Rivers of waste: anthropogenic litter in intermittent Sardinian rivers, Italy (Central Mediterranean)

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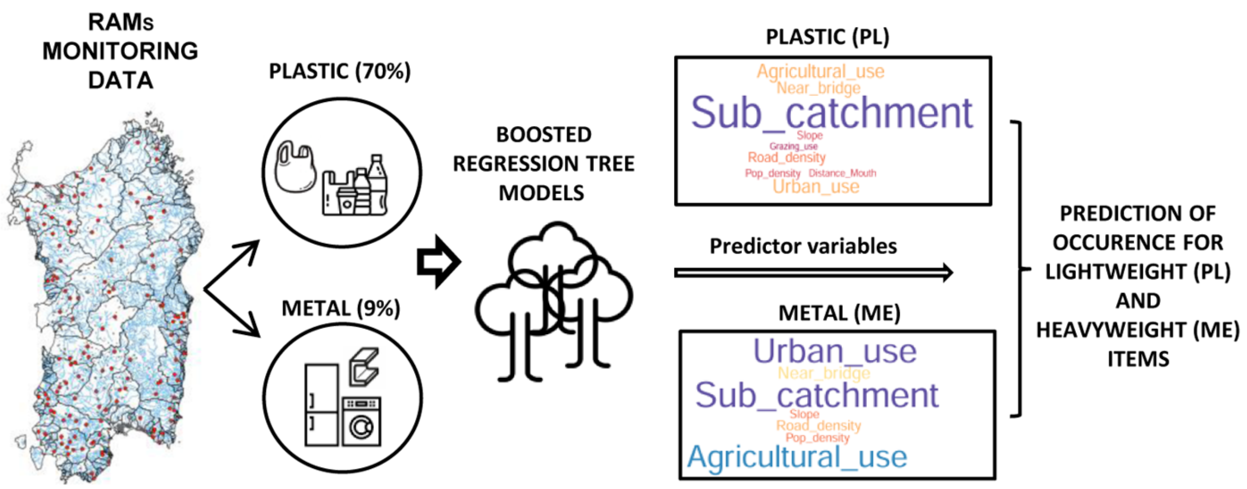
Graphical abstract



Abstract

While the increasing accumulation of anthropogenic litter in the marine environment has received considerable attention over the last decade, litter occurrence and distribution in rivers, the main source of marine litter, have been comparatively less investigated. Moreover, little information is available about the amount and typology of Riverine Anthropogenic Macro-litter (RAM) entering marine environments from intermittent rivers in low populated areas of the Mediterranean basin. To provide insights on this issue, we investigated density and composition of RAM accumulated over a total of 133 riverbanks, belonging to 37 river basins in the Sardinia Island (Mediterranean Sea). We report here that plastics, especially single-use items, represent the most frequent and abundant RAM category in all investigated basins. Statistical modelling revealed that occurence of lightweight RAM (especially plastic) is mostly explained by levels of urban (12.3% of the relative contribution) and agricultural (12%) land use of the territory, whereas the proximity of bridges to the sampling point (21%) and the local population density (19.8%) are best predictors of heavy weighted RAM items (i.e., large metal items, appliances) occurence. Our results confirm that plastics represent an important component of RAM and pinpoint that, beside plastic reduction policies and better waste management, actions aimed at abating and monitoring litter contamination should be localized on the proximity of bridges, whatever the local population density. Finally, to fill existing knowledge gaps in understanding the severity of litter discharge and accumulation in the Mediterranean Sea, land-to-sea systematic monitoring campaigns at appropriate spatial and temporal scales should be put in place.

Keywords: intermittent rivers; macro-litter, plastic, Non-linear Boosted Regression Tree Models

Introduction

Anthropogenic litter in aquatic environments is an emerging issue of global concern due to its negative impacts over the different hierarchical levels of ecological organization which, ultimately, have also socio-economic consequences (Conchubhair et al., 2019; Kühn et al., 2015; Newman et al., 2015; Rochman et al., 2016). In the last few decades, the focus of investigation on the accumulation of anthropogenic litter (mainly plastic) has been heavily skewed towards the marine environment (Galgani et al., 2015), despite the fact that rivers represent the most important conduits for the transportation of anthropogenic litter to the marine environment (Blettler et al., 2018; Jambeck et al., 2015; Schmidt et al., 2017).

It has been postulated that few very large rivers could be the major sources of plastic contamination of the oceanic contamination (Lebreton et al., 2017; Schmidt et al., 2017). However, a recent modelling study, based on field observation, revealed that about 1000 rivers located in highly populated areas and mainly distributed in Asian countries can cumulatively discharge annually between 0.8 and 2.7 million metric tons of macro-plastic (i.e. plastic debris >5 mm) into the global oceans, which account for >80% of riverine annual plastic emissions to the sea (Meijer et al., 2021).

Nevertheless, despite the current literature estimates, the real quantification of total plastic transport from land to seas remains still largely uncertain because of operational difficulties to obtain *in situ* measurements and due to the lack of standard observation techniques (Broere et al., 2021; Edelson et al., 2021; van Emmerik and Schwarz, 2020; Weiss et al., 2021). Intermittent rivers and ephemeral streams are common across Europe and dominate river networks in Mediterranean regions (Skoulikidis et al., 2017; Stubbington et al., 2018). As being ecosystems with unpredictably temporal dynamics of water supply, the role of intermittent rivers in RAM transport to the sea has been almost entirely ignored (Table S1).

Riverine Anthropogenic Macro-litter (RAM) refers to the fraction of solid waste (>5 mm) present in rivers and on riverbanks (González-Fernández et al., 2021; Schmidt et al., 2017). Anthropogenic Macro-litter originates from mismanagement of urban waste, sewage outlets from wastewater treatment plants, illegal dumping, loss of products from industrial and agricultural activities (Bruge et al., 2018; Faure et al., 2015; Galafassi et al., 2019; Kiessling et al., 2019).

Plastic debris are considered dominant in riverine contamination, whereas other materials such as glass, metal are relatively minor contributors due to the intrinsic features of the materials (e.g., specific weight, buoyancy) that likely prevent them to be dislocated via river flow (Castro-Jiménez et al., 2019; Cesarini and Scalici, 2022; González-Fernández et al., 2021; Rech et al., 2014). Besides the aesthetic, ethical and socio-economic damage (Rochman et al., 2016; Williams and Simmons, 1996), the contamination of plastic in riverine ecosystems can cause numerous negative consequences for biota and environment. Plastic debris can potentially degrades into microplastics that could be ingested by aquatic organisms, such as fishes and zooplankton (Galafassi et al., 2021; Rehse et al., 2018). Moreover the presence and accumulation of the trapped plastic in riparian vegetation can cause negative effects on the plant status and survival of trees (van Bijsterveldt et al., 2021).

