Marine Pollution Bulletin 229 (2026) 119731

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Uneven seas: seabed litter hotspots, diffuse losses, and the mitigation power of fishing fleets

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ARTICLE INFO

Keywords:
Fishing for litter
Seafloor litter
Bottom trawling
Marine Strategy Framework Directive (MSFD)
Ecosystem-based mitigation

ABSTRACT

This study evaluates the efficacy and spatial dynamics of passive Fishing for Litter (FFL) schemes in the Northern Adriatic (Goro) and Southern Tyrrhenian (Salerno) seas. The primary research question is to determine how distinct regional maritime activities and fishing effort influence the quantity, composition, and removal efficiency of seafloor macrolitter. Over a six-month period (2022–2023), 14 commercial bottom trawlers collected litter during routine operations. Despite comparable fleet characteristics, results revealed pronounced spatial heterogeneity; area-standardized removal reached 27.4 kg km^{-2} in Goro and 92.3 kg km^{-2} in Salerno, while effort-weighted LPUE differed markedly (2.83 vs 9.57 kg h^{-1}). Stratification of rates showed that hotspot conditions increased LPUE by factors of ~2.7–3.5, confirming that removal is driven by localized high-density events. Compositional analysis indicated distinct source pathways: diffuse aquaculture debris dominated in Goro, whereas clustered bulky waste (~73% of mass) characterized Salerno. Annual mitigation potential was estimated at 4.3 t yr^{-1} (Goro) and 10.2 t yr^{-1} (Salerno), with modest treatment costs (€1500–€4750 yr^{-1}). These findings demonstrate that FFL is an effective yet spatially dependent tool. Integrating such heterogeneity into assessment frameworks is essential to support MSFD implementation and targeted, ecosystem-based management strategies.

1. Introduction

Marine litter is widely recognized as one of the most pervasive anthropogenic pressures affecting marine ecosystems, with the Mediterranean Sea identified as a global hotspot of accumulation due to its semi-enclosed nature, high coastal population density, intense maritime traffic, and productive fisheries (Cózar et al., 2015; Galgani et al., 2000; UNEP/MAP, 2020). Seafloor litter, in particular, represents a chronic and largely underestimated component of this problem. Unlike floating debris, benthic litter accumulates over long temporal scales, affects benthic habitats and organisms, interferes with fishing activities, and contributes to “ghost fishing” when composed of abandoned, lost, or otherwise discarded fishing gear (ALDFG) (Macfadyen et al., 2009; FAO, 2018).

Fishing for Litter (FFL) schemes have emerged as a pragmatic mitigation measure, engaging fishers directly in the collection and removal of litter encountered during routine fishing operations (OSPAR, 2010; KIMO, 2017). FFL initiatives were originally developed in the North Sea and North-East Atlantic as voluntary programs that allowed fishers to bring ashore marine debris collected in their nets, supported by dedicated port reception facilities and waste management systems (OSPAR, 2010). Over time, the approach has been progressively adapted to Mediterranean contexts, where fleet structures, fishing grounds, and waste management systems differ substantially from those in northern Europe. In this region, extensive monitoring through trawl surveys, such as the Mediterranean International Trawl Survey (MEDITS), has highlighted a widespread and heterogeneous distribution of seafloor litter, emphasizing the need for active removal strategies (García-Rivera et al., 2017; Consoli et al., 2018; Spedicato et al., 2019). Pilot projects and regional campaigns have been implemented in Spain, France, Croatia, Italy, and Greece, often within EU-funded programs and national marine strategies (Arcadis, 2013; UNEP/MAP, 2019). These initiatives have

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https://doi.org/10.1016/j.marpolbul.2026.119731
Received 4 March 2026; Received in revised form 1 April 2026; Accepted 8 April 2026

demonstrated that FFL schemes can generate robust datasets on litter composition and spatial distribution while simultaneously delivering an ecosystem service through active removal.

In the northern Adriatic, Mistri et al. (2024) provided an assessment of the potential service offered by fishers acting as "cleaners of the sea." Through a passive FFL campaign conducted between May 2020 and May 2021, trawlers operating from the major fishing ports of Chioggia and Goro removed more than 6 t of marine litter from approximately 265 km^2 of fishing grounds over 256 fishing days. The study quantified not only the mass and spatial distribution of litter, but also its typological composition, highlighting the predominance of ALDFG (48% of total litter), with plastic components, particularly mussel socks and fishing nets, accounting for the majority of this fraction.

Importantly, Mistri et al. (2024) also addressed a frequently overlooked aspect of FFL operations: the recyclability of recovered materials. Although approximately 2.4 t of plastic were retrieved, only a small proportion of these items was free from biological fouling. Extensive colonization by encrusting and adherent organisms substantially limited the potential for recycling using locally available technologies, underscoring the need for innovation in waste treatment and valorization pathways. This finding is consistent with observations from other Mediterranean FFL initiatives, where biofouling and contamination have been identified as major constraints for circular-economy approaches to marine litter management (Arcadis, 2013; UNEP/MAP, 2019).

Building on the positive outcomes of the 2020–2021 campaign, particularly in terms of removal efficiency and stakeholder engagement, the initiative was replicated during 2022–2023 with an expanded geographical scope. The new phase involved the trawl fisheries of Goro in the northern Adriatic and, for the first time, the fleet of Salerno in the southern Tyrrhenian Sea. This extension aimed to test the replicability of the FFL scheme under contrasting environmental and socio-economic conditions. Whereas the northern Adriatic is characterized by shallow, highly productive, sediment-rich environments influenced by the Po River inputs, the southern Tyrrhenian coast near Salerno presents steeper bathymetric gradients and distinct hydrodynamic regimes, with the Sele River representing the primary fluvial input and potential transport pathway for land-based materials.

Comparative assessments across basins are essential to determine whether the efficiency of FFL as a mitigation measure is context-dependent and to what extent litter composition reflects local fishing practices, aquaculture intensity, and coastal urbanization. While many studies provide localized inventories of removed waste, a significant gap remains in understanding how diverse basin characteristics and regional maritime pressures influence the success of these programs. This study addresses this gap by employing a standardized, effort-weighted monitoring approach across two geomorphologically and socio-economically distinct basins, moving beyond simple abundance counts to provide a spatially explicit assessment of mitigation potential.

The aim of this study was to quantify spatial contrasts in seabed litter composition, density, and removal efficiency between two structurally comparable Mediterranean fishing fleets, and to evaluate the mitigation capacity of Fishing for Litter (FFL) programmes as scalable management tools. By integrating composition analysis, effort-standardized performance metrics (LPUE), spatial normalization, and annualized mitigation estimates, we sought to infer dominant litter source pathways and assess the broader policy relevance of fleet-based removal within MSFD Descriptor 10 and regional marine governance frameworks.

2. Materials and methods

2.1. Study area

The study was conducted in two Italian marine areas characterized by distinct geomorphological and hydrodynamic settings: the Northern Adriatic Sea (Goro fishing grounds) and the Southern Tyrrhenian Sea (Salerno fishing grounds). The Northern Adriatic is a shallow, semi-enclosed basin (mean depth < 35 m) strongly influenced by riverine inputs, most notably the Po River, which represents the largest contributor of freshwater discharge, sediments, and microplastics to the area (Munari et al., 2021), together with high sedimentation rates, intensive trawling, and widespread aquaculture activities. These combined pressures enhance both the accumulation and the redistribution of benthic marine litter across fishing grounds.

