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Shallow Seafloor Litter: Tracking their Sources and Spatiotemporal Trends in the Presence of Oceanographic Drivers through efficient monitoring.

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Abstract Seafloor litter is the least exploited component of marine litter. The spatially variable distribution of their densities over time is a cumulative effect of sources' intensities and natural drivers like wind/wave and current conditions in interaction with seafloor morphology. Making safe interpretations about the exact spatiotemporal distribution of benthic litter requires good knowledge of the local above-mentioned seafloor components. In this work, visual monitoring over 3 years of a shallow urbanized bay in Syros Island, Cyclades, Greece, was proved a reliable way to assess the intensity of litter sources along their coasts. It showcased that spatial ranges that are influenced mainly by the annual ocean dynamics should be treated with caution or even excluded from the analysis. There, intense litter fluxes over the year, hinder any effort to separate local anthropogenic littering intensity changes from natural litter input-output fluctuations. Towed underwater camera surveying and auxiliary bathymetric and swath sonar backscatter datasets were used to find links between the seafloor litter transport dynamics and the seabed micro- and macro-topography, finally indicating litter traps and sinks.

1. Introduction

Seafloor litter research is currently being practiced in various instances by repurposing equipment employed for commercial works in deep waters (i.e. > 50 m). This is mostly performed by trawlers and in some cases Remotely Operated Vehicles (ROVs), used for fishery operations (Alomar et al., 2020; Koutsodendris et al., 2008; Prevenios et al., 2017; Canals et.al., 2021) or for underwater inspection (van den Beld et al., 2017) respectively, while small scale efforts can be found using custom made scientific trawlers (Galimany et al., 2019). However, using trawlers has direct physical and biological impacts on the seafloor and its associated ecosystems, being destructive to habitats and generating CO_2 at high levels (Sala et al., 2021), while abandoned, lost, and discarded fishing gear, also known as "ghost gear", comprises a considerable portion of marine-based benthic debris. It has been therefore planned to be phased out in the future, while they are also limited to soft bottoms and certain depths. On the other hand, visual seafloor mapping is unobtrusive by nature, allowing observations of litter in vulnerable ecosystems, e.g., rocky bottoms, coral reefs or seagrass bottoms, and provides detailed information on litter position. The Marine Strategy Framework directive (MSFD), in its monitoring plan, is considering including observations, through both diving and imagery, in addition to trawl surveys. The protocols (Galgani et al., 2013) enable harmonized surveys and data, while a data collection framework is already under implementation within the EU database EMODNET (Vinci et al., 2020).

State-of-the-art methods for seafloor litter research have recently been reviewed in Canals et al., 2021 and ROVs are the preferred means for collecting high detail seafloor litter data as they carry high-definition cameras and can provide positioning data. Yet, the use of Towed Underwater Cameras (TUC) is considered an accepted method for shallow seafloor litter assessment (European Commission, 2013), which moreover allow for automated litter detection (Politikos et.al., 2021). TUC seem to be the most cost-effective means for shallow seafloor image exploration, in terms of initial and maintenance cost and survey speeds.

In Ermoupoli Bay, the Capital City of Cyclades Islands in Aegean Sea, monitoring litter densities in coastal areas was performed for 3 years through TUC surveys. This work aspires to find a link between seafloor litter densities and marine litter fluxes in urbanized bays. To weight any naturally driven bias in the seafloor litter load, their spatial distribution was associated with bathymetry as well as to annual ocean dynamics applying in the area. Important litter transport dynamics and sources were made evident in both spatial and temporal scales, highlighting the importance of monitoring the trade-off between anthropogenic pressure changes and environmental drivers controlling shallow seafloor litter in areas that are next to urban environments.

2. Materials and methods

2.1. Data collection

During the LIFE DEBAG project, six seafloor litter surveys were implemented, using TUCs, in Ermoupoli Harbor basin, which is the full Ermoupoli Bay. A 14-km long TUC survey plan (see Figure 1) was followed as closely as possible in each monitoring period, mobilizing a SeaViewer 950 analog towed camera with a GoPro Hero5 camera attached on its top, recording 4k video in a wide field of view mode. A small rib speedboat was used, on which the required GPS (Hemisphere V100) has been installed. The survey lines were planned in an average spacing of 50 m between them, to achieve a fitting trade-off between time efficiency and spatial coverage. The total seafloor coverage was more than 405 hectares. 36 hours of underwater video has been acquired, corresponding to 72 km of survey lines. The camera was towed behind the vessel at a maximum speed of 1.5 knots, continuously adapting its cable-out as to be kept at about 1.5-2 m above the seafloor. The Hypack 2013 was used for navigation and GPS fixes' data storage.