Abundance, composition and distribution of RAM are influenced by the cumulative effects of an array of environmental characteristics, including: i) the presence of floating (e.g., hyacinth) (Schreyers et al., 2021) and riparian vegetation (e.g., arboreal, reeds, etc.) that act as a barrier, especially during flooding events (Cesarini and Scalici, 2022; Williams and Simmons, 1996; Windsor et al., 2019); ii) tidal influence, iii) seasonal changes of the water level, iv) flow rate (Battulga et al., 2019; Vriend et al., 2020b), and v) curvature and shape of the river (Calcar and van Emmerik, 2019).

Moreover, RAM accumulation can be also influenced by several anthropogenic pressures like land use (Cowger et al., 2019; McCormick and Hoellein, 2016), shipping activities and the presence of fluvial infrastructures (irrigation and drainage channels, wastewater treatment plants, dams and bridges) (Calcar and van Emmerik, 2019; Mihai, 2018; Schirinzi et al., 2020; Simon-Sánchez et al., 2019), human population and road density (Battulga et al., 2019; Jambeck et al., 2015; McCormick and Hoellein, 2016).

The Mediterranean Sea is one of the most important accumulation zones of marine litter worldwide (Cózar et al., 2015; Eriksen et al., 2014; Suaria et al., 2016). Information about RAM inputs from permanent rivers associated with highly populated areas in the Mediterranean Sea is available (e.g. Crosti *et al.*, 2018; Castro-Jiménez *et al.*, 2019; Schirinzi *et al.*, 2020; Cesarini and Scalici, 2022), but, to date, information about RAM from intermittent rivers is still almost absent (Table S1).

To address this knowledge gaps, by contending that RAM's role could be more important than previously thought or hypothesized, this study aims: (1) to assess density and composition of RAM in riverbanks of intermittent rivers in Sardinia; (2) to determine the main factors affecting the occurrence, composition, and distribution of RAM.

Materials and Methods

Study area

The study area is in Sardinia (Italy), the second largest island (ca. 24,106 km²) in the Mediterranean Sea. Sardinia, with a population of 1,630,474, corresponding to a density of nearly 67.7 inhabitants km^{-2}, is one of the less densely populated regions in Italy.

Sardinia is characterized by complex topography with the presence of a long mountain range (Sardinian-Corse Mountain System) that influence the local circulation and spatial distribution of the rainfall (Marras et al., 2021). Bi-seasonal climatic features, with hot arid summers, rainy autumn/winter seasons along with extreme precipitation events, determine irregular flow and strong seasonal hydrological fluctuations (De Waele et al., 2010; Palmas et al., 2020; Podda et al., 2020; Sabatini et al., 2018). The hydrographic network is characterized by the dominance of non-perennial rivers (90% of the total) (Skoulikidis et al., 2017). The recurrent temporal overlap of the dry season with a high water demand for agriculture irrigation, industry and domestic purposes have led the construction of a total of 54 larger dams (Marchetto et al., 2009; Montaldo and Sarigu, 2017), that, interrupt the continuity of perennial rivers (Tirso, Flumendosa and Coghinas), strongly influencing their natural hydrological cycle (Moccia et al., 2020; Naselli-Flores et al., 2014). According to available data provided by Autonomous Region of Sardinia, all dams have both surface and bottom-discharge systems and an average height of 42.5 ± 3 m. While punctual data on the volume of discharge per year was not available, it was possible to assert that the main discharge system is from surface with an average of 884.5 ± 130 m^3 sec^{-1}.

Furthermore, in Sardinia it has been predicted that the future reduction of mean precipitation due to global warming, may further exacerbate droughts with a strong decrease of mean runoff (Marras et al., 2021). For all reasons mentioned above, we considered all investigated rivers as intermittent.

Anthropogenic macrolitter occurrence, abundance, and composition

Litter monitoring was conducted over a total of 133 sampling sites (belonging to 37 river basins), covering different altitudinal zones and environmental conditions across 2018 and

2020 (Figure 1). Litter occurrence on the riverbanks was determined according to the Rivers-OSPAR protocol (van Emmerik et al., 2020a) that was based on the OSPAR beach litter guidelines (OSPAR, 2010). Sampling was carried out on both riverbanks of each river and data of each river were cumulated. The methodological approach was based on the count of macro-litter items (>5 mm) on 100 m long stretches of riverbanks parallel to the waterline, from the waterline itself to the maximum level of floodplain landward (Figure S1). All visible RAM items, deposited in the riverbanks and/or entrapped in the vegetation, were counted within the entire sampling area and, for each station, litter density was calculated as the number of items per kilometer of riverbank (items km^{-1}).

The items were collected and sorted according to the UNEP-Code master list classification for beach litter items (Cheshire et al., 2009; Galgani et al., 2018). The list comprised 128 sub-categories grouped into nine anthropogenic litter materials: artificial polymer materials (PL), rubber (RB), cloth/textile (CL), paper/cardboard (PC), processed/worked wood (WD), metal (ME), glass and ceramics (GC), other materials (OT), undefined (UN).

Factors affecting the occurrence, composition, and distribution of RAM

To determine factors affecting the occurrence, composition and distribution of RAM we first identified from the literature an array of eleven potential variables, grouped into three categories (geomorphology, land use and human pressure; Table S2), assumed to mostly influence the occurence of litter items (presence/absence).

Geo-morphological variables include: i) the sub-catchment area (km^2) above the sampling site as a proxy of catchment runoff; ii) the river order as a proxy of upstream–downstream gradients (according to Strahler method’s (Strahler, 1957); iii) the stream slope as a proxy of potential water velocities. Season of sampling was also used as a proxy of river discharge events, considering the peculiar abovementioned climatic features of Sardinia. Land use data, obtained from the CORINE database, were merged in four categories: natural use (which includes forests and semi-natural areas, among others, but excludes recreational use of the territory), agricultural use, grazing use and urban use. Land cover was expressed as the percentage (%) of each of these categories in the sub-catchment area above each sampling site.

Human pressure proxies were estimated in terms of: i) road density (km km^{-2}), ii) population density (population km^{-2}), iii) the presence/absence of river bridges immediately above the sampling point. When bridges were present, the transects started at the bridge, moving downstream from there. In addition, since the presence of weirs and dams could negatively influence the presence and transport waste items in the riverbanks, the number of dams above the sampling station were also considered.

Georeferenced datasets on hydrographic data, roadways, larger dams, and land use were acquired from the Regional Land Information System of Sardinia.

Statistical analyses

Density from each station was then used to generate distribution maps of the most important litter categories. The free Quantum GIS Desktop, version 2.18.3 (QGIS) (http://www.qgis.org/) software was used for creating distribution maps and to extract the exploratory variables. Sub-catchment area, slope as well as the stream order of each sampling site were calculated based on 10-m resolution Digital Elevation Model (DEM). For the entire river network generated by flow accumulation, stream order was derived with the Strahler method’s (Strahler, 1957).