In contrast, the Salerno fishing grounds are located along the southern Tyrrhenian coast and are characterized by steeper bathymetric gradients, more heterogeneous substrates, and lower sediment input compared to the Adriatic. Sampling depths ranged from 12 to 24 m in Goro and from 28 to 65 m in Salerno. Both areas support intensive small- and medium-scale bottom trawl fisheries.

2.2. Fishing for Litter scheme and sampling design

Passive Fishing for Litter (FFL) activities were carried out over a six-month period (December 2022 – July 2023) by 14 commercial bottom trawlers, eight from Goro and six from Salerno, participating on a voluntary basis using otter trawl gear (OTB). Litter was collected during routine fishing operations without altering tow duration or routes, with each fishing trip serving as an individual sampling unit.

For each trip, the following information was recorded: (i) fleet (Goro or Salerno); (ii) vessel ID; (iii) date of fishing; (iv) geographic coordinates (latitude, longitude); (v) fishing depth (m); (vi) fishing duration (hours); (vii) litter mass by category (plastic, metal, glass, "other"); and (viii) total litter mass (kg). Litter categories were defined according to MSFD Descriptor 10 classification schemes (European Union Marine Strategy Framework Directive), in which the "other" category includes bulky items not classified as plastic, metal, or glass. Based on previous findings in the Northern Adriatic (Mistri et al., 2024), where benthic litter was largely associated with mussel aquaculture activities, particularly discarded mussel socks, these items were assigned to the "other" category rather than to the general plastic fraction. This approach allows aquaculture-derived debris to be distinguished from other plastic materials and supports a more accurate assessment of source-specific contributions. Wood, consisting of branches and tree trunks transported to sea by rivers, was not considered in the present study, which focuses exclusively on litter of anthropogenic origin. The swept area for each haul was calculated as the product of the distance trawled and the effective horizontal net opening. In the absence of real-time gear-geometry sensors, a constant horizontal wing spread of 20 m was adopted as the reference width. This value was determined based on the specific technical characteristics of the otter trawl gear and the standardized metal otter boards used to ensure a stable net spread during routine operations. This constant-opening proxy is a widely accepted standard in trawl-based litter assessments when sensor-derived geometry is unavailable:

$$\text{Surface}\ (\text{km}^2) = [\text{distance}\ (\text{m})^{*}\ \text{horizontal opening}\ (\text{m})\,]/10^6$$

Distance was obtained from the mean speed of the boat (≈2.8 knots during trawls) and the duration of trawling:

$$\text{Distance}\ (\text{m}) = \text{speed}\ (\text{miles/h})^{*}\ \text{time}\ (\text{h})^{*}\ 1852$$

The swept area was used to calculate the amount of litter on bottom area (i.e. kg km^{-2}). All analyses were conducted within the framework of MSFD Descriptor 10 (Marine Litter), with emphasis on: (i) seafloor litter removal rates; (ii) material composition; (iii) effort-standardized indicators; and (iv) fleet-based mitigation potential. The selected indicators were intended to support evaluation of fisheries-based mitigation as a complementary management instrument under MSFD and circular-economy strategies.

Geostatistical interpolation was applied to the georeferenced sampling points within a GIS environment to characterize the spatial distribution of marine litter. Specifically, the Inverse Distance Weighting (IDW) algorithm was employed, estimating values at unsampled locations by weighting surrounding data relative to the inverse of the squared distance. This process yielded distribution maps (expressed in kg) for plastics, metals, glass, other materials, and total litter across the study area.

2.3. Data processing and statistical analyses

Structural vessel information was obtained from the EU Fleet Register and included Fleet (port of registration), EU CFR number, Length Overall (LOA, m), Gross Tonnage (GT), Engine Power (kW), and Year of Construction. These variables were used to characterize fleet structure and to compute size-standardized removal indicators.

Trip-level data were extracted from operational records and included fleet, vessel code, fishing date, fishing location (latitude and longitude), depth (m), fishing duration (hours), and litter mass by material category (plastic, metal, glass, other) as well as total litter mass (kg). Fishing effort was expressed as total fishing hours per trip and aggregated at vessel level where appropriate. Litter per unit effort (LPUE) was calculated as:

$$\mathrm{LPUE} = \mathrm{Total\ Litter\ Mass\ (kg)/Fishing\ hours}$$

Material composition was expressed both as total mass (kg) and as percentage contribution to total litter mass. Size-standardized indicators (kg GT^{-1} and kg kW^{-1}) were also calculated: to account for vessel capacity, litter removal performance was standardized by gross tonnage (GT) and engine power (kW). For each vessel, total litter mass collected during the study period was divided by structural parameters:

$$\mathrm{kg\,GT^{-1}} = \mathrm{Total\ litter\ mass\ (kg)/GT}$$

$$\mathrm{kg\,kW^{-1}} = \mathrm{Total\ litter\ mass\ (kg)/Engine\ power}$$

These metrics provide capacity-normalized indicators of litter removal performance. To account simultaneously for fishing effort and vessel capacity, combined standardized indicators were calculated at vessel level as:

$$\mathrm{kg\,h^{-1}\,GT^{-1}} = \mathrm{Total\ litter\ mass\ (kg)/Fishing\ hours\ (h)} \times \mathrm{GT}$$

$$\mathrm{kg\,h^{-1}\,kW^{-1}} = \mathrm{Total\ litter\ mass\ (kg)/Fishing\ hours\ (h)} \times \mathrm{kW}$$

These metrics represent litter removal efficiency per unit of time and per unit of vessel structural capacity, allowing direct comparison between fleets independent of vessel size, engine power, and fishing duration.

Statistical analyses were performed using R (version 4.4.0; R Core Team, 2024). Normality of distributions was assessed using the Shapiro–Wilk test (Shapiro and Wilk, 1965). Given frequent deviations from normality and limited vessel-level sample sizes, non-parametric tests were applied. Between-fleet comparisons were conducted using the Mann–Whitney *U* test (Mann and Whitney, 1947). Differences among multiple vessels were evaluated using the Kruskal–Wallis test (Kruskal and Wallis, 1952), followed by Holm-adjusted pairwise comparisons when appropriate (Holm, 1979) via the *stats* package. Correlations between continuous variables were assessed using Spearman's rank correlation coefficient (Spearman, 1904). All statistical tests were two-tailed with a significance threshold of $\alpha = 0.05$.

2.4. Estimation of fleet-based mitigation potential

Fleet-based mitigation potential was estimated using an effort-standardized approach based on litter per unit effort (LPUE, kg·h^{-1}), rather than mean litter mass per trip, in order to account for variability in fishing duration and to better reflect operational effort. Annual mitigation potential was then estimated as a scenario-based extrapolation by scaling observed LPUE to assumed annual fishing effort:

$$\mathrm{Annual\ removal} = \mathrm{LPUE_{fleet}} \times \mathrm{H_{annual}}$$

where H_{annual} represents the total annual fishing effort expressed in hours. In the absence of full-year, spatially explicit effort data, annual fishing effort was approximated using a conservative assumption of 150 fishing days per year multiplied by the mean observed fishing hours per trip. This assumption reflects typical activity levels of small- to medium-scale Mediterranean trawl fisheries (STECF, 2022).