Full coverage multibeam echosounder (MBES) bathymetric data were provided by the port authorities of Ermoupoli, with a raster resolution of 2 m while a supplementary survey was conducted using an EG&G 272-TD Sidescan Sonar (SSS), transmitting at 100-kHz with a 100 m ground scanning range per side. An SSS backscatter mosaic was created using the SeaView MOSAIC (Moga Software) software.

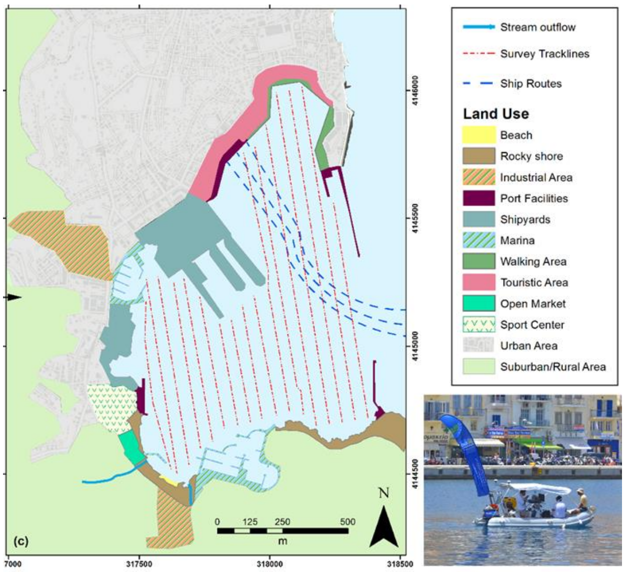

Figure 1 Overview of Ermoupoli's bay survey area with annotations regarding: (a) Any potential litter sources including urban, recreational, marine navigational or industrial ones, and (b) The TUC survey lines realized 7 times during the 3 years long monitoring plan.

Finally, to validate the accuracy of the litter density trends over time, not being affected by any change in climate conditions, they have been compared to wind and wave regime, as acquired by copernicus.eu in a daily time step for the full monitoring period.

2.2 Data treatment

Litter classification was performed using the dedicated TGML/JRC guidance document on monitoring marine litter in European seas (European Commission, 2013). More than 14 litter types described in this protocol were clearly visible in the video footages, but a supplementary "unspecified" class was added to include all unrecognized items. The latter items, although having been included in the total litter abundance estimations, they have not been used in type-specific analyses. The acquired video files were visually inspected, and a snapshot (in png image format) was stored for each detected litter item using the VLC open-source multimedia framework, programmed to put prefixed indicative of the time passed since the beginning of each video. The video snapshots were arranged in suitably named folders according to the litter categories detected within. A data management and annotation tool was implemented in MATLAB programming environment, manipulating the structured folders' tree and extracting an excel spreadsheet with the video file-name each litter item was found in, the corresponding snapshot image filename, the litter-types found in, their quantities and their geographic position. The exact time that each snapshot was taken was estimated by adding the time in seconds passed since the start of each video and the UTC time saved with the video during the acquisition phase. The geographic coordinates of each snapshot and its included litter items were estimated via its time stamp, by matching it with the corresponding time in the GPS fixes, performing linear interpolation when falling between two consecutive fixes. Given the layback between the vessel and the TUC, ranging up to 50-60 m in the deeper parts of the survey area, effort has been put to optimize video snapshot geolocation, by finding common landmarks in the SSS backscatter mosaic.

Regarding the wind and wave data, three climate indicators were estimated, namely wind and wave energy (sum of square speed and height respectively) with direction towards the bay (240° ± 30°) as well as with the total wind energy, averaged over a week's interval.