Since the artificial polymers and metal materials (PL and ME, respectively) were the most abundant anthropogenic litter material (cumulatively accounting for ca. 80% of total litter), we tested whether and to which extent some potential explanatory variables were putative drivers for PL and ME litter occurence using a non-linear Boosted Regression Tree model (BRT, Elith *et al.*, 2008). As we aimed at identifying the conditions that might represent a threshold over which light (PL) and heavy materials (ME) could be found, we used only presence/absence transformed data. BRT models have been used to analyse the relationships between response and predictor variables in different fields of environmental science (Ju et al., 2021; Lagarde et al., 2021; Lemm et al., 2021; Saha et al., 2021). BRT models allow testing different types of predictive variables by fitting complex non-linear relationships and handling interaction effect between predictors, while not depending on the normality and homoscedasticity of the data (Déath, 2007; Elith et al., 2008).

To fit the BRT models, the learning rate (the importance of each iteration in the model) and tree complexity were set through an iterative process to ensure that the final model outcome consisted of at least 1000 decision trees (Elith *et al.*, 2008). The relative importance of each predictor variable has been also calculated from the BRT model and was visualised in partial dependence plots. BRT models were run with a Bernoulli link function. The BTRs' performance was evaluated by the amount of total deviance explained (DEV %) and by cross-validated correlation between model prediction and observed data (R^2 of CV) (Derville et al., 2016; Ju et al., 2021; Nieto and Mélin, 2017; Saha et al., 2021). The predictive performance of the BTRs were also tested and evaluated using the threshold-independent Receiver-Operating Characteristic (ROC) curve and the estimation of the area under ROC plot (AUC) (Amorim et al., 2016; Derville et al., 2016; Saha et al., 2021; Wang et al., 2021). Collinearity among covariates was tested by computing pairwise scatter plots among covariates. Covariates showing relevant Sperman's Rho ($\rho > 0.7$) were discarded from the modelling. The Variance Inflation Factor (VIF) was also used to check collinearities among explanatory variables; those showing VIF >3 were also discarded from the analysis (Zuur et al., 2010).

All analyses were carried out using the statistical software package R (R Core Team, 2021). BRTs are estimated using the "dismo" library (Hijmans et al., 2011). The ROC analysis was performed using the R package pROC (Robin et al., 2011).

Results

A total of 2078 RAM items were collected from the 37 river basins, covering ca. 22 linear km of riverbanks. Out of 133 sampling stations, 114 (85.7%) showed the presence of litter items, and only 19 were litter free. Overall, 28 sub-categories of litter items were found on Sardinian rivers, even if the top 5 most abundant types of items represented most of the litter found (~70%, Table S3). Artificial polymers materials (PL, 70.4%) were the most abundant category, followed by Metal (ME, 9.3%), Cloth/Texile (CL, 8.5%) and Glass & Ceramic (GC, 7.4%) (Figure 2a). Other materials (including rubber; RB), paper; PE, and processed wood; WD) represented cumulatively 4.4% of all the litter. Artificial polymers items consisted mostly of single-use plastic items such as bags (PL07, 60%), bottles caps and lids (PL01, 16%) and small bottles (PL02, 11%) (Figure 2b). Metal dominant categories were equally cans (ME03; 37%) and metallic objects larger than 50cm (ME10; 38%).

Overall, the mean litter density for all investigated riverbanks was 156±19 items km^{-1} (median value of 90 items km^{-1}). The highest litter mean density was measured in the river basins of Flumini Mannu (R2_1) (393±100 items km^{-1}), Mannu di San Sperate (R2_2) (386±168 items km^{-1}), Pelau (O3) (335±335 items km^{-1}) and Flumendosa (P_1) (318±263 items km^{-1}) (Figure 2c). With the exception of Pelau river basin (O3), where the highest litter densities were measured at the most upstream location and mainly composed of glass and ceramic items (GC) (670 items km^{-1}) (Figure 3a), likely too heavy to be transported downstream as per other lighter materials. All other river basins were characterized by litter dominated by PL, with the highest PL items densities recorded in downstream sampling stations (Figure 3b).

Analysis of multi-collinearity among predictive variables revealed strong correlations between natural use (Natural_use), agricultural use (Agricoltural_use) (ρ = -0.9), number of larger dams above the sampling station (Dams) and sub-catchment area (Sub_catchment) (ρ = 0.7). After removing Natural_use and the Dams variables, the VIF values did not exceed 3.0.

The results of BTR model revealed that the presence of plastic litter (PL) is influenced by the joint effect of geomorphological variables, land use and human pressures. The PL model accounted for 40% of the total deviance and a CV correlation between predicted and observed data of 0.70. The analysis of the relative importance of the different predictors revealed that the sub-catchment area (Sub_catchment) (34.5%), urban use (Urban_use) (12.3%), agricultural use (Agricoltural_use) (12.0%), the presence of a bridge above the sampling point (Near_bridge) (10.1%) and road density (Road_density) (7.5%) represented the highest share in relative explained deviance (Table 1). The partial responses of single predictors showed a predominantly positive linear trend with a plateau for Sub_catchment, Urban_use, Road_density and Agricoltural_use (Figure S2a). In particular, the sub-catchment curve is steeper than that of all other predictors and reaches a peak at a relatively small surface area (60 km^{-1}). The effects of land use variables were approximately J-shaped, with the probability of occurence of PL litter significantly increased after 0.5% and 6.5% of coverage area for urban and agricultural use, respectively (Figure S2a). The PL litter is also found most in stretches of rivers characterized by the presence of a bridge. Road density concentration had a consistent positive relationship with PL items' probability of occurence (Figure S2a).

The BRT model applied to heavy materials (ME) explained 16% of the predicted deviance and a CV correlation between predicted and observed data of 0.57. The most significant predictor for ME occurence were the sub catchment area above the sampling station (22.6%) followed by the presence of a bridge (Near_bridge, 21.1%) and population's density (Pop_density, 19,8%) (Table 1, Figure S2b).

The outcomes of the AUC of ROC curves confirmed that the machine learning (BRTs) models have a good prediction capability for detecting the probability of occurrence of either PL or ME (0.92 and 0.83, respectively) (Table 1).

Discussion

Our study provides evidence that a high frequency (~ 86%) of intermittent rivers in Sardinia are contaminated by Riverine Anthropogenic Macro-litter (RAM). We show here that RAM composition in Sardinian intermittent rivers is dominated by PL items (~70 %) followed by metal (ME) and glass (GL) (9% and 7%, respectively). Our results confirm previous studies worldwide which reported PL items as the globally dominant category in riverbanks (Battulga et al., 2019; Bruge et al., 2018; Carpenter and Wolverton, 2017; Hoellein et al., 2014; Kiessling et al., 2019; Rech et al., 2014; Schöneich-Argent et al., 2020; van Emmerik et al., 2020a). Within the PL macro-category, single-use items such as plastic bags (~60%) and bottle caps and/or covers (11%) are the most common items on

Sardinian riverbanks, as also observed in other European locations (Bernardini et al., 2020; Winton et al., 2020).