To account for spatial heterogeneity, LPUE values were stratified by defining hotspot conditions as trips exceeding the 75th percentile of fleet-specific LPUE distributions, with remaining observations classified as background. Annual mitigation potential was estimated using an effort-weighted approach and treated as a scenario-based extrapolation rather than a predictive value. This approach assumes a temporally uniform distribution of fishing effort and consistent access to litter accumulation areas (hotspots) throughout the year, conditions that may not fully reflect actual fishing patterns.

Uncertainty in mean removal rates was quantified using non-parametric bootstrap resampling (Efron and Tibshirani, 1993) of trip-level data to derive 95% confidence intervals (CI) for LPUE and mean litter mass per trip, implemented using the *boot* package in R. These intervals were subsequently propagated to annual per-vessel and per-fleet estimates through linear scaling.

To complement effort-based indicators, removal density was also expressed as mass per unit area (kg·km^{-2}), calculated by dividing the total litter removed by the estimated seabed area trawled during the campaign and consistent with scaling approaches previously applied in the Northern Adriatic (Mistri et al., 2024). This metric provides a spatially explicit measure of removal intensity and facilitates comparison with other trawl-based seabed litter assessments. To provide an economic framing, projected annual removal volumes were combined with indicative waste treatment costs (€/tonne) derived from national municipal waste management statistics (ISPRA, 2023). Treatment cost per tonne was based on the national average cost (€/t) for municipal waste management. Total programme cost per tonne removed was defined as:

$$\begin{aligned}\text{€/t removed} &= \text{treatment cost (€/t)} \\ &\quad + \text{(total incentive costs/tonnes removed)}\end{aligned}$$

This formulation allows a first-order evaluation of cost-effectiveness, while acknowledging that both removal estimates and associated costs are scenario-dependent, and supports the integration of FFL activities within Marine Strategy Framework Directive (MSFD) Descriptor 10 reporting frameworks (European Parliament and Council, 2008; UNEP/MAP, 2019).

3. Results and discussion

3.1. Fleet composition and operational characteristics

A total of 14 vessels were included in the structural comparison, comprising 8 vessels registered in Goro and 6 vessels registered in Salerno (Table 1). Overall, the two fleets exhibited highly comparable morphometric and technical characteristics. Mean vessel length (LOA) was 12.96 ± 2.55 m in Goro and 12.63 ± 4.18 m in Salerno. A Mann–Whitney *U* test indicated no significant difference between fleets ($U = 30.0$, $p = 0.768$). Although variability was slightly higher in Salerno, reflecting a broader internal size range, central tendency values were nearly identical. Gross tonnage (GT), used as a proxy for vessel carrying capacity, averaged 14.22 ± 11.79 in Goro and 12.83 ± 9.39 in Salerno. Again, no statistically significant difference was detected ($U = 26.5$, $p = 1.000$). The age structure of the fleets was similarly homogeneous. Mean year of construction was 1995.0 ± 10.65 for Goro vessels and 1994.8 ±

Table 1

Technical characteristics and litter collection metrics for the trawler fleets of Goro and Salerno. Data include vessel identification code (id), year of construction (Built), length overall (LOA), gross tonnage (GT), engine power (kW), and performance indicators (see text for explanation).

Fleet	Vessel id	Built	LOA (m)	GT	kW	Fishing effort (h)	Total kg	kg trip^{-1}	LPUE (kg h^{-1})	kg GT^{-1}	kg kW^{-1}	kg h^{-1} GT^{-1}	kg h^{-1} kW^{-1}
Goro	GO1	1979	14.82	12	183	74	205	29.3 ± 9.8	2.7 ± 0.7	17.1	1.1	0.231	0.015
	GO2	1991	14.99	19	161.8	126	421.5	35.1 ± 22.1	3.2 ± 1.8	22.2	2.6	0.176	0.021
	GO3	1986	17.15	43	279.5	251	912	38 ± 31.3	3.6 ± 2.9	21.2	3.3	0.084	0.013
	GO4	1993	11.68	6	95.6	164	477	31.8 ± 18.5	3.1 ± 2.3	79.5	5.0	0.485	0.030
	GO5	1994	12.03	12	128	145	325.5	21.7 ± 15.6	2.2 ± 1.5	27.1	2.5	0.187	0.018
	GO6	1994	12.57	8	55.1	190	445.5	23.5 ± 14.8	2.4 ± 1.6	55.7	8.1	0.293	0.043
	GO7	1999	12.03	10	39	55	191	31.8 ± 27.3	3.7 ± 3.5	19.1	4.9	0.347	0.089
	GO8	2017	13.28	15	211	229	514	22.3 ± 13.1	2.2 ± 1.4	34.3	2.4	0.150	0.011
Salerno	SA1	1991	11.38	9	162	126	1335	70.3 ± 61.3	10.4 ± 8.5	148.3	8.2	1.177	0.065
	SA2	1991	9.87	4	59	134	1428	71.4 ± 48.3	10.8 ± 7.5	357.0	24.2	2.664	0.181
	SA3	1991	14.85	21	161.8	136	1304	68.6 ± 51.7	9.4 ± 6.8	62.1	8.1	0.457	0.059
	SA4	1992	13.7	19	96	161	1154	60.7 ± 45.4	7.5 ± 5.8	60.7	12.0	0.377	0.075
	SA5	1994	7	1	80.9	98	1207	67.1 ± 44.4	16.9 ± 25.2	1207.0	14.9	12.316	0.152
	SA6	2010	18.98	23	176.47	158	1353	71.2 ± 55.1	9.7 ± 8.1	58.8	7.7	0.372	0.049

7.52 for Salerno vessels. The Mann–Whitney U test confirmed the absence of significant differences (U = 30.5, $p = 0.720$), indicating comparable modernization profiles. Taken together, these results demonstrate that the Goro and Salerno fleets are structurally equivalent in terms of vessel length, tonnage, and age composition. The absence of statistically significant morphometric differences strengthens subsequent performance comparisons, as observed contrasts in litter removal efficiency cannot be attributed to intrinsic differences in vessel size or capacity.

3.2. Inter-fleet differences in FFL performance

A total of 235 fishing trips were analyzed (Goro: $n = 121$; Salerno: $n = 114$). The temporal and spatial distribution of these operations followed the standard commercial activity of the involved fleets, which is inherently non-linear as it depends on favorable weather-marine conditions and fluctuating market demand for specific seafood products. Total fishing effort amounted to 2047 h, with Goro accounting for 1234 h and Salerno 813 h. Despite lower total effort, Salerno removed substantially more litter. Total litter mass collected was 7781.0 kg in Salerno compared to 3491.5 kg in Goro. Mean litter mass per trip was significantly higher in Salerno (68.25 ± 50.37 kg) than in Goro (28.86 ± 21.04 kg) (Mann–Whitney U, $p < 0.001$). Using an effort-weighted approach, fleet-level LPUE was estimated at 2.83 kg·h^{-1} (95% CI: 2.50–3.18) in Goro and 9.57 kg·h^{-1} (95% CI: 8.25–10.96) in Salerno. ($p < 0.001$). Fishing duration per trip was significantly longer in Goro (mean 10.20 h) than in Salerno (7.13 h; $p < 0.001$), while fishing depth was significantly greater in Salerno (mean 45.0 m) than in Goro (16.8 m; $p < 0.001$). When standardized by the total seabed area effectively trawled (Goro = 127.2 km^2; Salerno = 88.9 km^2), removal density amounted to 27.3 kg·km^{-2} (95% CI: 23.5–31.4) in Goro and 92.3 kg·km^{-2} (95% CI: 76.1–110.5) in Salerno. This threefold difference supports the presence of localized accumulation hotspots in the Tyrrhenian fishing grounds.

