends on the continental shelf

In FMW (including GoL and CI data), marine litter is widely distributed and was found in 87% of the 1 892 trawling tows. The mean densities of litter, calculated for each year (Figure 2), ranged from 49.63 items/km² (standard deviation = 48.61 items/km²) in 2009, with 95% of values less than 137.52 items/km², to 289.01 items/km² (std dev = 298.16 items/km²) in 2015, with 95% of values less than 866.09 items/km². On average, plastic (except those from fishing) and fishing object densities represent 71% and 5% of total litter, respectively. The mean densities of litter, calculated for each year, ranged from 34.57 items/km² (std dev = 73.22 items/km²) in 2005 to 250.62 items/km² (std dev = 273.90 items/km²) in 2015 for plastics and from 0.27 items/km² (std dev = 1.86 items/km²) in 2009 to 28.29 items/km² (std dev = 74.13 items/km²) in 2014 for fishing related items. Between 2013 and 2017, the period during which weight data were available, the average of total litter mass per km² varied between 9.18 kg/km² (std dev = 18.95 kg/km²) in 2016 and 1 942.42 kg/km² (std dev = 17 972.58 kg/km²) in 2013, with extreme values found in different periods than for densities. The Mann-Kendall test showed a significant increase in the densities of total litter, plastic litter and fishing gears over twenty four years ($p<0.001$). Globally, for the three litter categories tested, the results for a six-year period (Table 1, supplementary materials) and for the densities (Figure 2) indicate the presence of a slight increase at the end of the 1990s, followed by a period of significant decrease at the beginning of the 2000s and ending with a greater increase, both in duration and in amplitude, from 2008 and at least until the mid-2010s.

In the GoL, marine litter was found in 85% of the 1 447 trawls with the mean densities of litter, calculated for each year, ranging from 29.32 items/km² (std dev = 30.08 items/km²) in 2005, with 95% of the values lower than 80.97 items/km², to 228.59 items/km² (std dev = 202 items/km²) in 2015, with 95% of values lower than 590.15 items/km². On average, plastic (except those from fishing) and fishing object densities represented respectively 73% and 6% of total litter. The mean densities of plastic, calculated for each years, varied respectively from 19.42 items/km² (std dev = 18.36 items/km²) in 2005 to 199.43 items/km² (std dev = 180.40 items/km²) in 2015 for plastics and from 0 item/km² (std dev = 0 item/km²) in 2009 to 33.39 items/km² (std dev = 85.11 items/km²) in 2014 for fishing-related litter. The average total litter mass per km² varied between 5.92 kg/km² (std dev = 13.48 kg/km²) in 2016 and 22.40 kg/km² (std dev = 128.14 kg/km²) in 2017, with extreme values observed at different periods than for densities. As for FMW, statistical analysis showed a significant increase for the three categories (total litter, plastic litter and fishing gears) over twenty four years ($p<0.001$). The same trends over rolling six-year periods appeared in the GoL, except for the first increasing trend (Figure 2, results of statistical analyses not shown) and the decreasing trend for fishing-related litter.

In Corsica, marine litter was found in 93% of the 445 trawls, with the mean densities of litter, calculated for each year, ranging from 77.01 items/km² (std dev = 81.55 items/km²) in 2010, with 95% of values lower than 266.94 items/km², to 459.75 items/km² (std dev = 437.70 items/km²) in 2015, with 95% of values lower than 1 043.11 items/km². On average, plastic and fishing object densities represented 68% and 4% of total litter, respectively. The annual mean densities varied from 34.12 items/km² (std dev = 50.50 items/km²) in 1995 to 395.29 items/km² (std dev = 415.18 items/km²) in 2015 for plastics and from 1.02 items/km² (std dev = 3.55 items/km²) in 2009 to 38.09 items/km² (std dev = 67.6 items/km²) in 2016 for fishing-related litter. The average total litter mass per km² varied between 17.69 kg/km² (std dev = 26.22 kg/km²) in 2014 and 7 069.21 kg/km² (std dev = 34 410.61 kg/km²) in 2013, with extreme values in periods different than for densities. Globally, the statistical trend analysis shows the same results as for FMW. However, an interruption of the growth period was observed at the end of the time series (Figure 2 - results of statistical analysis not shown).