The mean density of total litter for the whole study period is 156 items km^{-1} (median 90 items km^{-1}) with a remarkable heterogeneity among different river basins, despite their distance from each other. The Flumini Mannu is the most polluted basin (393± 100 items km^{-1}), followed by the Mannu di San Sperate (386±168 items km^{-1}) and Flumendosa (318±263 items km^{-1}). Differences in geographical locations, social and economic context and sampling techniques make comparisons of RAM abundance among freshwater studies very challenging (Blettler et al., 2018; van Emmerik et al., 2019b; Vriend et al., 2020a). Nevertheless, considering those studies focused on riverbanks that used the same sampling approach of this study, we report here that the RAMs' mean abundance in the intermittent rivers in Sardinia are an order of magnitude lower than those reported for the Rhine and the Meuse rivers (North Sea) (median value 2060 items km^{-1}) (van Emmerik et al., 2020a, 2020c). It is worth of notice that these systems are characterized by different hydrological and anthropogenic factors such as discharge and population density.

The machine learning method (BRTs) identified the relative importance of a set of different factors able to explain a significant proportions of variance observed for light weight (PL) and heavy weight (ME) RAMs occurring along the Sardinian riverbanks. The model applied to the PL macro-category has a relatively good explanatory power and identifies, in decreasing order, the sub-catchment area surface, the urban and agricultural percentage use of land and the presence/absence of bridges as the most important predictors of RAM occurrence.

Our model predicted that the larger the sub-catchment area surface above the sampling station, the more the occurrence of light (PL) RAMs can be expected. The primary role of the sub-catchment area surface can be associated with the fact that most plastic waste originates, generally, from land-based areas due to the littering or illegal landfill of waste (Chae and An, 2018; Geyer et al., 2017). There, light (PL) RAMs may be washed away from drainage areas by the additive effects of wind, heavy rainfall and floods (Bruge et al., 2018; Carpenter and Wolverton, 2017; Windsor et al., 2019; Zylstra, 2013). Moreover, the larger the sub-catchment area, the more riparian vegetation plays a role in litter accumulation. In this regard, we report here that, for instance, plastic bags were mostly found trapped in the vegetation at the riverside, which is known to act as a trap for floating materials (Schöneich-Argent et al., 2020; Schreyers et al., 2021; van Emmerik and Schwarz, 2020; Williams and Simmons, 1996). Moreover, given that the floodplains were, sometimes, covered by dense arboreal, shrubs and herbaceous vegetation associations occurence and abundance of the smaller sized of PL items could be likely underestimated.

The same, though lower, explanatory power on litter occurrence is observed for the agricultural and urban percentage use of the territory, the increase of which has been already reported to positively affect PL RAMs' occurrence (Bruge et al., 2018; Carpenter and Wolverton, 2017; Cowger et al., 2019; Glanville and Chang, 2015; Guerranti et al., 2020; van der Wal et al., 2015). This effect appears particularly relevant in the subset of Sardinian rivers (Flumini Mannu and Mannu di San Sperate) that run along the Campidano plain, characterized by an almost entire occupancy of the territory by agricultural and dense different urban uses.

The third explanatory factor of PL RAMs occurrence identified by our model is the presence of bridges immediately above the sampling station. This result could depend on the slowdown of the river flow which favors the accumulation of waste on the riverbanks (Hoellein et al., 2014; Kiessling et al., 2019; Lebreton et al., 2017). Moreover, the prevalence of plastic bags in those localities suggests the persistence of the incorrect behavior of abandoning waste in places that, due to the landscape attractivity of bridges, makes them often used for refreshment breaks of tourists, motorists, and campers.

The sub-catchment area, the presence of bridges and the population density are the most important predictors also of the occurrence of heavy materials (ME) in Sardinian riverbanks. The highest abundance of discarded house appliances and aluminum drink cans (38% and 37% of the total ME items, respectively) suggests that the illegal disposal and dumping of ME are main sources of litter.

The 2019 report on Sardinian Urban Waste Management has estimated a total production of urban waste of ~740 tons year^{-1} with 454 kg/habitant/year (ARPAS, 2019).

Even if Sardinia is considered the second best performing region in Italy in terms of waste management with a recycling rate of 73% (ARPAS, 2019), a certain fraction of the total household waste generated is currently susceptible to uncontrolled disposal in unauthorized landfill and river dumping. Our results reveal also that illegal landfills in proximity of bridges and secondary roads are much more common in sub-catchment areas characterized by higher population density. This result, again, fits with the observations made on riverbanks of Chile, Wales and Romania, where the combination of illegal dumping and human presence, more than the road density, have been identified as the main sources of litter items occurrence (Cowger et al., 2019; Kiessling et al., 2019; Mihai, 2018; Rech et al., 2014; Williams and Simmons, 1997).

Moreover, we cannot exclude that other factors, not included in this study, and associated with hydrological (runoff, flow velocity, discharge, vegetation cover) and anthropogenic factors (tourism and recreation activities, poor waste management practices on land) could explain a certain portion of RAMs occurrence variance in riverbanks and their potential transport to the sea (Bruge et al., 2018; Kiessling et al., 2019; Schirinzi et al., 2020; Windsor et al., 2019). In this regard, heavy rain and extreme flooding events have been suggested to affect the transport and accumulation of RAM items (Axelsson and van Sebille, 2017; van Emmerik et al., 2020b, 2019b, 2019a). Despite the above biases, we must notice here that, since we limited our analysis to macroscopic RAMs (> 5mm), the potential severity of our results could rise when considering smaller size items (Schöneich-Argent et al., 2020). The complex hydrological scenario that characterizes Sardinian coastal marine waters (Olita et al., 2013; Palmas et al., 2017) does not allow to infer about the actual linkages between the abundance of macro-litter observed across marine coastlines (Alvito et al., 2018; Cau et al., 2022) and their occurrence in riverbanks, since floating debris might end up well far from the source (Cózar et al., 2015; González-Fernández et al., 2021).

Finally, it is worth of mention the higher quantities of litter items near bridges indicated that these areas can act both as sinks and source of RAM. In this perspective, more supportive infrastructures for the disposal of urban litter and monitoring and surveillance measures should be envised. Surveillance of illegal waste disposal sites is often complicated by the relative geographical isolation of disposal locations which hinders the efficiency and cost effectiveness of intensive surveillance (Glanville and Chang, 2015; Tasaki et al., 2007). Surveillance cameras aimed at detecting illegal dumping action (Yun et al., 2019), could represent a powerful control method to be positioned in critical spots such as bridges. Also, the identification of bridges as sink and source can represent a useful insights for prioritizing mitigation actions foreseen by local authorities or cleanup activities.

Conclusions

Overall, the results of our study, though limited to a regional spatial scale, highlight that a certain, not irrelevant, amount of RAM litter can accumulate along the banks of intermittent rivers, confirming and posing light on the severity of riverine contamination and its potential to transport waste into the sea. This issue would appear more crucial in the southern Mediterranean Sea, in which most rivers have an intermittent water flow regime.

Finally, to fill existing knowledge gaps in understanding the severity of litter discharge and accumulation, temporally and spatially replicated land-to-sea systematic monitoring campaigns should be put in place.

We pinpoint also that further special effort should be also paid to optimize and standardize protocols of identification, characterization and quantification of RAMS in different environments (Bernardini *et al.*, 2020; van Emmerik *et al.*, 2020b; Vriend *et al.*, 2020b).