Material composition differed between fleets in both absolute mass and proportional contribution (Fig. 1). Across all trips combined, total litter collected amounted to 11,272.5 kg. The dominant fraction was the “other” category (6311.0 kg; 56.0%), followed by metal (1376.0 kg; 12.2%), glass (1197.0 kg; 10.6%), and plastic (826.5 kg; 7.3%) (remaining mass corresponds to minor rounding differences across trips). At fleet level, marked differences were observed. In Salerno, total litter mass reached 7781.0 kg, with the “other” category representing the largest fraction (5710.0 kg; 73.4% of fleet total), followed by metal (1144.0 kg; 14.7%), glass (561.0 kg; 7.2%), and plastic (366.0 kg; 4.7%). In Goro, total litter mass was 3491.5 kg, with a more even distribution among categories. The “other” fraction accounted for 601.0 kg (17.2%), metal for 232.0 kg (6.6%), glass for 636.0 kg (18.2%), and plastic for 460.5 kg (13.2%). When expressed per trip, metal, glass, and other fractions were significantly higher in Salerno than in Goro (Mann–Whitney U tests, $p < 0.001$), whereas plastic mass per trip did not differ significantly between fleets ($p > 0.05$).

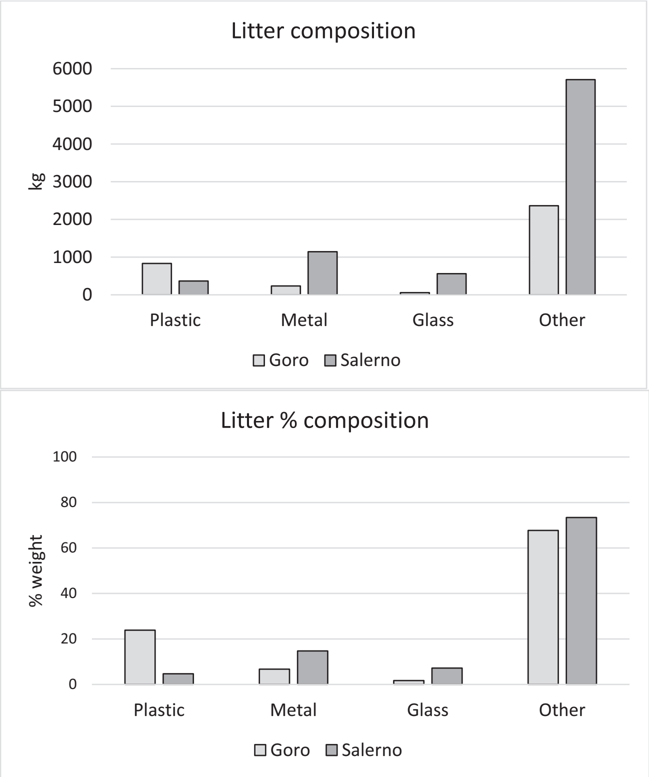

Fig. 1. Amount of litter collected by weight (above) and its percentage composition relative to the total (below).

These results indicate not only a higher overall litter burden in Salerno, but also clear compositional differences between study areas. The dominance of the “other” category in Salerno suggests the presence of heavier or mixed debris types, whereas Goro exhibited a relatively higher proportional contribution of plastic and glass. Overall, the data reveal pronounced spatial variability in both total litter mass and material composition between the two fleets. Figs. 2 and 3 illustrate the spatial distribution of the various marine litter categories across the two study areas.

To evaluate whether differences in litter removal between fleets were influenced by vessel structural capacity, total litter mass collected per

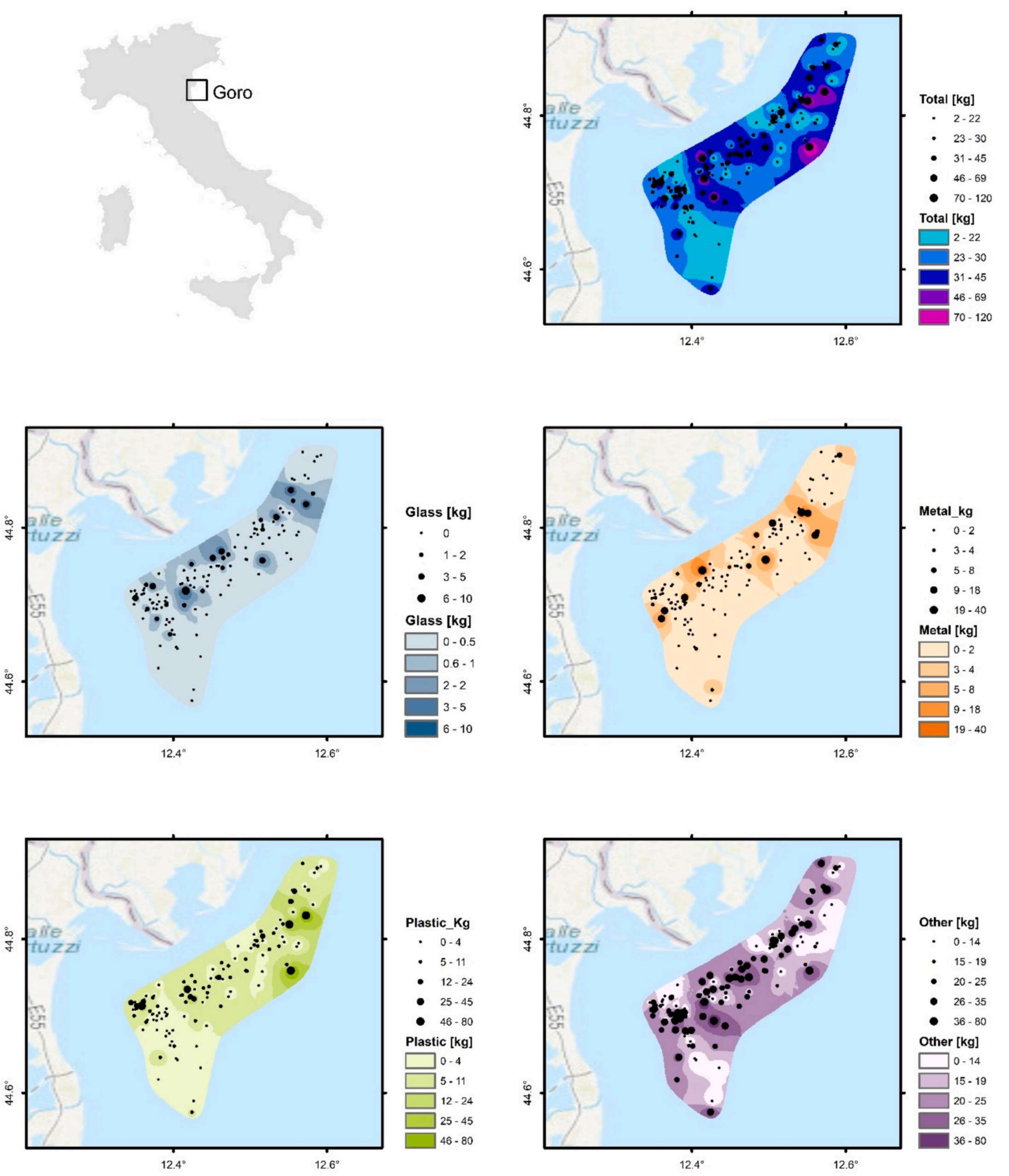

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Fig. 2. Spatial distribution and isodensity maps of marine litter categories trawled by the Goro fleet.