3. Results

A decreasing trend of litter densities on the seafloor of Ermoupoli can well be attributed to the effectiveness of LIFE DEBAG project, having mainly targeted though plastic bags (Figure 2a,b). The fact that not only plastic bags but also almost all litter types decreased in Ermoupoli capital by about 32% (Figure 1.a) during the project, strongly suggests that it has brought about a drastic improvement on the marine environment of the Island. No strong seasonal variability in litter abundances was observed in the shallower parts (<18m) of the bay, thus constituting those areas ideal for monitoring litter sources and their discharges over time. Those areas are under dynamic equilibrium over the year, given the low hydrodynamics of a semi-enclosed area, and thus any change in litter densities may indicate changes in litter discharges that lead to new input/ sink equilibriums. In Ermoupoli Bay an almost monotonic decrease of litter densities was detected in its shallower parts (Figure 2.d), coinciding with the awareness raising activities in the context of LIFE DEBAG project, thus validating its effectiveness. This concept is further proofed by the fact that plastic bags, the targeted litter type of the project, showed the steepest average decrease over the 3 years of the monitoring of about 65%. Litter density correlation with bathymetry was much more evident at the shallower parts of the bay (<20m), while in its deeper parts (>40m), a pulsed seafloor litter decongestion was revealed (Figure 2.d). This occurred during winter and spring and was followed by higher litter accumulation during summer and early autumn (Figure 2.e). This annual litter density periodicity in the deeper parts of the bay is likely related to environmental drivers, as suggetsed by the wind/ wave energies dissipating in the Bay (Figure 2.c) inducing stronger bottom currents during winter, oriented from the open sea, mainly affecting the deeper parts of the bay close to its opening towards the Aegean Sea. This annual pattern was not detected in the shallower parts of the bay, where no seasonal fluctuation was observed throughout the 3 years of monitoring, rather than a monotonical decreasing trend (Figure 2.e). The latter indicates that seafloor litter in very shallow areas and especially in semi-enclosed environments of relatively low energies can be well correlated to the litter discharges from the sources along the coastline. In such environments, the ratio between litter inputs from the local sources and sinks to the deeper seafloor or the water column seems to be in a relative balance throughout the year.