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References

Alvito, A., Bellodi, A., Cau, A., Moccia, D., Mulas, A., Palmas, F., Pesci, P., Follesa, M.C., 2018. Amount and distribution of benthic marine litter along Sardinian fishing grounds (CW Mediterranean Sea). Waste Manag. 75. doi:10.1016/j.wasman.2018.02.026

Amorim, E., Ramos, S., Elliott, M., Bordalo, A.A., 2016. Immigration and early life stages recruitment of the European flounder (*Platichthys flesus*) to an estuarine nursery: The influence of environmental factors. J. Sea Res. 107, 56–66. doi:10.1016/j.seares.2015.07.005

ARPAS, 2019. 21 ° Rapporto sulla gestione dei rifiuti urbani in Sardegna Anno 2019.

Atwood, E.C., Falcieri, F.M., Piehl, S., Bochow, M., Matthies, M., Franke, J., Carniel, S., Sclavo, M., Laforsch, C., Siegert, F., 2019. Coastal accumulation of microplastic particles emitted from the Po River, Northern Italy: Comparing remote sensing and hydrodynamic modelling with in situ sample collections. Mar. Pollut. Bull. 138, 561–574. doi:10.1016/j.marpolbul.2018.11.045

Axelsson, C., van Sebille, E., 2017. Prevention through policy: Urban macroplastic leakages to the marine environment during extreme rainfall events. Mar. Pollut. Bull. 124, 211–227. doi:10.1016/j.marpolbul.2017.07.024

Battulga, B., Kawahigashi, M., Oyuntsetseg, B., 2019. Distribution and composition of plastic debris along the river shore in the Selenga River basin in Mongolia. Environ. Sci. Pollut. Res. 26, 14059–14072. doi:10.1007/s11356-019-04632-1

Bernardini, G., McConville, A.J., Castillo Castillo, A., 2020. Macro-plastic pollution in the tidal Thames: An analysis of composition and trends for the optimization of data collection. Mar. Policy 119, 104064. doi:10.1016/j.marpol.2020.104064

Blašković, A., Guerranti, C., Fastelli, P., Anselmi, S., Renzi, M., 2018. Plastic levels in sediments closed to Cecina river estuary (Tuscany, Italy). Mar. Pollut. Bull. 135, 105–109. doi:10.1016/j.marpolbul.2018.07.021

Blettler, M.C.M., Abrial, E., Khan, F.R., Sivri, N., Espinola, L.A., 2018. Freshwater plastic pollution: Recognizing research biases and identifying knowledge gaps. Water Res. 143, 416–424. doi:10.1016/j.watres.2018.06.015

Broere, S., van Emmerik, T., González-Fernández, D., Luxemburg, W., de Schipper, M., Cózar, A., van de Giesen, N., 2021. Towards underwater plastic monitoring using echo sounding. Front. Earth Sci. 9, 628704. doi:10.3389/feart.2021.628704

Bruge, A., Barreau, C., Carlot, J., Collin, H., Moreno, C., Maison, P., 2018. Monitoring litter inputs from the Adour River (Southwest France) to the marine environment. J. Mar. Sci. Eng. 6, 1–12. doi:10.3390/jmse6010024

Calcar, C.J. Van, van Emmerik, T., 2019. Abundance of plastic debris across European and Asian rivers. Environ. Res. Lett. 14, 124051. doi:10.1088/1748-9326/ab5468

Campanale, C., Stock, F., Massarelli, C., Kochleus, C., Bagnuolo, G., Reifferscheid, G., Uricchio, V.F., 2020. Microplastics and their possible sources: The example of Ofanto river in southeast Italy. Environ. Pollut. 258, 113284. doi:10.1016/j.envpol.2019.113284

Carpenter, E., Wolverton, S., 2017. Plastic litter in streams : The behavioral archaeology of a pervasive environmental problem. Appl. Geogr. 84, 93–101. doi:10.1016/j.apgeog.2017.04.010

Castro-Jiménez, J., González-Fernández, D., Fornier, M., Schmidt, N., Sempéré, R., 2019. Macro-litter in surface waters from the Rhone River: Plastic pollution and loading to the NW Mediterranean Sea. Mar. Pollut. Bull. 146, 60–66. doi:10.1016/j.marpolbul.2019.05.067

Cau, A., Franceschini, S., Moccia, D., Gorule, P.A., Agus, B., Bellodi, A., Cannas, R., Carugati, L., Cuccu, D., Dessì, C., Marongiu, M.F., Melis, R., Mulas, A., Porceddu, R., Porcu, C., Russo, T., Follesa, M.C., 2022. Scattered accumulation hotspots of macro-litter on the seafloor: Insights for mitigation actions. Environ. Pollut. 292, 118338. doi:10.1016/j.envpol.2021.118338

Cesarini, G., Scalici, M., 2022. Riparian vegetation as a trap for plastic litter. Environ. Pollut. 292, 118410. doi:10.1016/j.envpol.2021.118410

Chae, Y., An, Y.J., 2018. Current research trends on plastic pollution and ecological impacts on the soil ecosystem: A review. Environ. Pollut. 240, 387–395. doi:10.1016/j.envpol.2018.05.008

Cheshire, A.C., Adler, E., Barbière, J., Cohen, Y., Evans, S., Jarayabhand, S., Jeftic, L., Jung, R.T., Kinsey, S., Kusui, E.T., Lavine, I., Manyara, P., Oosterbaan, L., Pereira, M.A., Sheavly, S., Tkalin, A., Varadarajan, S., Wenneker, B., Westphalen, G., 2009. UNEP / IOC Guidelines on Survey and Monitoring of Marine Litter.

Conchubhair, D.Ó., Fitzhenry, D., Lusher, A., King, A.L., Van Emmerik, T., Lebreton, L., Ricaurte-Villota, C., Espinosa, L., O’Rourke, E., 2019. Joint effort among research infrastructures to quantify the impact of plastic debris in the ocean. Environ. Res. Lett. 14, 065001. doi:10.1088/1748-9326/ab17ed

Constant, M., Ludwig, W., Kerhervé, P., Sola, J., Charrière, B., Sanchez-vidal, A., Canals, M., Heussner, S., 2020. Microplastic fluxes in a large and a small Mediterranean river catchments : The Têt and the Rhône , Northwestern Mediterranean Sea. Sci. Total Environ. J. 716, 136984. doi:10.1016/j.scitotenv.2020.136984

Cowger, W., Gray, A.B., Schultz, R.C., 2019. Anthropogenic litter cleanups in Iowa riparian areas reveal the importance of near-stream and watershed scale land use. Environ. Pollut. 250, 981–989. doi:10.1016/j.envpol.2019.04.052

Cózar, A., Sanz-Martín, M., Martí, E., González-Gordillo, J.I., Ubeda, B., Á.gálvez, J., Irigoien, X., Duarte, C.M., 2015. Plastic accumulation in the Mediterranean Sea. PLoS One 10, e0121762. doi:10.1371/journal.pone.0121762