vessel was standardized by gross tonnage (GT) and engine power (kW) (Table 1). When expressed as kg GT^{-1}, Salerno vessels exhibited substantially higher values than Goro vessels. Mean litter removal per GT was 315.67 kg GT^{-1} in Salerno compared to 34.52 kg GT^{-1} in Goro. This corresponds to an approximately nine-fold increase in tonnage-standardized removal efficiency. The difference was statistically significant (Mann–Whitney $U = 3.0$, $p = 0.0047$). Similarly, when standardized by engine power, litter removal expressed as kg kW^{-1} was significantly higher in Salerno (12.52 kg kW^{-1}) than in Goro (3.74 kg kW^{-1}), representing more than a three-fold difference ($U = 2.0$, $p = 0.0027$).

Since structural comparisons showed no significant differences in LOA, GT, or construction year between fleets, therefore, the markedly higher kg GT^{-1} and kg kW^{-1} values in Salerno reflect a genuine difference in removal performance rather than vessel capacity. At the individual vessel level, variability was evident within both fleets; however, even the highest-performing Goro vessels did not reach the mean standardized values observed in Salerno. This indicates that the observed inter-fleet difference is systematic rather than driven by outliers. Overall, size-standardized indicators confirm that Salerno vessels remove significantly more litter per unit of structural capacity, suggesting that environmental litter density, fishing grounds characteristics, or operational factors are the primary drivers of the observed performance gap.

To disentangle the combined influence of vessel capacity and fishing effort, litter removal was further standardized by both structural parameters (GT and kW) and total fishing hours. These combined indicators provide a measure of litter removal efficiency per unit time and

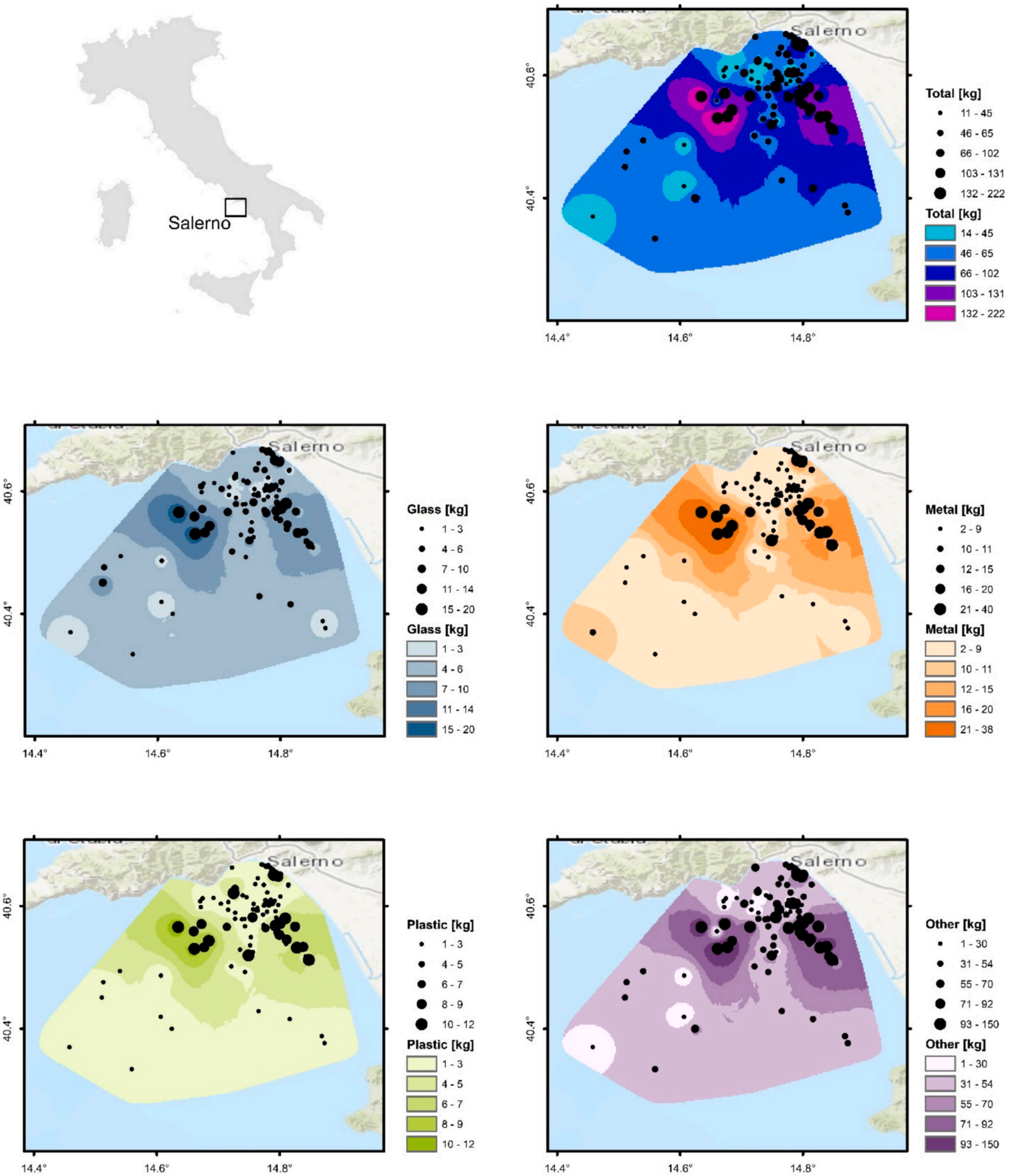

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Fig. 3. Spatial distribution and isodensity maps of marine litter categories trawled by the Salerno fleet.

per unit vessel capacity (Table 1). When expressed as kg h^{-1} GT^{-1}, mean values were 2.894 kg h^{-1} GT^{-1} in Salerno compared to 0.244 kg h^{-1} GT^{-1} in Goro. This represents an approximately 12-fold higher removal efficiency in Salerno after simultaneously accounting for fishing duration and vessel tonnage. The difference was statistically significant (Mann–Whitney $U = 3.0$, $p = 0.0047$). Similarly, the indicator kg h^{-1} kW^{-1} was significantly higher in Salerno (0.097 kg h^{-1} kW^{-1}) than in Goro (0.030 kg h^{-1} kW^{-1}) ($U = 4.0$, $p = 0.0080$), corresponding to more than a three-fold difference in engine-power- and effort-standardized performance. One Salerno vessel ($GT = 1$) exhibited an exceptionally high value of 12.32 kg h^{-1} GT^{-1}, substantially exceeding all other vessels. This extreme value results from the very low gross tonnage recorded for that unit, which amplifies the denominator in tonnage-standardized metrics.