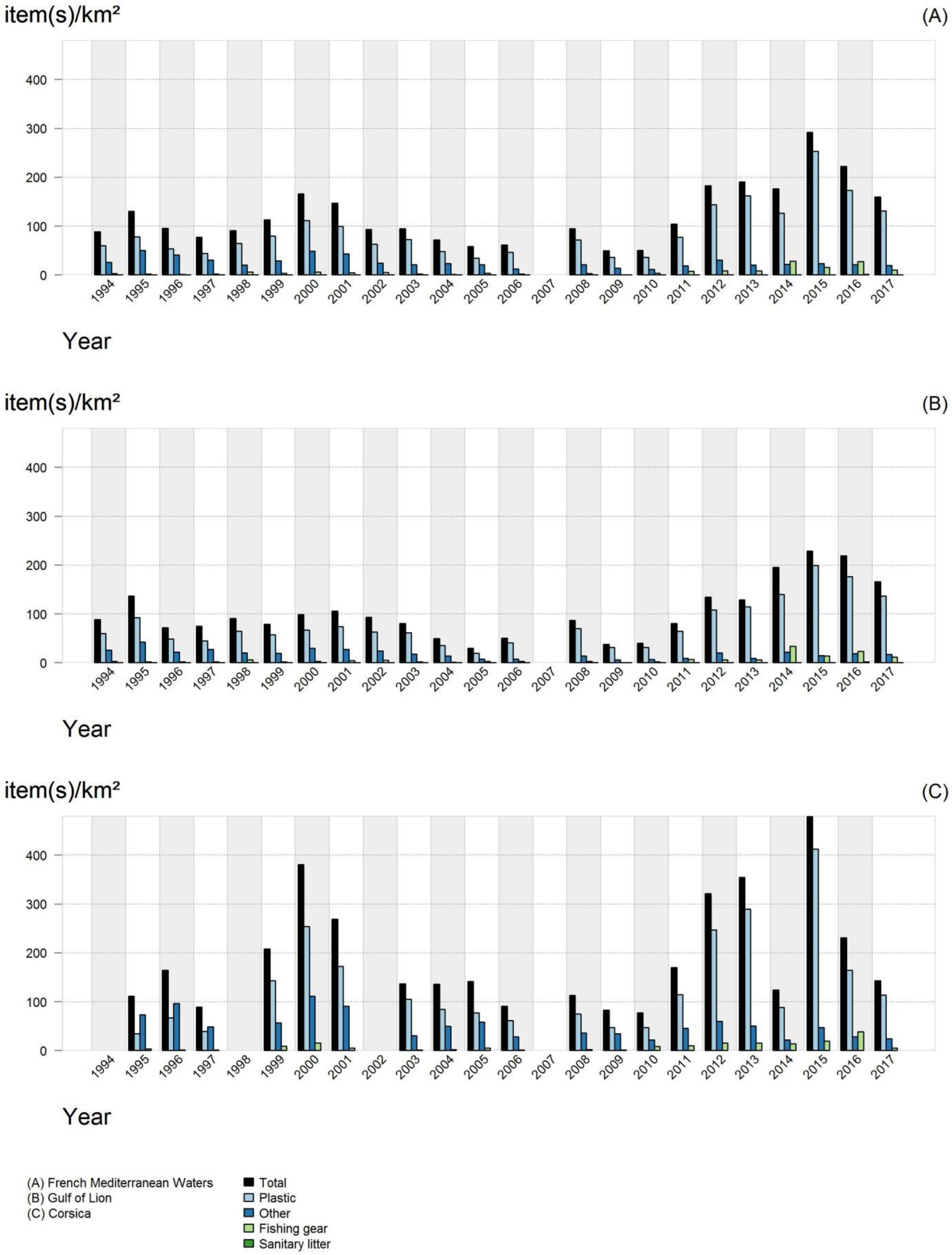


Figure 2: Annual mean densities of litter, expressed in items/km², from 1994 to 2017, for the French Water of the Mediterranean Sea data set (A), for the Gulf of Lion (B) and for the Corsica Island (C).

III.2 Litter composition on the continental shelf and slope

Globally, plastics represented at least 40% of the total marine litter densities in CI and at least 62% in the GoL (Figure 3). After plastic, the most common marine litter categories were ranked as glass/ceramics, metals and textiles (clothing and natural fibers). Detailed analysis of litter types was only possible after the implementation of the MSFD and its associated monitoring program, in 2013, in which more detailed categories of litter were measured. A comparison between 2013 and 2017 (Figure 4) shows that unspecified litter decreased over time, due to a better definition of litter types by operators. Thereafter, for each category of litter, the main conclusions about litter typologies are first given at the FMW scale, then the difference of litter composition are explained at GoL and CI scales.

Plastic litter is mainly composed of plastic bags, food packaging, synthetic ropes and strapping, plastic objects from fishing activities (nets and lines), sheets (*e.g.* tablecloth) and plastic bottles. Plastic bag quantities decreased between the two years for the GoL, unlike the CI where the values in 2017 were higher. However, the inter-annual variability (results not shown) was too high for this to be a sign of a real trend. In the GoL, the quantities of food packaging increased (Figure 4- B), while in Corsica the absence of data in 2017 did not allow making such an observation. Fishing activities generate plastic litter such as fishing nets, fishing lines and other fishing objects (*e.g.* hooks, floats). In CI, the amounts of fishing debris were stable until 2015, but variations were observed in 2016 (doubled amount) and 2017 (less than 5 items/km^2), while in the GoL no clear trend appeared. Plastic bottles decreased for both areas, and globally in CI the quantities were higher than in the GoL.

Glass debris are mainly bottles. For the GoL, pieces of glass and ceramic pots were also present. The quantities of glass bottles in CI were between four and seven times higher than in the GoL.

The metals mainly consisted of food or drink cans and packaging, large objects (*e.g.*barrel, piece of machinery, electronic device) and medium objects (*e.g.*paint bucket, oil pot, chemical jar) and hawsers. Overall, cans were more abundant in CI than in the GoL, except in 2016 where the quantities were identical. The quantities of cans decreased in CI. Large metallic objects were present in the GoL but on an occasional basis. Fishing litter was only present in 2015 and 2017 for the GoL.

Textiles essentially consisted of clothes, natural ropes, sanitary objects (*e.g.* diapers, cotton swabs) and large items such as carpets and mattresses. In the GoL, quantities of natural ropes and clothes are high in 2017. On the other hand, the quantities of sanitary items decreased. In CI, quantities of clothes were highly variable, with a difference of more than half between the two years studied. Big items and natural ropes were not observed every year. Sanitary litter was mainly hygienic litter such as sanitary protection and diapers. Rubbers were mainly tires and the quantities increased between the two years compared. The quantities of tires were higher in CI than in the GoL. In this category, the "other" typology was also important and may be composed of objects such as inner tubes, shoe insoles and flip-flops.