Crosti, R., Arcangeli, A., Campana, I., Paraboschi, M., González, D., 2018. ‘ Down to the river ’: amount , composition , and economic sector of litter entering the marine compartment , through the Tiber river in the Western Mediterranean Sea. Rend. Lincei. Sci. Fis. e Nat. 29, 859–866. doi:10.1007/s12210-018-0747-y

De Waele, J., Martina, M.L. V, Sanna, L., Cabras, S., Cossu, Q.A., 2010. Flash flood hydrology in karstic terrain: Flumineddu Canyon, central-east Sardinia. Geomorphology 120, 162–173. doi:10.1016/j.geomorph.2010.03.021

Déath, G., 2007. Boosted trees for ecological modeling and prediction. Ecology 88, 243–251. doi:10.1890/0012-9658(2007)88[243:BTFEMA]2.0.CO;2

Derville, S., Constantine, R., Baker, C.S., Oremus, M., Torres, L.G., 2016. Environmental correlates of nearshore habitat distribution by the Critically Endangered Maui dolphin. Mar. Ecol. Prog. Ser. 551, 261–275. doi:10.3354/meps11736

Edelson, M., Håbesland, D., Traldi, R., 2021. Uncertainties in global estimates of plastic waste highlight the need for monitoring frameworks. Mar. Pollut. Bull. 171, 112720. doi:10.1016/j.marpolbul.2021.112720

Elith, J., Leathwick, J.R., Hastie, T., 2008. A working guide to boosted regression trees. J. Anim. Ecol. 77, 802–813. doi:10.1111/j.1365-2656.2008.01390.x

Eriksen, M., Lebreton, L.C.M., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., Galgani, F., Ryan, P.G., Reisser, J., 2014. Plastic Pollution in the World’s Oceans: More than 5 Trillion Plastic Pieces Weighing over 250,000 Tons Afloat at Sea. PLoS One 9, e111913. doi:10.1371/journal.pone.0111913

Faure, F., Demars, C., Wieser, O., Manuel, K., De Alencastro, L.F., 2015. Plastic pollution in Swiss surface waters : nature and concentrations, interaction with pollutants. Environ. Chem. 12, 582–591. doi:10.1071/EN14218

Galafassi, S., Nizzetto, L., Volta, P., 2019. Plastic sources: A survey across scientific and grey literature for their inventory and relative contribution to microplastics pollution in natural environments, with an emphasis on surface water. Sci. Total Environ. 693, 133499. doi:10.1016/j.scitotenv.2019.07.305

Galafassi, S., Sighicelli, M., Pusceddu, A., Bettinetti, R., Cau, A., Temperini, M.E., Gillibert, R., Ortolani, M., Pietrelli, L., Zaupa, S., Volta, P., 2021. Microplastic pollution in perch (*Perca fluviatilis*, Linnaeus 1758) from Italian south-alpine lakes. Environ. Pollut. 288, 117782. doi:10.1016/j.envpol.2021.117782

Galgani, F., Giorgetti, A., Moigne, M. Le, Brosich, A., Vinci, M., Lipizer, M., Molina, E., Schlitzer, R., Hanke, G., Moncoiffe, G., Schaap, D., Giorgi, G., Addamo, A., Chaves Montero, M., 2018. EMODnet Thematic Lot n ° 4 - Chemistry Guidelines and forms for gathering marine litter data.

Galgani, F., Hanke, G., Maes, T., 2015. Global Distribution, Composition and Abundance of Marine Litter, in: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, Cham, pp. 29–56. doi:10.1007/978-3-319-16510-3_2

Gallitelli, L., Cesarini, G., Cera, A., Sighicelli, M., Lecce, F., Menegoni, P., Scalici, M., 2020. Transport and Deposition of Microplastics and Mesoplastics along the River Course: A Case Study of a Small River in Central Italy. Hydrology 7, 90. doi:10.3390/hydrology7040090

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3, 25–29. doi:10.1126/sciadv.1700782

Glanville, K., Chang, H.C., 2015. Mapping illegal domestic waste disposal potential to support waste management efforts in Queensland, Australia. Int. J. Geogr. Inf. Sci. 29, 1042–1058. doi:10.1080/13658816.2015.1008002

González-Fernández, D., Cózar, A., Hanke, G., Viejo, J., Morales-caselles, C., Bakiu, R., Barceló, D., Bessa, F., Bruge, A., Cabrera, M., Castro-jiménez, J., Constant, M., Crosti, R., Galletti, Y., 2021. Floating macrolitter leaked from Europe into the ocean. Nat. Sustain. 4, 474–483. doi:10.1038/s41893-021-00722-6

Guerranti, C., Cannas, S., Scopetani, C., Fastelli, P., Cincinelli, A., Renzi, M., 2017. Plastic litter in aquatic environments of Maremma Regional Park (Tyrrhenian Sea, Italy): Contribution by the Ombrone river and levels in marine sediments. Mar. Pollut. Bull. 117, 366–370. doi:10.1016/j.marpolbul.2017.02.021

Guerranti, C., Perra, G., Martellini, T., Giari, L., Cincinelli, A., 2020. Knowledge about microplastic in mediterranean tributary river ecosystems: Lack of data and research needs on such a crucial marine pollution source. J. Mar. Sci. Eng. 8. doi:10.3390/jmse8030216

Hijmans, R.J., Phillips, S., Leathwick, J., Elith, J., 2011. dismo: Species Distribution Modeling [WWW Document]. R Packag. version 1.1-4. URL http://cran.r-project.org/web/packages/dismo/index.html. (accessed 11.10.21).

Hoellein, T., Rojas, M., Pink, A., Gasior, J., Kelly, J., 2014. Anthropogenic Litter in Urban Freshwater Ecosystems : Distribution and Microbial Interactions. PLoS One 9, e98485. doi:10.1371/journal.pone.0098485

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science (80-.). 347, 768–771. doi:10.1126/science.1260352

Ju, M.C., Zhang, T.L., Li, X.K., Li, B.Y., Li, Y.P., Liu, Q.Y., Wang, Q.X., Bu, C.F., 2021. Large scale environmental drivers of biocrust distribution and development across a sandy desert in China. Catena 200, 105137. doi:10.1016/j.catena.2020.105137

Kiessling, T., Knickmeier, K., Kruse, K., Brennecke, D., Nauendorf, A., Thiel, M., 2019. Plastic Pirates sample litter at rivers in Germany - Riverside litter and litter sources estimated by schoolchildren. Environ. Pollut. 245, 545–557. doi:10.1016/j.envpol.2018.11.025

Kühn, S., Rebolledo, E.L.B., van Franeker, J.A., 2015. Deleterious Effects of Litter on Marine Life, in: Bergam, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, Cham, pp. 75–116. doi:10.1007/978-3-319-16510-3

Lagarde, R., Peyre, J., Amilhat, E., Bourrin, F., Prellwitz, F., Simon, G., Faliex, E., 2021. Movements of non-migrant european eels in an urbanised channel linking a mediterranean lagoon to the sea. Water (Switzerland) 13, 1–14. doi:10.3390/w13060839