Despite significantly longer fishing durations per trip in Goro, vessels still exhibited markedly lower combined standardized values. This indicates that increased effort alone does not compensate for lower litter density in that area. The persistence of inter-fleet differences after controlling for vessel size (GT), engine power (kW), and fishing effort strongly suggests that seabed litter density and spatial accumulation patterns drive the observed performance gap. Within-fleet variability was modest relative to the between-fleet contrast, and even the highest-performing Goro vessels did not reach the mean standardized efficiency observed in Salerno. Overall, effort- and size-standardized indicators confirm that higher removal efficiency in Salerno reflects genuine spatial differences in litter availability rather than structural or operational effects.

3.3. Fleet-based mitigation potential

The estimation of fleet-based mitigation potential was estimated using an effort-weighted approach based on LPUE (kg·h^{-1}). The substantial difference in fleet-level LPUE (2.83 kg·h^{-1} in Goro, and 9.57 kg·h^{-1} in Salerno) highlights a markedly higher removal efficiency in the Tyrrhenian sector, consistent with a hotspot-driven distribution. Assuming a scenario of temporally uniform fishing effort (150 fishing days·yr^{-1}), annual fishing effort was estimated at approximately 1530 h·yr^{-1} in Goro and 1070 h·yr^{-1} in Salerno, based on observed mean fishing duration. Under this assumption, the potential annual removal was estimated at ~4.33 t·yr^{-1} for Goro and ~ 10.24 t·yr^{-1} for Salerno. Bootstrap resampling confirmed the robustness of these estimates, with LPUE ranging from 2.50 to 3.18 kg·h^{-1} in Goro and 8.25–10.96 kg·h^{-1} in Salerno (95% CI).

When expressed per unit area, removal density amounted to 27.3 kg·km^{-2} in Goro and 92.3 kg·km^{-2} in Salerno, indicating substantially higher litter concentration in the latter. This result is fully consistent with the observed spatial clustering of heavy debris and supports the interpretation of localized accumulation hotspots in the Salerno fishing grounds.

Given the pronounced spatial heterogeneity observed in both study areas, removal efficiency was further explored by distinguishing between background and hotspot conditions. Hotspots were defined as trips exceeding the 75th percentile of LPUE within each fleet. This stratification revealed substantial differences in removal rates. In Goro, LPUE increased from 1.97 kg·h^{-1} in background conditions to 5.37 kg·h^{-1} in hotspot areas, while in Salerno it increased from 6.02 to 20.99 kg·h^{-1}, corresponding to approximately 2.7-fold and 3.5-fold increases, respectively. These results demonstrate that a significant proportion of total litter removal is driven by relatively few high-intensity events, particularly in the Tyrrhenian fishing grounds. Incorporating hotspot stratification provides a more realistic representation of fisheries-based litter removal, particularly when considering the likelihood of repeated fishing in high-density accumulation zones. However, given the strong spatial heterogeneity of litter distribution, these annual values should be interpreted as scenario-based estimates rather than predictive values, as they assume temporally uniform fishing effort and consistent access to accumulation areas.

From an economic perspective, combining effort-weighted annual removal estimates with indicative waste treatment costs (€345–€464 per tonne; ISPRA, 2023) yields relatively low annual management costs. Under the scenario-based extrapolation, estimated treatment expenditures range from approximately €1500–€2000 yr^{-1} for Goro and €3500–€4750 yr^{-1} for Salerno, reflecting the higher removal efficiency observed in the latter. Expressed per unit mass, these values correspond directly to the assumed treatment cost range (€/t), but total annual costs remain modest due to the limited absolute volumes removed.

It should be noted that these estimates include only waste handling and treatment costs and do not account for additional operational expenses (e.g., onboard handling time, gear wear, logistics, or incentives). Conversely, they also do not capture ecosystem service benefits associated with litter removal, such as reduced ghost fishing, improved benthic habitat quality, and enhanced environmental status under MSFD Descriptor 10. Consequently, cost-effectiveness expressed solely as €/t removed likely underestimates the broader societal value of fleet-based mitigation, particularly in hotspot-dominated systems such as those identified in Salerno.

3.4. Putative sources and pathways of recovered litter

The pronounced contrast in litter composition, removal efficiency, and spatial signal between Goro and Salerno provides insight into likely source pathways, although attribution necessarily remains probabilistic.

In the Goro fishing grounds, the "other" fraction consisted almost entirely of mussel socks used in offshore aquaculture, which dominated the recovered mass. Plastic represented an additional substantial component, whereas metal and glass contributed only marginally to total mass. At fleet scale, mean LPUE was 2.83 kg h^{-1}, and mean trip-level removal was 28.86 kg·trip^{-1}, with relatively moderate variability and no extreme single-trip outliers. Size- and effort-standardized indicators were consistently low compared to Salerno (e.g., 0.244 kg h^{-1} GT^{-1}), suggesting a broadly distributed but moderate-density litter field rather than concentrated accumulation zones. The absence of disproportionately large recovery events, together with the relatively homogeneous vessel-level performance, supports a mechanism in which debris is diffusely redistributed across fishing grounds rather than concentrated in discrete seabed hotspots. Such a pattern is consistent with storm-driven structural failures of offshore mussel farming infrastructure, generating episodic yet spatially dispersed inputs of aquaculture-derived materials that subsequently settle over a wide area (Mistri and Munari, 2019). Under this scenario, the dominant pathway is operational loss from aquaculture installations rather than land-based dumping. Consequently, mitigation priorities include improving infrastructure resilience, reinforcing anchoring systems, implementing rapid post-storm recovery protocols, and promoting material design modifications to reduce fragmentation and long-term persistence.

In contrast, the Salerno fishing grounds exhibited a markedly different compositional and operational profile. The "other" fraction, accounting for approximately 73% of total fleet mass, consisted largely of tyres and bulky household appliances, while metal and glass also contributed proportionally more than in Goro. Mean LPUE was substantially higher, reaching 9.57 kg h^{-1}, and mean trip-level removal reached 68.25 kg·trip^{-1}, with several disproportionately high-mass recovery events. Stratified analysis further showed that LPUE increased to 20.99 kg h^{-1} under hotspot conditions, confirming that removal is driven by localized high-density accumulations. Fleet-based mitigation scaling further indicated a projected removal potential of 61.43 t·year^{-1}, nearly double that of Goro despite fewer participating vessels. The combination of high mean removal rates, strong between-trip variability, and the presence of heavy, high-density objects suggests a fundamentally different source mechanism. Tyres and large appliances have limited hydrodynamic mobility after deposition and therefore tend to accumulate in discrete seabed "hotspots" (e.g., depressions, channels, or anthropogenic dumping sites). The clustering of high-mass recoveries at specific coordinates is thus more consistent with localized inputs than with diffuse operational leakage. The persistence of high values even after standardization for vessel size (315.67 kg GT^{-1}) and effort (2.894 kg h^{-1} GT^{-1}) indicates that the elevated removal signal in Salerno is attributable to localized high-density litter accumulation.

While multiple mechanisms could produce such accumulations, including harbour losses, transport accidents, or historical disposal practices, the predominance of tyres and bulky waste, materials that are costly to manage on land, raises the possibility that at least part of the Salerno signal reflects deliberate disposal at sea. This interpretation must remain cautious: the data do not identify responsible actors nor exclude alternative pathways. Nevertheless, the combination of material composition, elevated trip-level variance, and spatial clustering is compatible with a localized "convenience disposal" hypothesis. This reading gains contextual relevance given that the region has been historically affected by documented waste-management challenges (Alberti, 2022) and has been subject to EU-level legal scrutiny regarding systemic waste governance deficiencies (CJEU, 2010; European Parliament, 2025). Although these rulings concern terrestrial waste systems, they provide institutional context that may help explain the presence of bulky, high-density items at discrete seabed locations.