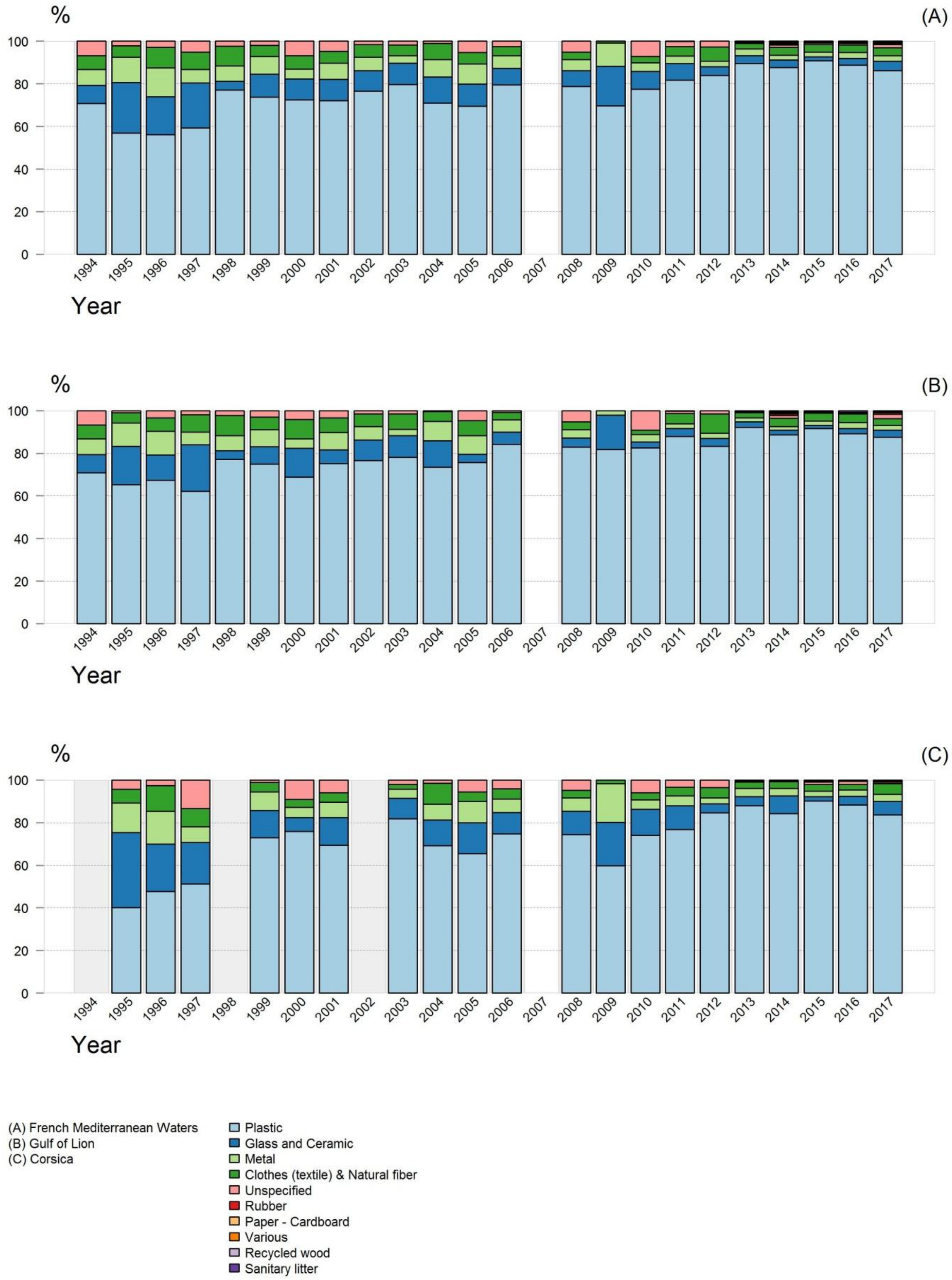


Figure 3: Percentages of annual average densities of seafloor litter by category for (A) French Water Mediterranean Sea, (B) Gulf of Lion and (C) Corsica Island.

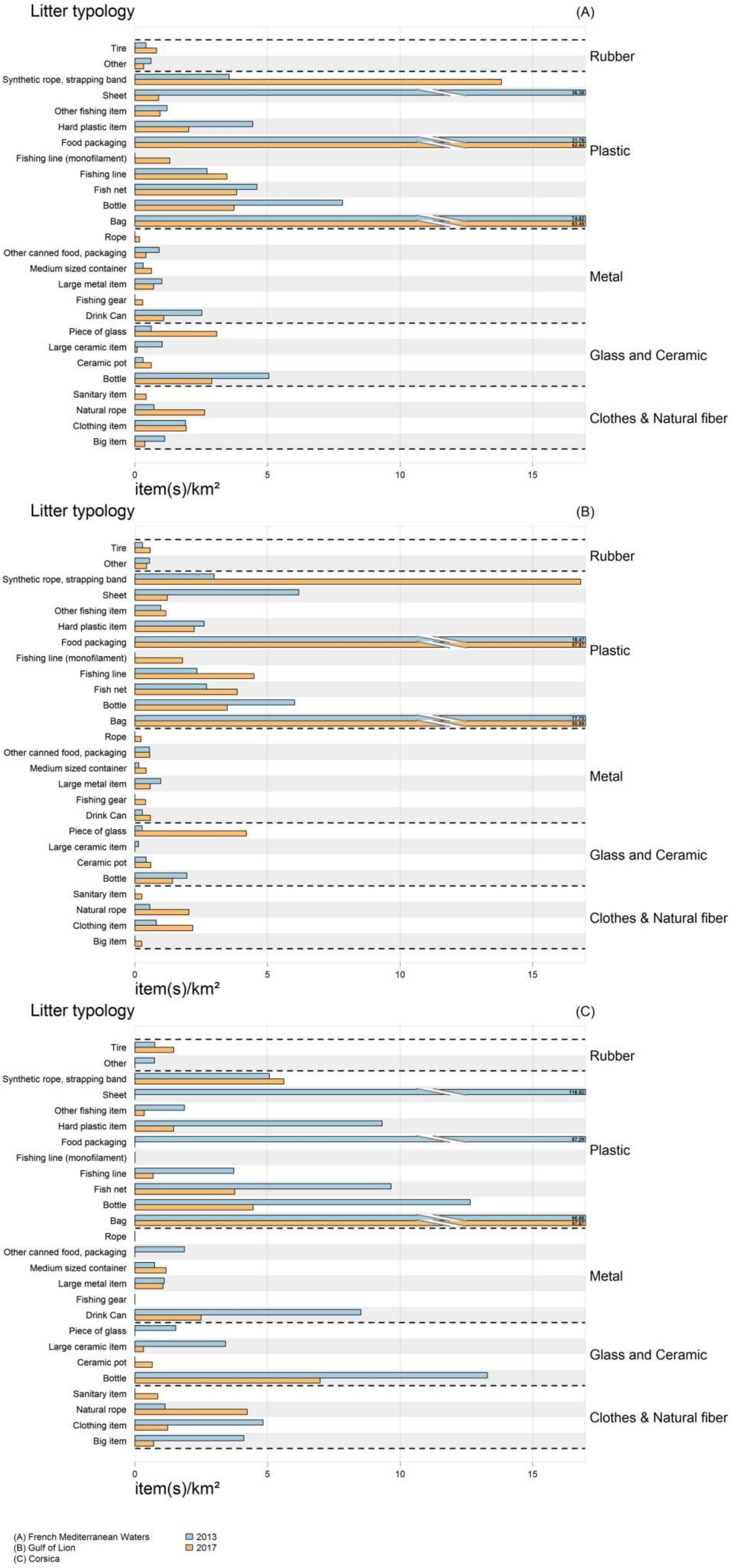


Figure 4: Categories and typologies of marine litter in item(s)/km² found in 2013 and 2017 in FMW, GoL and CI.

III.3 - Marine litter categories vs depth on the continental shelf

For all depths and for the two areas studied, plastic was the largest category of litter, except between 100 and 200 m depth in CI where glass exceeded plastic. With regards to weight, the importance of the different types of litter was more variable, with an absence of debris between 150 and 200 m in the GoL and 200 and 250 m in CI.