Lebreton, L.C.M., Zwet, J. Van Der, Damsteeg, J., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world’ s oceans. Nat. Commun. 8, 15611. doi:10.1038/ncomms15611

Lemm, J.U., Venohr, M., Globevnik, L., Stefanidis, K., Panagopoulos, Y., van Gils, J., Posthuma, L., Kristensen, P., Feld, C.K., Mahnkopf, J., Hering, D., Birk, S., 2021. Multiple stressors determine river ecological status at the European scale: Towards an integrated understanding of river status deterioration. Glob. Chang. Biol. 27, 1962–1975. doi:10.1111/gcb.15504

Llorca, M., Vega-Herrera, A., Schirinzi, G., Savva, K., Abad, E., Farré, M., 2021. Screening of suspected micro(nano)plastics in the Ebro Delta (Mediterranean Sea). J. Hazard. Mater. 404, 124022. doi:10.1016/j.jhazmat.2020.124022

Marchetto, A., Padedda, B.M., Mariani, M.A., Lugliè, A., Sechi, N., 2009. A numerical index for evaluating phytoplankton response to changes in nutrient levels in deep mediterranean reservoirs. J. Limnol. 68, 106–121. doi:10.4081/jlimnol.2009.106

Marras, P.A., Lima, D.C.A., Soares, P.M.M., Cardoso, R.M., Medas, D., Dore, E., Giudici, G. De, 2021. Future precipitation in a Mediterranean island and streamflow changes for a small basin using EURO-CORDEX regional climate simulations and the SWAT model. J. Hydrol. 603, 127025. doi:10.1016/j.jhydrol.2021.127025

McCormick, A.R., Hoellein, T.J., 2016. Anthropogenic litter is abundant , diverse , and mobile in urban rivers : Insights from cross-ecosystem analyses using ecosystem and community ecology tools. Limnol. Oceanogr. 61, 1718–1734. doi:10.1002/lno.10328

Meijer, L.J.J., Emmerik, T. Van, van der Ent, R., Schmidt, C., Lebreton, L., 2021. More than 1000 rivers account for 80 % of global riverine plastic emissions into the ocean. Sci. Adv. 7, eaaz5803. doi:10.1126/sciadv.aaz5803

Mihai, F.C., 2018. Rural plastic emissions into the largest mountain lake of the Eastern Carpathians. R. Soc. Open Sci. 5, 172396. doi:10.1098/rsos.172396

Moccia, D., Salvadori, L., Ferrari, S., Carucci, A., Pusceddu, A., 2020. Implementation of the EU ecological flow poloicy in Italy with focus on Sardinia. Adv. Oceanogr. Limnol. 11, 22–34.

Montaldo, N., Sarigu, A., 2017. Potential links between the North Atlantic Oscillation and decreasing precipitation and runoff on a Mediterranean area. J. Hydrol. 553, 419–437. doi:10.1016/j.jhydrol.2017.08.018

Naselli-Flores, L., Lugliè, A., Naselli-flores, L., Lugliè, A., 2014. Laghi artificiali dell' Italia meridionale e delle isole maggiori. Biol. Ambient. 28, 1–8.

Newman, S., Watkins, E., Farmer, A., ten Brink, P., J.P, S., 2015. The Economics of Marine Litter, in: Bergam, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, Cham, pp. 367–394. doi:10.1007/978-3-319-16510-3

Nieto, K., Mélin, F., 2017. Variability of chlorophyll-a concentration in the Gulf of Guinea and its relation to physical oceanographic variables. Prog. Oceanogr. 151, 97–115. doi:10.1016/j.pocean.2016.11.009

Olita, A., Ribotti, A., Fazioli, L., Perilli, A., Sorgente, R., 2013. Surface circulation and upwelling in the Western Sardinia sea: A numerical study. Cont. Shelf Res. doi:10.1016/j.csr.2013.10.011

OSPAR, 2010. Guideline for monitoring marine litter on the beachs in the OSPAR Maritime Area, OSPAR Commission.

Palmas, F., Olita, A., Addis, P., Sorgente, R., Sabatini, A., 2017. Modelling giant red shrimp larval dispersal in the Sardinian seas : density and connectivity scenarios. Fish. Oceanogr. 26, 364–378. doi:10.1111/fog.12199

Palmas, F., Righi, T., Musu, A., Frongia, C., Podda, C., Serra, M., Splendiani, A., Caputo Barucchi, V., Sabatini, A., 2020. Pug-Headedness Anomaly in a Wild and Isolated Population of Native Mediterranean Trout *Salmo trutta* L ., 1758 Complex

(Osteichthyes : Salmonidae). Dyversity 535. doi:10.3390/d12090353

Podda, C., Palmas, F., Frau, G., Chessa, G., Culurgioni, J., Diciotti, R., Fois, N., Sabatini, A., 2020. Environmental influences on the recruitment dynamics of juvenile European eels, *Anguilla anguilla*, in a small estuary of the Tyrrhenian Sea, Sardinia, Italy. Aquat. Conserv. Mar. Freshw. Ecosyst. 30, 1638–1648. doi:10.1002/aqc.3362

R Core Team, 2021. R: A Language and Environment for Statistical Computing [WWW Document]. R Found. Stat. Comput. Vienna. URL https://www.r-project.org

Rech, S., Macaya-Caquilpán, V., Pantoja, J.F., Rivadeneira, M.M., Jofre Madariaga, D., Thiel, M., 2014. Rivers as a source of marine litter - A study from the SE Pacific. Mar. Pollut. Bull. 82, 66–75. doi:10.1016/j.marpolbul.2014.03.019

Rehse, S., Kloas, W., Zarfl, C., 2018. Microplastics reduce short-term effects of environmental contaminants. Part I: Effects of bisphenol a on freshwater zooplankton are lower in presence of polyamide particles. Int. J. Environ. Res. Public Health 15. doi:10.3390/ijerph15020280

Robin, X., Turck, N., Hainard, A., Tiberti, N., Lisacek, F., Sanchez, J.-C., Muller, M., 2011. pROC: an open-source package for R and S+ to analyze and compare ROC curves. BMC Bioinformatics 8, 12–77.