3.5. Comparison with other European FFL experiences

The removal rates and spatial patterns observed in this study are broadly consistent with, yet in some cases exceed, values reported from other Mediterranean and European Fishing for Litter (FFL) initiatives.

Trip-level removal in our case ranged from 28.9 kg·trip^{-1} in Goro to 68.3 kg·trip^{-1} in Salerno. These values fall within the upper range of Mediterranean trawl-based litter removals. For example, regional FFL initiatives in the Adriatic–Ionian area reported aggregate removals of 122 t collected by 124 vessels across 15 ports during the DeFishGear project (DeFishGear, 2016), demonstrating the scalability of fleet-based mitigation. However, those reports primarily provide total tonnage rather than density metrics, limiting direct comparison on a swept-area basis. Table 2 summarizes representative Mediterranean FFL and trawl-based benthic-litter studies.

When spatially normalized (27.4 kg·km^{-2} in Goro and 92.3 kg·km^{-2} in Salerno), these densities are lower than extreme hotspot values documented in parts of the northwestern Mediterranean but fall within the same order of magnitude. Along the Catalan margin, benthic litter densities exceeding 100–200 kg·km^{-2} have been reported in sectors influenced by major urban and riverine inputs (Sardà et al., 2022). Likewise, deep Mediterranean basins and submarine canyons can act as accumulation sinks, with reported densities exceeding several hundred kg·km^{-2} under geomorphologically confined conditions (Ramirez-Llodra et al., 2013). Our annualized mitigation estimate of approximately 100.7 t·year^{-1} across 14 vessels demonstrates a removal capacity comparable to other European FFL programmes when participation is sustained. For instance, national FFL networks coordinated in the United Kingdom through KIMO report substantial cumulative removals across ports, although density-standardized comparisons remain limited due to differences in reporting metrics (KIMO International, 2020). These comparisons underscore a key point: FFL can deliver measurable mitigation volumes, but interpretation must account for local density, composition, and dominant source pathways.

The spatial heterogeneity and the dominance of land-based sources observed in the Goro and Salerno basins reflect broader patterns seen in other semi-enclosed European basins, such as the Black Sea. While many Mediterranean FFL programmes focus on active fishing grounds, research along the southeastern Black Sea coast has highlighted how the "source-to-sink" pathway, driven by riverine transport and coastal urban pressure, creates significant accumulation zones on the inner shelf (Erüz et al., 2023; Özşeker et al., 2024). Similar to our observations near the Po and Sele rivers, studies in the Black Sea demonstrate that seasonal runoff and proximity to metropolitan centres are primary drivers of macrolitter density (Erüz and Özşeker, 2017). However, a key distinction in mitigation strategy emerges: whereas Black Sea research often emphasizes monitoring at the river–sea interface (Terzi et al., 2020), our results suggest that FFL schemes in the Mediterranean are particularly effective at intercepting "legacy" bulky waste and aquaculture-derived debris that have already settled on the seafloor. This comparison underscores that FFL is not merely a localized cleaning tool but also a necessary cross-regional strategy to manage the final sink of terrestrial litter, a challenge shared by both Mediterranean and Black Sea coastal governance frameworks (Özşeker et al., 2024).

Beyond the Black Sea, the efficiency of FFL in Goro and Salerno shows distinct differences compared with established North Sea and Spanish Mediterranean schemes. While North-East Atlantic programmes (OSPAR) often report high volumes of Abandoned, Lost, or otherwise Discarded Fishing Gear (ALDFG), averaging 0.5–1.0 kg per haul in some regions (OSPAR, 2017), our Mediterranean data indicate a more significant contribution from aquaculture-specific debris (Goro) and illegally dumped bulky waste (Salerno). This pattern is consistent with findings from Spanish Mediterranean FFL trials, where land-based plastics often exceed 60% of the total catch (García-Rivera et al., 2017). Furthermore, whereas early Mediterranean pilot projects in Greece and France reported variable LPUE due to small fleet sizes (Arcadis, 2013), our study demonstrates that a standardized, multi-vessel approach achieves more stable removal rates (up to 9.57 kg·h^{-1} in Salerno), suggesting that FFL is a highly scalable tool for MSFD Descriptor 10 compliance across diverse European coastal settings.

3.6. Management implications and methodological constraints

The estimation of fleet-based mitigation potential demonstrates that structured FFL schemes can provide a measurable contribution to seabed litter reduction, consistent with MSFD Descriptor 10 objectives (European Parliament and Council, 2008). Using an effort-weighted approach based on fleet-level LPUE (kg·h^{-1}), annual removal was estimated at approximately 4.33 t·yr^{-1} in Goro and 10.24 t·yr^{-1} in Salerno, reflecting the substantially higher removal efficiency observed in the Tyrrhenian sector. When expressed in treatment-equivalent terms using indicative waste management costs (€345–€464 t^{-1}; ISPRA, 2023), this corresponds to annual expenditures of approximately €1500–€2000 in Goro and €3500–€4750 in Salerno. These values provide a first-order benchmark for cost-effectiveness comparisons within EU Circular Economy and Green Deal frameworks (European Commission, 2019, 2020). Given the pronounced spatial heterogeneity of litter distribution, these estimates should be interpreted as scenario-based values, assuming temporally uniform fishing effort and consistent access to accumulation hotspots.

Interpretation of removal metrics, however, requires caution. In Goro, total mass was largely driven by aquaculture-derived mussel socks, whereas in Salerno the "other" fraction (≈73% of total mass) consisted predominantly of tyres and bulky appliances. These heavy items disproportionately influence mass-based indicators and may overemphasize bulky waste relative to lighter plastic fractions. This effect is further reflected in area-standardized indicators, with substantially higher litter density in Salerno (≈92 kg·km^{-2}) compared to Goro (≈27 kg·km^{-2}), consistent with localized accumulation hotspots. If policy priorities focus on plastic leakage reduction or recyclability, total mass alone may therefore be insufficient. As shown in northern Adriatic assessments (Mistri et al., 2024), biofouling and degradation further limit recycling potential, highlighting the need to report plastics, metals, and bulky items separately for circular-economy planning.

Taken together, these results indicate that FFL is most effective when

Table 2
Summary of representative Mediterranean Fishing-for-Litter (FFL) and trawl-based benthic-litter studies.