In the GoL, glass, metal, plastic and fishing litter densities were mostly accumulated at similar depths. These debris were mainly found in the continental shelf (*i.e.* between 0 and 150 m depth) and from 300 m depth on the continental slope. Glass and metals, more dense, mainly accumulated deeper than 700 m. Regarding weight, heavy plastic items were more present along the coast, between 0 and 50 m depth, and between 400 and 600 m depth on the continental slope. Heavy fishing litter items also accumulated along the coast and on the continental slope between 450 and 500 m depth and deeper between 800 and 850 m depth. Heavy glass items were found between 200 and 300 m depth and also at greater depths, from 800 m. Finally, heavy metal items were mainly found between 600 and 650 m depth. Clothes debris (data not shown) were present at all depths, with the highest weight percentages located between 50 and 100 m.

In CI, a positive correlation was found between glass density and surface mass. Glass accumulated on the mid-continental shelf, between 50 and 150 m depth, and on the continental slope between 300 and 500 m depth. Metal density and surface mass were negatively correlated. Heavy metal items mainly accumulated between 250 and 300 m depth on the continental slope and less significantly between 450 and 500 m depth. Fishing-related litter densities and masses were also negatively correlated with heavy fishing litter found between 150 and 200 m depth. Clothes (data not shown) were mainly located between 150 and 350 m.

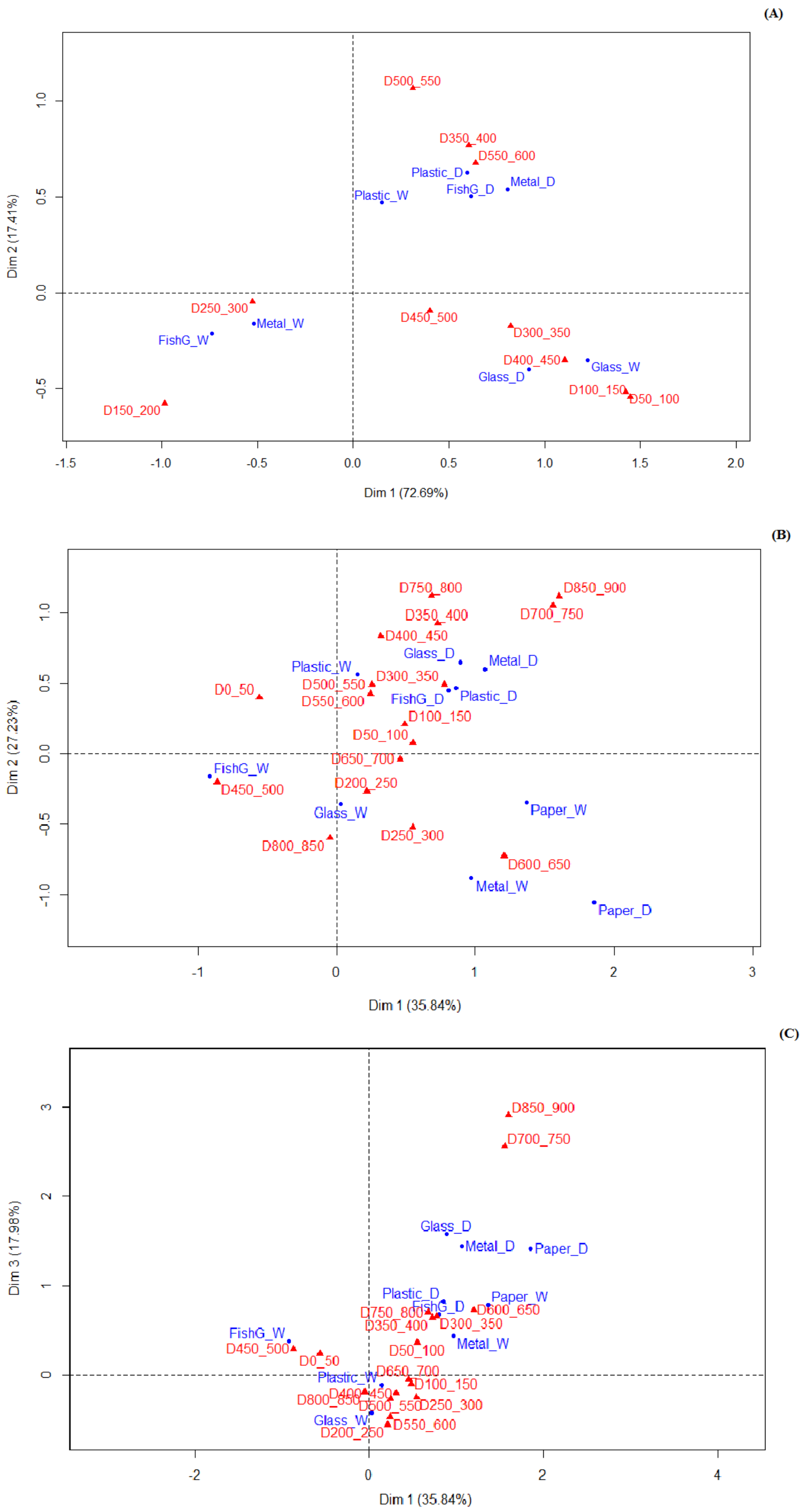


Figure 5: Correspondence Analysis between depths and densities (D) and Weights (W) of the main litter categories (fishG = fishing gear) in CI (A, axes 1 and 2 = 90% of the total variance) , GoL (B and C, axes 1, 2 and 3 = 81% of the total variance)

III.4 - Spatiotemporal variability of marine litter on the continental shelf

The spatial estimation of the marine debris pollution level was calculated from the weighted average of densities and the results were divided into three pollution levels (*i.e.* low, medium and high), each representing around 33% of the meshes (Figure 6). For the GoL, 40% of the meshes were classified as low pollution, 36% as medium pollution and 23% as high pollution. Only three meshes did not include debris and five "sensitive areas" were identified (high or medium pollution). Two areas were located in the western part of the GoL: the first located northwest of the GoL facing Leucate and the second north of the Spanish border between Perpignan and Collioure. The third area was present at the end of the continental slope, in the canyon heads of Marti and its proximity (Bourcart and Sète canyons). The fourth was located in the head of Petit-Rhône canyon. Finally, an accumulation area was identified offshore of Marseille on the continental shelf and in Marseille and Planier canyon heads. The center of the GoL continental shelf and the coastline were relatively unaffected, with the exception of a few meshes classified as high pollution.