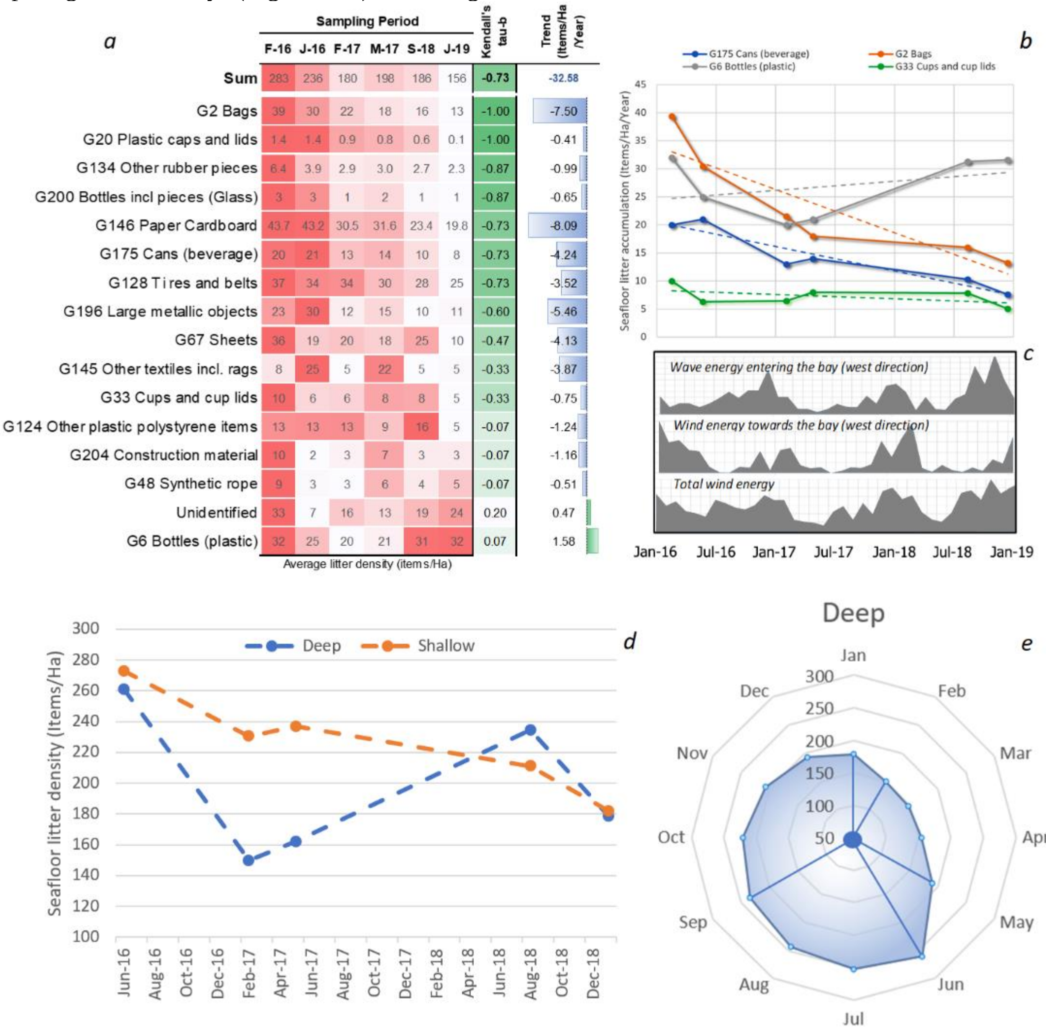

Figure 2 (a) Temporal assessment of average litter density per sampling period. Kendall's tau-b statistical test has been applied between the days passed and the mean litter density of each period, (b) The trend (in items/Ha/Year) indicates the actual slope of a linear regression model to the density data per indicator litter type, (c) wave and wind energy timeseries plot, (d) comparison of temporal trends of total litter densities between shallow (< 20 m depth) and deep (>20 m depth) parts of the bay and (e) radar-chart of annual fluctuation of total litter densities in the deeper (>20m) parts of the bay.

Given the transport dynamics, no safe conclusions can be drawn about the litter sources' contribution on the seabed litter load. In Table 1, the percentage of each litter type is correlated to any major activity on the shore (see Figure 1), after litter occurrences had been narrowed to those being in less than 100 m distance from each source. The shipyard, the marinas, the walkabout within the touristic area as well as the boatyard have been proven to be the main contributor of marine litter in the area. The majority of "Tires and belts" seem to be resting in proximity to the shipyard and the marinas, accounting for their 39% and 22% respectively. Plastic bags on the other hand, are more dispersed among potential coastal light sources suggesting multisource feedback since weak peak seems to be present in proximity to the boatyard, the shipyard and the urban markets. It should be mentioned

that "Plastic bags" is the most abundant litter type associated to the urban market, given that bags where not banned or under levy, according to the respective Greek legislation, during the full monitoring period. "Cans (beverage)" are the most abundant litter items close to the marinas and the walkabout within the touristic zone of the town, proving to be a reasonable indicator for recreational activities. "Paper – cardboard" is also in good spatial relation to the walkabout, while it is a considerable litter component on the seafloor close to the marinas and the shipyard. Finally, a significant amount of "plastic bottles", accounting for more than 11% of its total items, have been found in proximity to the marinas and the shipyard while they were also the second most abundant litter type close to the urban market, with about 5% of bottles found there.

	G33-Cups and cup lids	G175-Cans (beverage)	G2-Bags	G6-Bottles	G128-Tires and belts	G146-Paper Cardboard	Rest
Shipyard	9.6%	13.2%	**13.5%**	11.4%	**38.7%**	**16.3%**	**32.1%**
Marina	**16.7%**	**19.8%**	10.8%	**14.3%**	22.0%	**14.9%**	15.9%
Walk about	7.9%	**15.3%**	6.7%	4.9%	4.2%	**19.1%**	10.0%
Boatyard	**15.8%**	9.9%	**13.8%**	7.4%	5.6%	4.8%	8.1%
Ship routes	6.1%	5.4%	3.7%	0.8%	5.8%	6.8%	5.8%
Urban market	3.5%	2.9%	**12.1%**	3.7%	0.8%	3.3%	4.1%
Industrial zone	0.9%	7.0%	5.1%	0.0%	2.5%	1.3%	3.4%

Table 1 The percentage of each litter type that is correlated to any major activity (potential litter source) on the shore (as indicated in Fig. 1)

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