Area	Method / programme	Reported metric (kg·km^{-2} or reported)	Putative source	Source
Northwestern Mediterranean	Commercial bottom-trawler collections	Local hotspots (up to 200 kg·km^{-2})	Urban/riverine discharge, coastal population pressure; mixed plastics and fishing gear	Balcells et al., 2023
Northwestern Mediterranean	Research trawl surveys	High local densities (>100 kg·km^{-2})	Urban/riverine discharge, coastal hydrodynamics concentrating litter near shore	Sardà et al., 2022
Northern Mediterranean	MEDITS international multi-year bottom-trawl survey	Widespread occurrence; percentile-based item densities reported (e.g., 85th–95th percentiles for plastics: 147–316 items·km^{-2})	Mixed: coastal/riverine inputs, shipping, fisheries	Spedicato et al., 2019
Deep Mediterranean basins & canyons	Research trawl surveys (MEDITS, dedicated cruises)	High densities in confined sinks (>1000 kg·km^{-2})	Hydrodynamic funneling, canyons, long-term accumulation of mixed debris; ship-origin in high-traffic zones	Ramirez-Llodra et al., 2013
Adriatic–Ionian	DeFishGear multi-port coordinated FFL campaigns	122 t removed by 124 vessels across 15 ports (project aggregate)	Mixed: coastal urban sources, fisheries/gear, ports	Ronchi et al., 2019

interpreted and implemented as a targeted, hotspot-driven mitigation strategy rather than as a uniform removal mechanism, reinforcing its role as a cost-efficient and spatially adaptive tool within ecosystem-based marine management.

Methodological constraints also limit direct policy translation. Although swept-area normalization confirmed substantially higher litter density in Salerno than in Goro, mass-based indicators do not capture the prevalence of small fragments, and seasonal variability is not explicitly resolved. The winter–summer observation window may be influenced by several seasonal drivers, including variable riverine inputs, increased land-based waste during peak tourist periods, storm-induced resuspension and transport of seabed litter, and fluctuations in fishing effort, all of which can affect both litter availability and LPUE.

Furthermore, the dataset relies on a limited sample of 14 vessels over a six-month period, which restricts the interannual representativeness and broader spatial applicability of the results in a highly heterogeneous basin such as the Mediterranean. In this context, climatic variability (e.g., shifts in precipitation patterns, storm frequency, and large-scale atmospheric modes) can modulate both the transport and accumulation of marine litter, while episodic events may generate short-term but substantial deviations from average conditions.

Future research should therefore extend the temporal scale through multi-year monitoring, incorporate explicit seasonal replication (e.g., comparing LPUE and litter composition across seasons), and expand spatial coverage by involving a larger fleet in order to validate the robustness and generalizability of these findings. In addition, particular attention should be given to episodic “pulse” inputs from major river systems, such as the Po in the Adriatic and the Sele in the Tyrrhenian basin. Hydrological extremes, including floods and high-discharge events, can trigger abrupt transfers of large volumes of land-based waste to coastal and benthic environments, temporarily reshaping litter abundance and composition. These transient inputs are not captured within the present monitoring window but may represent a key driver of both seasonal and interannual variability in seabed litter distribution.

The economic estimates remain conservative, as they exclude operational opportunity costs and do not monetize ecosystem-service benefits such as reduced ghost fishing or improved benthic habitat quality (Beaumont et al., 2007; Borja et al., 2020). Overall, FFL should be viewed as a complementary mitigation tool rather than a substitute for preventive measures.

3.7. Policy implications at regional and national scale

The marked spatial heterogeneity documented in this study calls for differentiated governance responses. Despite structurally comparable fleets, seabed litter density and composition differed substantially between the study areas, reflecting distinct dominant source pathways.

In the northern Adriatic (Goro), the predominance of mussel socks indicates aquaculture-related diffuse losses as the principal driver. Policy priorities in such systems should therefore emphasize preventive measures, including strengthened aquaculture infrastructure standards, storm-resilience requirements, material traceability, and post-event recovery protocols. Coordinated fisheries–aquaculture frameworks could substantially reduce future inputs.

By contrast, the Salerno case is characterized by bulky waste and localized seabed hotspots. While definitive attribution is not possible, the material signature and spatial concentration are consistent with localized dumping or historical disposal practices. This context suggests the need for enhanced surveillance, targeted enforcement, and stronger integration between marine monitoring systems and terrestrial waste governance. Cross-sectoral coordination among maritime authorities, environmental agencies, and waste regulators may therefore be warranted.

At the national scale, the combined mitigation capacity of approximately 100 t·year^{-1} demonstrates that structured FFL programmes can make tangible contributions to MSFD implementation. However, effective marine litter governance requires coupling fleet-based removal with prevention, enforcement, and standardized density-based monitoring within an ecosystem-based management framework. Diffuse operational losses and concentrated dumping phenomena require distinct but coordinated policy responses.

Future assessments should incorporate high-resolution fishing effort data (e.g., Global Fishing Watch) to enable spatially explicit estimates of FFL mitigation potential. This would strengthen the integration of fisheries-based litter removal into MSFD Descriptor 10 monitoring, support the objectives of the European Green Deal, and enhance evidence-based, ecosystem-based marine management.

4. Conclusion

This study confirms that commercial trawl fisheries can deliver a measurable and operational contribution to seabed litter mitigation through structured Fishing for Litter (FFL) schemes. Across two contrasting Italian marine areas, removal efficiency was shaped primarily by spatial heterogeneity and vessel-level variability. Size-normalized indicators demonstrated that litter removal does not scale proportionally with vessel capacity, underscoring the need for effort-standardized metrics when assessing mitigation performance.

Model outputs confirmed a hotspot-driven distribution of benthic litter, with non-linear depth effects and a clear effort-dilution pattern whereby longer fishing duration reduced standardized removal efficiency. These findings indicate that litter accumulation is controlled more by localized depositional dynamics than by fishing effort alone. Annual scaling suggests that participating fleets can remove several tens of tonnes of litter per year, representing a tangible contribution to MSFD Descriptor 10 targets.

While FFL cannot substitute upstream prevention of land-based inputs, it constitutes a pragmatic and scalable mitigation measure, particularly in hotspot-dominated systems. By combining effort-standardized indicators, size normalization, and fleet-level scaling, the analytical framework developed here provides a transferable approach for integrating fisheries-based mitigation into marine litter monitoring and policy implementation across Mediterranean and European contexts.

To build upon these findings, future research should prioritize long-term monitoring programs to capture seasonal and inter-annual fluctuations in litter dynamics, which are essential for evaluating the long-term efficacy of MSFD mitigation measures. Furthermore, expanding the scope to compare different fishing gears, such as set nets or pelagic trawls, could provide a more comprehensive mapping of litter across the entire water column and various benthic habitats. Finally, integrating high-resolution source-tracking analyses and hydrodynamic modeling will be crucial to distinguish between land-based inputs and sea-based activities. Such advancements will allow for the development of highly targeted, evidence-based management strategies tailored to the unique socio-economic and environmental pressures of Mediterranean coastal basins.

CRediT authorship contribution statement

Michele Mistri: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Fabio Mantovani:** Methodology. **Gennaro Scognamiglio:** Funding acquisition, Conceptualization. **Virginia Strati:** Software, Formal analysis. **Cristina Munari:** Writing – original draft, Validation, Methodology, Formal analysis, Data curation.

Funding

This study was funded by the Italian Ministero dell'Agricoltura, della Sovranità Alimentare e delle Foreste (MASAF), under the Operational

Programme FEAMP 2014/2020 – Measure 1.40 (CUP J89I22000480007), within the project *BLU Marine litter Recovery – Blu Mater*, awarded to UNCIAGROALIMENTARE.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The funder had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Acknowledgements

The authors gratefully acknowledge the crews of the trawlers operating from Goro and Salerno for their work at sea and their active collaboration throughout the project. We also thank Enza Iadevaia (UNCIAGROALIMENTARE) and Loretta Malvarosa (NISEA) for their essential technical support and coordination during the implementation of the study.

Data availability

Data will be made available on request.

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