In Corsica, 13% of the meshes were classified as low pollution, 25% as medium pollution and 62% as high pollution. The high pollution level represented more than half of all the CI meshes, indicating that eastern Corsica is subject to a strong pressure on the sea floor and that the CI is more impacted than the GoL. The accumulation areas were located in the northern and middle-North parts of the island, with pressure decreasing in the south. The least impacted areas were located above Aleria city and at the southern part of the eastern Corsican coast (between Porto-Vecchio until the strait of Bonifacio).

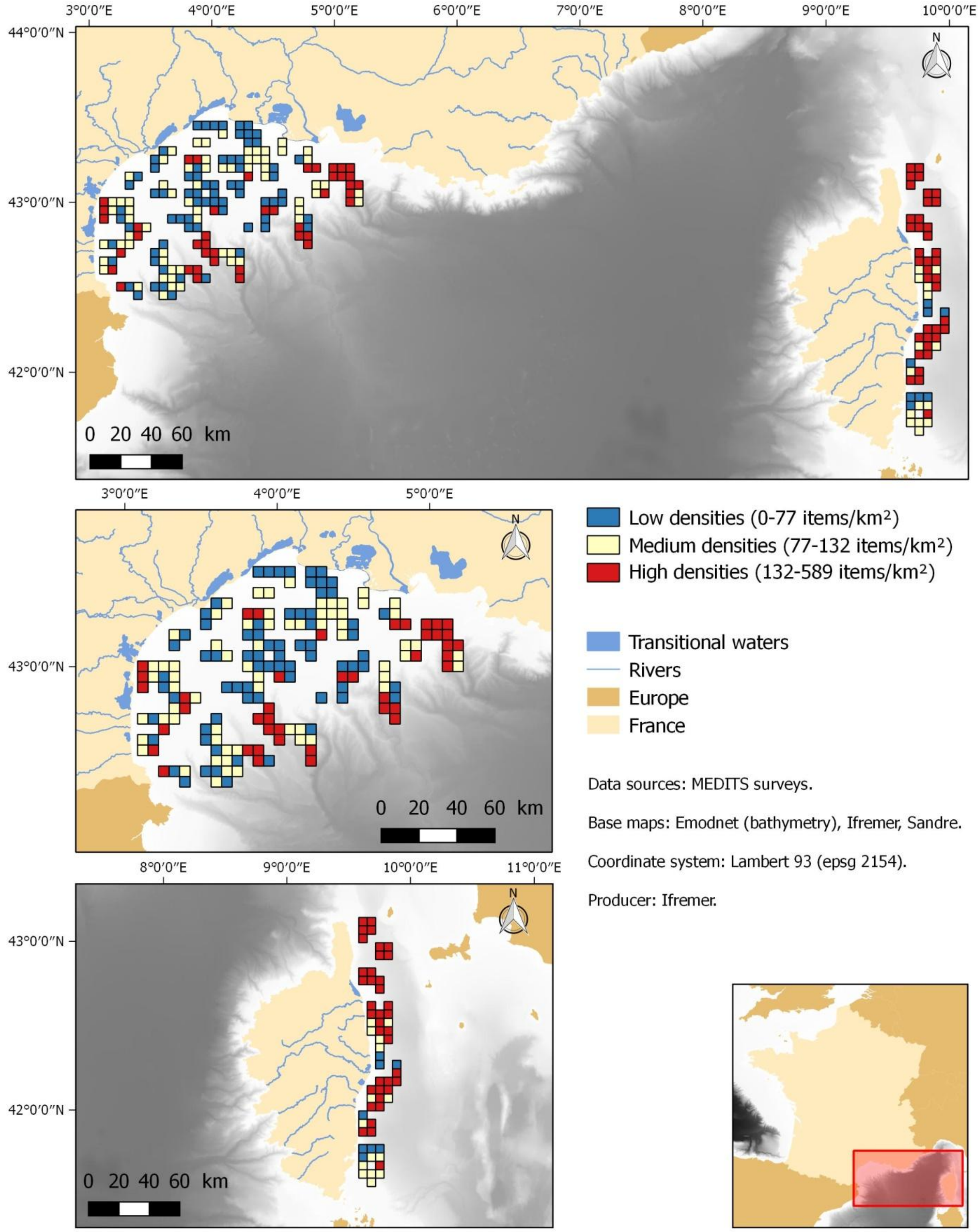


Figure 6: Map of marine litter accumulation areas from weighted averages of densities. Study areas are delimited by cells of three square-nautical miles and weighted averages of densities are calculated in each cell. Three color codes correspond to three pollution levels, each representing around 33% of the meshes. Bathymetry provided by EMODnet (Marine Information Service, 2016).

In order to complete this spatial analysis, the results from the trend analysis for total litter, plastic and fishing gear (density and mass per unit area) were mapped for each trawl station (Figure 1, supplementary material). Regarding total debris, the densities show a significant increase only at six sites in the GoL and four sites in Corsica, when only one site, located in Corsica, was shown to decrease. In the GoL, four stations were located near the coast in the northwestern part, in front of the towns of Agde and Sete, where summer tourist pressure is high, and in front of the Thau lagoon, where shellfish farming and recreative boating are important activities. The latter two stations were located near the canyon heads of Marti and Petit-Rhône. For CI, two stations were located on the southeastern coast near Porto-Vecchio and two further north, between Aleria and Bastia. As for the GoL, these four stations were located near cities or tourist areas. Only one station showed a significant decrease in CI, since it was located near the mouths of the Golo river with flowing water, and sometimes flooding washing the area of litter that is transported offshore.

For plastic litter density, a total of 16 stations indicated a significant positive trend and none indicated a significant negative trend. In the GoL, these stations were mainly located: *(i)* near the coast in the middle of the gulf, in front of the towns of Narbonne and Agde and the city of Montpellier; and *(ii)* offshore of Marseille. For Corsica, they were mainly located in the northeastern part of of the island, between Bastia and Aleria, where the local population is the most dense and in the south, a touristic area.

Concerning the density of fishing gear, the GoL is more impacted than Corsica, with 13 stations presenting a significant increase located globally along the coast and along the continental slope in offshore of Marseille. A single station showed a significant decrease near the beginning of the Petit-Rhône canyon. In Corsica, only three stations showed a significant increase, in the north with reduced fishing activity and in the central part of the eastern coast where fishing, fish and oyster farming occur.

Weight data were only available from 2013, without possible analysis of long-term trends. Only two stations showed an increase, near the Petit-Rhône canyon (total weight), and offshore of Perpignan (fishing gear weight), a commonly affected area. In the GoL and for total weights, four stations showed a significant decrease in debris and were located at the edge of the continental shelf near the slope break. On the other hand, for the plastic weights the decreases were generally localized in the middle of the continental shelf and in the southwestern part of the gulf. Overall, regarding to the weight of litter for total, plastic and fishing gear typologies, there was no increase for CI, where there were even two stations in the southeast of the island that showed a reduction in weight.

III.5 Marine litter in canyons

All the 30 French Mediterranean canyons were contaminated by debris with an average of 3.24 items/km (std = 2.10 items/km; range of data from 0.27 to 7.60 items/km; Figure 7). The Ligurian Sea's canyons had the highest abundances with an average of 4.88 items/km (std = 0.73 items/km) and values ranging from between 2.98 (La Ciotat) to 7.61 items/km (Cassidaigne). CI's canyons had less debris with an average value of 3.39 items/km (std = 0.64 items/km) ranging from 0.78 (Ile-Rousse) to 6.82 items/km (Ajaccio). Finally, GoL's canyons had the lowest abundances with an average of 1.25 items/km (std = 0.32 items/km) and extreme densities varying from 0.27 (Marti) to 3.80 items/km (Grand-Rhône). Sète and Marti canyons were the less impacted, with low densities but 100% plastic. Plastic was observed in every canyon, representing 26% of total debris with the highest plastic abundances in the Cassidaigne (2.46 items/km), Ajaccio (2.36 items/km) and Sagone (2.24 items/km) canyons. For each region, fishing gears were more prevalent than plastic and represented 29.5% of total marine debris, with values ranging from 0 to 3.36 items/km. In GoL canyons, fishing gears represented 33.75% of total debris, with the highest densities in the Lacaze-Duthiers (2.28 items/km), Provost, Boucart, Montpellier and Couronne canyons. In the Ligure canyons, fishing gears represented 25.33% of total debris, with the highest densities in the Cassidaigne canyon (3.36 items/km) and the lowest in La Ciotat canyon. Several canyons were observed with no fishing gear on the sea floor (*i.e.* Marti, Sète, Petit-Rhône, Grand-Rhône, St-Tropez), all located in the central part of the GoL or in Saint Tropez. In the CI canyons, fishing gears represented 33.61% of total debris and all the canyons of Corsica were affected by this type of litter, although fishing is not well developed in the island and is mainly artisanal. With 3.05 items/km, the Sagone canyon had the highest value. Metals represented 16.73% of total debris (up to 46% for Toulon canyon) and values ranged from 0 to 3.23 items/km for all the canyons. The Ligurian canyons were all contaminated by metal debris. The maxima was found in the Toulon and Sicié canyons, both situated offshore of a large naval base where metal materials including weapons and munitions, have been dumped regularly. Metals were less present in the CI (8.39%) and in the GoL (14.82%) canyons, except in the Grand-Rhône and Saint-Florent canyons. Glass and ceramics accounted for 16.72% of total debris with values ranging from 0 to 2.22 items/km. The Ligurian canyons were all contaminated with higher densities in the Saint-Tropez canyon (1.82 items/km). In the GoL and in CI, only two canyons had high values, the Grand-Rhône (1.80 items/km) and Ajaccio (1.74 items/km) canyons, respectively. For this material, most items were glass bottles, the result of urbanization and tourism while the high concentrations present in the Grand-Rhône canyon came from the Rhône drainage basin. Wood debris represented on average 7.78% of total debris with densities ranging from 0 to 3.32 items/km. The GoL canyons were not affected by wood debris. In the Ligurian Sea, the La Ciotat canyon had the highest value. In CI, the canyons located in the middle of the western part received wood debris (Galeria, Porto, Cargese).

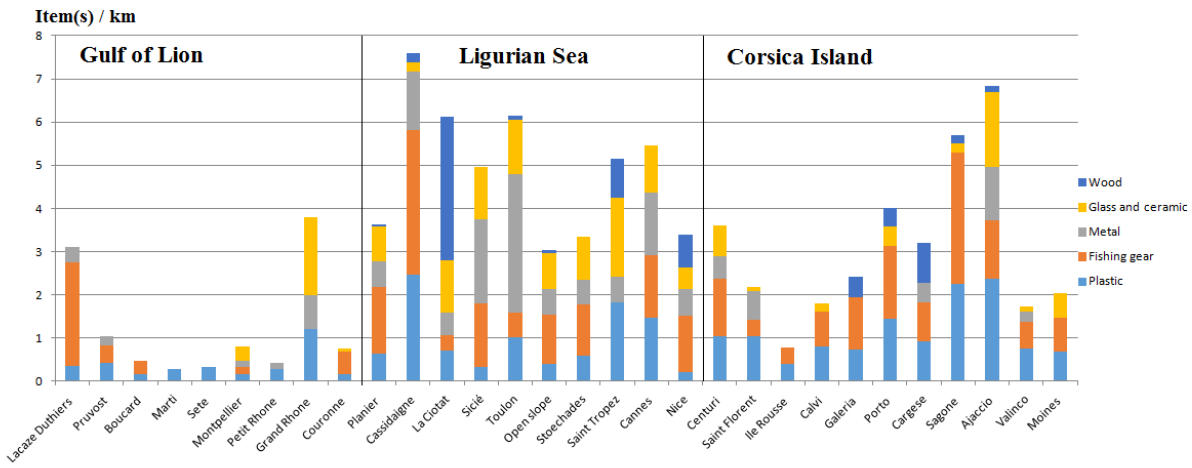


Figure 7: Histogram of mean densities per main categories (item(s)/km) in the French canyons.

IV Discussion and conclusion

The maximum averages of marine litter densities found in the FMW were 289.01 ± 298.16 items/km², 228.59 ± 202 items/km² for GoL and 459.75 ± 437.7 items/km² for Corsica. The Mediterranean is strongly impacted by marine litter (Galgani et al., 2013a) and is considered as probably the most affected basin in Europe (García-Rivera et al., 2017). Indeed, a similar study conducted in the North Sea over twenty-five years (Maes et al., 2018) showed mean values ranging from 21.6 (median =14.1) to 49.1 (median=40 items/km², which corresponds to the lowest annual mean values for the areas investigated in the present study (GoL and CI). In comparison with other studies carried out in the Mediterranean region (Alvito et al., 2018; Ioakeimidis et al., 2014), the densities in the western basin were found to be in the same range as several areas of the eastern Mediterranean, such as the Aegean Sea (416 to 1.211 items/km²), the Black Sea (291 ± 237 items/km²) and above the densities found in the Levantin basin (24 ± 28 items/km²).

As with all the other studies performed in the Mediterranean Sea, plastic accounts for the largest part of sea floor litter (Alvito et al., 2018; García-Rivera et al., 2017). This threat originates mainly from single use plastics such as bags, food packaging and synthetic ropes and strapping, most of them of telluric origin. However, despite a general slight increase of plastic materials found on the sea floor, some specific items like plastic bags had different trends, depending on the area. Despite feedback on recent national (French) policies such as bans of non-degradable plastic, launched in 2016, the implementation of the onshore collection and recycling of single use plastics would reduce the inputs to the sea. Currently, other actions exist or are being implemented (Xanthos and Walker, 2017) such as the extension of the ban, in 2017, of all types of plastic bag, the ban of other Single Use Plastics as part of the Plastic Strategy (Penca, 2018), and the implementation of the directive on port reception facilities. The effectiveness of these reduction measures will be evaluated in a few years by assessment studies on specific items. With detailed information in the types of item found on the sea floor, the present study will provide baseline values and support assessments of the effectiveness of these reduction measures. A large percentage of plastic originates from fishing activities, as in oceanic areas (Rodriguez and Pham, 2017) and mainly concerns fishing lines and nets that reflect fishing practices. Indeed, in the GoL fishing activities are important, with several fishing harbors, and based on the use of both trawl and monofilament lines, while in CI, trawling activities are far more limited. Reduction measures focused on abandoned or lost fishing gears are not implemented in the Mediterranean. Although some initiatives have been carried out by some fisheries, these actions were carried out only as experiments. Plastic bottles, metallic cans and glass bottles are also a threat, especially in Corsica. The island is subject to large influxes of tourists in summer, with many ferries, and around 22000 ships cross the Corsican channel every year, which represents a considerable source of litter, and more particularly bottles and cans thrown overboard. Italy, with a stronger seasonal influx of tourists, and more significant shipping, including ferries, generates the same types of debris (bottles and cans) that are often transported to Corsican shores by currents. Typically, the largest part of debris is transported by surface currents originating from Italy and, to a lesser extent from the southern basin of Corsica.

Litter accumulates under high anthropogenic pressure from towns, tourism and shipping routes, which is the case for the offshore areas of the town of Martigues and the city of Marseille, but the distribution of debris is also affected by depth. Generally, debris found in deeper parts of the basin mainly originate from the adjacent continental shelves. Indeed, in the GoL the general circulation from the east and both the Rhône river and wind induced currents (Mistral and Tramontane) prevent accumulation on the continental shelf and transport the debris to the south and / or deeper areas. In Corsica, sources for sea floor debris are more diffuse but involve the Italian rivers Volturno, Tevere, Ombrone, Arno and the main harbors of Napoli, Livorno and Genoa, with various dispersion schemes in relation to the season (Donzo et al., 2018). Typically, the current reaching the north Tyrrhenian Sea creates a mesoscale eddying structure offshore of Bastia (Faure et al., 2012), dividing the main flux into two currents with different orientations (northern and southern). The northern current creates a initial accumulation zone located to the north of the island. Once on the seabed, litter cannot move to the Ligurian waters in the north because of the lower depth of the mountain pass between Capria island and Corsica, which acts as a natural barrier for litter movement. On the contrary, the southern current drains part of the debris to the south of CI.

As a consequence of the shelf/slope break, debris were not found between 150 and 200 m depth in the GoL and from 200 to 250 m depth in the Corsican channel. Indeed, these areas are subjected to strong currents bringing debris directly along the continental slope to the deeper and calmer areas where they preferentially accumulate. The accumulation of heavier glass and metallic debris occurs close to their source, while lighter debris can be transported far from sources and over long distances by currents.

Fishing gears however, accumulate in the GoL down to 50 m, close to fishing grounds, and between 450 and 500 m depth, more probably after cascading, a very common pattern in the northwestern Mediterranean sea (Canals et al., 2006). Due to different fishing practices, based more on the use of lines, the accumulation of fishing debris in CI is mainly located between 150-200 m.

This study correspond to the rare study on long-term trends for trawling marine litter in the Mediterranean Sea. The overall statistical analysis indicates a significant increase in the quantities of debris, with temporal variability (two periods of increase and one period of decrease), over 24 years. The densities of total debris, plastics and fishing gear are stable (no significant trend) for most stations, with only a few points with a significant increase. On the other hand, the total and plastic weights do not indicate any trend for most of the sites, or a decreasing trend (negative trend) for a small number of stations. A comparison with data published in Galgani et al. (2015) clearly demonstrated the recent changes. Typically, data on both "density" and "weight" are complementary and should not be considered separately for trend analysis. This will be of importance for regular monitoring, in the framework of both the MSFD and UNEP Map regional plans, also when considering the definition of baselines, thresholds and possibly reduction targets. Monitoring certain specific categories (plastics, plastic bag, fishing gear) will also largely underpin the evaluation of the efficiency of reduction measures. The results will also help in the location of accumulation areas, a specific recommendation from the UNEP Map regional Plan, a prerequisite for the recovery of Abandoned, Lost or otherwise Discarded Fishing Gear (ALDFG) or funding for litter operations.

Finally, coupling information from trawling and from videos enable covering different substrates and depths. In canyons, the most common debris categories are plastic and fishing gears, followed by metal, glass and ceramics, and wood, with ranking similar to those observed on the continental shelf and slope. These two types of inventories confirmed the common patterns for both the continental shelf/slope and canyons, under the influence of local effectors such as the dominant economic sectors in the area, the geomorphology of the seafloor and hydrodynamics. Aggregating data to integrate the various types of variables for a more global analysis of marine litter at the regional level has now become critical. This should be considered as a necessary step to spatially map data from all types of substrate in single layers.

The French Mediterranean seafloor is greatly affected by marine litter, although other sites in the eastern Mediterranean may have shown higher values. Policies such as the UNEP MAP regional plan and the European plastic strategy, the two main drivers, have not yet shown any reduction since they were launched recently. One of the main challenges in debris management remains the identification of sources, particularly land-based ones, in order to better prevent inputs to the marine environment (Schneider et al., 2018; Tunca Olguner et al., 2018).

Plastics, fishing gears, metals and glass remain the most important categories some of whose sources still have to be detailed. Because litter has a high spatial and temporal variability, regardless of the metric used, monitoring needs to be strengthened in specific areas, with higher resolution, especially near coastlines, urban areas and in canyons where processes are more complex.

Although the deep marine environment is considered a hostile environment, difficult to access and requiring considerable resources, marine litter studies have become critical in order to better protect the deep Mediterranean ecosystem, and support targeted and effective actions for its preservation (Consoli et al., 2018). To achieve this, opportunistic approaches are well-adapted. Regular fish stock assessment cruises such as the MEDITS project (http://www.sibm.it/SITO%20MEDITS/principaleprogramme.htm) enable carrying out marine litter research and monitoring on a regular and annual basis. Common protocols implemented in partner countries also enable large scale assessments and provide an efficient tool for ensuring better comparisons between different regions.

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Supplementary materials

Table 1 – supplementary materials: Summary of Mann-Kendall tests applied to marine litter data over rolling six-year periods between 1994 and 2017 (excepted for the periods including 2007 where there are only five years of data), considering a threshold of significance of 5% ($\alpha = 0.05$). 0: no significant trend; + (red background): significant increasing trend; - (blue background): significant negative trend. Symbols in parenthesis indicate that the trend is not significant after Bonferroni correction, considering 57 tests (αper comparison = 0.05/57 = 0.00088

	Total debris	Plastic debris	Fishing debris
1994-1999	0	0	0
1995-2000	0	(+)	+
1996-2001	(+)	+	+
1997-2002	0	0	0
1998-2003	0	0	0
1999-2004	-	-	(-)
2000-2005	-	-	-
2001-2006	-	-	0
2002-2007 *	(-)	0	0
2003-2008*	0	0	0
2004-2009*	0	(+)	0
2005-2010*	0	0	0
2006-2011*	0	0	(+)
2007-2012*	+	+	+
2008-2013	+	+	+
2009-2014	+	+	+
2010-2015	+	+	+
2011-2016	+	+	+
2012-2017	0	0	0

0	Not significant (p>0.05)
+	Significant effect with increase (p<0.05)
-	Significant effect with decrease (p<0.05)
()	Not significant after Bonferroni correction (p>0.00088)
*	data over rolling five-year period (2007 missing)

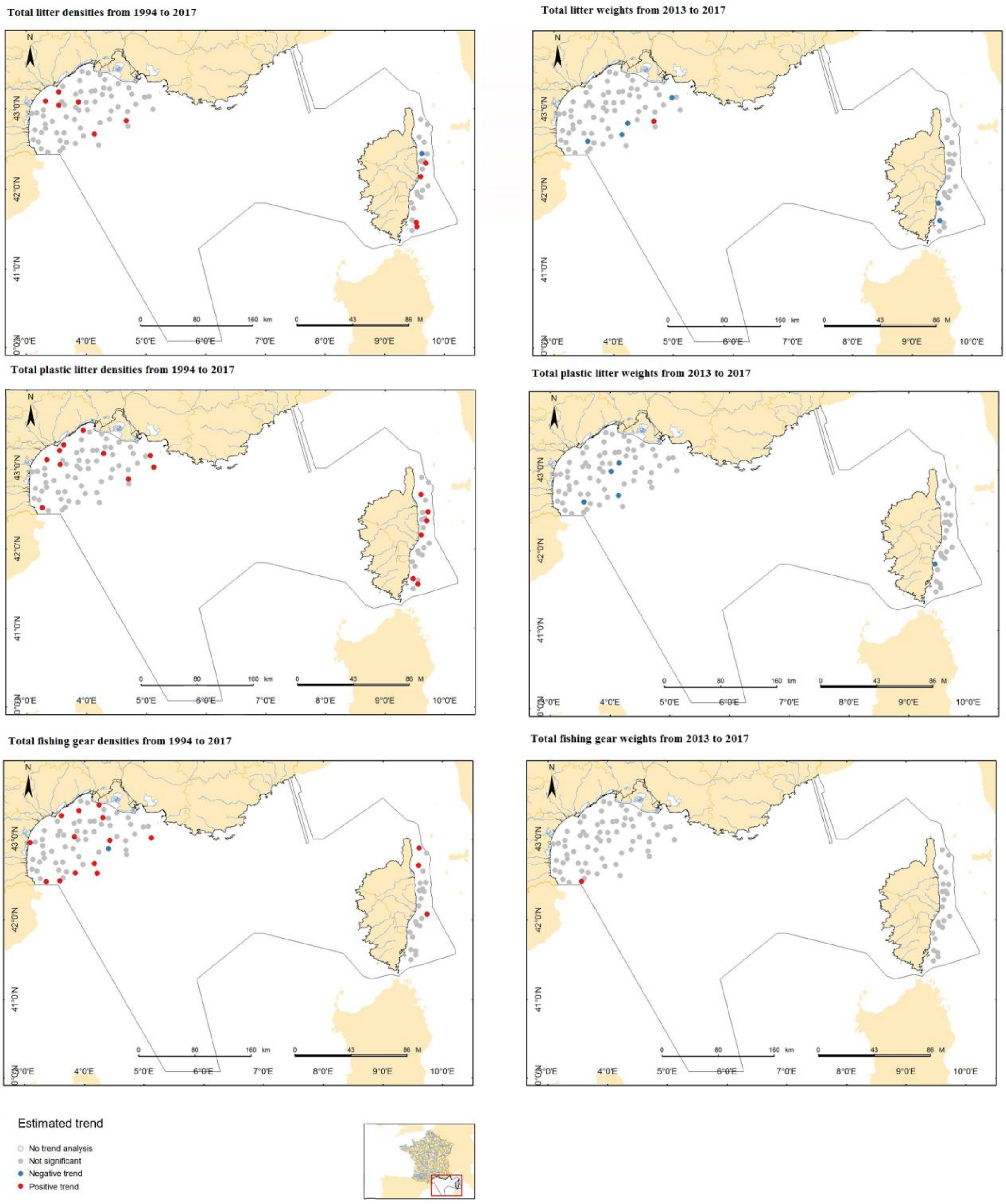

Figure 1 – supplementary materials: Trend analysis for each trawling station of the MEDITS cruises. Tests on total litter, plastic litter and fishing gear were performed in samples from 1994 to 2017 for litter densities and from 2013 to 2017 for weights. The significance of results on trends was evaluated using a Mann-Kendall statistical test ($p < 0.05$).