Rocamora, C., Puerto, H., Abadía, R., Brugarolas, M., Martínez-Carrasco, L., Cordero, J., 2021. Floating Debris in the Low Segura River Basin (Spain): Avoiding Litter through the Irrigation Network. Water 13, 1074. doi:10.3390/w13081074

Rochman, C.M., Browne, M.A., Underwood, A.J., van Franeker, J.A., Thompson, R.C., Amaral-Zettler, L.A., 2016. The ecological impact of marine debris: unraveling the demostrated evidence from what is percived. Ecology 97, 302–312. doi:https://doi.org/10.1890/14-2070.1

Sabatini, A., Podda, C., Frau, G., Cani, M. V., Musu, A., Serra, M., Palmas, F., 2018. Restoration of native Mediterranean brown trout *Salmo cettii* Rafinesque, 1810 (Actinopterygii: Salmonidae) populations using an electric barrier as a mitigation tool. Eur. Zool. J. 85, 138–150. doi:10.1080/24750263.2018.1453554

Saha, S., Arabameri, A., Saha, A., Blaschke, T., Ngo, P.T.T., Nhu, V.H., Band, S.S., 2021. Prediction of landslide susceptibility in Rudraprayag, India using novel ensemble of conditional probability and boosted regression tree-based on cross-validation method. Sci. Total Environ. 764, 142928. doi:10.1016/j.scitotenv.2020.142928

Schirinzi, G.F., Köck-Schulmeyer, M., Cabrera, M., González-Fernández, D., Hanke, G., Farré, M., Barceló, D., 2020. Riverine anthropogenic litter load to the Mediterranean Sea near the metropolitan area of Barcelona , Spain. Sci. Total Environ. 714, 136807. doi:10.1016/j.scitotenv.2020.136807

Schmidt, C., Krauth, T., Wagner, S., 2017. Export of Plastic Debris by Rivers into the Sea. Environ. Sci. Technol. 51, 12246–12253. doi:10.1021/acs.est.7b02368

Schmidt, N., Thibault, D., Galgani, F., Paluselli, A., Sempéré, R., 2018. Occurrence of microplastics in surface waters of the Gulf of Lion (NW Mediterranean Sea). Prog. Oceanogr. 163, 214–220. doi:10.1016/j.pocean.2017.11.010

Schöneich-Argent, R.I., Dau, K., Freund, H., 2020. Wasting the North Sea? – A field-based assessment of anthropogenic macrolitter loads and emission rates of three German tributaries. Environ. Pollut. 263, 114367. doi:10.1016/j.envpol.2020.114367

Schreyers, L., van Emmerik, T., Nguyen, T.L., Phung, N.-A., Kieu-Le, T.C., Castrop, E., Bui, T.-K.L., Strady, E., Kosten, S., Biermann, L., van den Berg, S.J.P., van der Ploeg, M., 2021. A field guide for monitoring riverine macroplastic entrapment in water hyacinths. Front. Environ. Sci. 9, 716516. doi:10.3389/fenvs.2021.716516

Simon-Sánchez, L., Grelaud, M., Garcia-Orellana, J., Ziveri, P., 2019. River Deltas as hotspots of microplastic accumulation: The case study of the Ebro River (NW Mediterranean). Sci. Total Environ. 687, 1186–1196. doi:10.1016/j.scitotenv.2019.06.168

Skoulikidis, N.T., Sabater, S., Datry, T., Morais, M.M., Buffagni, A., Dör, G., Zogaris, S., Sánchez-montoya, M., Bonada, N., Kalogianni, E., Rosado, J., Vardakas, L., Maria, A., Girolamo, D., Tockner, K., 2017. Non-perennial Mediterranean rivers in Europe : Status , pressures , and challenges for research and management. Sci. Total Environ. 577, 1–18. doi:10.1016/j.scitotenv.2016.10.147

Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. Trans. Am. Geophys. Union 38, 913–920. doi:10.1029/TR038i006p00913

Stubbington, R., Chadd, R., Cid, N., Csabai, Z., Miliša, M., Morais, M., Munné, A., Pařil, P., Pešić, V., Tziortzis, I., Verdonschot, R.C.M., Datry, T., 2018. Biomonitoring of intermittent rivers and ephemeral streams in Europe: Current practice and priorities to enhance ecological status assessments. Sci. Total Environ. 618, 1096–1113. doi:10.1016/j.scitotenv.2017.09.137

Suaria, G., Avio, C.G., Mineo, A., Lattin, G.L., Magaldi, M.G., Belmonte, G., Moore, C.J., Regoli, F., Aliani, S., 2016. The Mediterranean Plastic Soup: Synthetic polymers in Mediterranean surface waters. Sci. Rep. 6, 37551. doi:10.1038/srep37551

Tasaki, T., Kawahata, T., Osako, M., Matsui, Y., Takagishi, S., Morita, A., Akishima, S., 2007. A GIS-based zoning of illegal dumping potential for efficient surveillance. Waste Manag. 27, 256–267. doi:10.1016/j.wasman.2006.01.018

van Bijsterveldt, C.E.J., van Wesenbeeck, B.K., Ramadhani, S., Raven, O. V., van Gool, F.E., Pribadi, R., Bouma, T.J., 2021. Does plastic waste kill mangroves? A field experiment to assess the impact of macro plastics on mangrove growth, stress response and survival. Sci. Total Environ. 756, 143826. doi:10.1016/j.scitotenv.2020.143826

van der Wal, M., van der Meulen, M., Tweehuijsen, G., Peterlin, M., Palatinus, A., Kovac, M., Coscia, L., Krzan, A., 2015. SFRA0025 : Identification and Assessment of Riverine Input of (Marine) Litter, Final Report for the European Commission DG Environment under Framework Contract No ENV.D.2/FRA/2012/0025. Bristol.

van Emmerik, T., Roebroek, C.T.J., de Winter, W., Vriend, P., Boonstra, M., Hougee, M., 2020a. Riverbank macrolitter in the Dutch Rhine-Meuse delta. Environ. Res. Lett. doi:10.1088/1748-9326/abb2c6

van Emmerik, T., Schwarz, A., 2020. Plastic debris in rivers. WIREs Water 7, e1398. doi:10.1002/wat2.1398

van Emmerik, T., Strady, E., Kieu-Le, T.C., Nguyen, L., Gratiot, N., 2019a. Seasonality of riverine macroplastic transport. Sci. Rep. 9, 1–9. doi:10.1038/s41598-019-50096-1

van Emmerik, T., Tramoy, R., van Calcar, C., Alligant, S., Treilles, R., Tassin, B., Gasperi, J., 2019b. Seine Plastic Debris Transport Tenfolded During Increased River Discharge. Front. Mar. Sci. 6, 642. doi:10.3389/fmars.2019.00642

van Emmerik, T., van Klaveren, J., Meijer, L.J.J., Krooshof, J.W., Palmos, D.A.A., Tanchuling, M.A., 2020b. Manila River Mouths Act as Temporary Sinks for Macroplastic Pollution. Front. Mar. Sci. 7. doi:10.3389/fmars.2020.545812

van Emmerik, T., Vriend, P., Roebroek, J., 2020c. An evaluation of the River-OSPAR method for quantifying macrolitter on Dutch riverbanks. Wageneingen. doi:10.18174/519776

Vriend, P., Roebroek, C.T.J., van Emmerik, T., 2020a. Same but Different: A Framework to Design and Compare Riverbank Plastic Monitoring Strategies. Front. Water 2. doi:10.3389/frwa.2020.563791

Vriend, P., van Calcar, C., Kooi, M., Landman, H., Pikaar, R., van Emmerik, T., 2020b. Rapid Assessment of Floating Macroplastic Transport in the Rhine. Front. Mar. Sci. 7, 10. doi:10.3389/fmars.2020.00010

Wang, S., Liu, Z., Tong, M., Xiang, J., Zhang, Ying, Gao, Q., Zhang, Yiwen, Lu, L., Jiang, B., Bi, P., 2021. Real-time forecasting and early warning of bacillary dysentery activity in four meteorological and geographic divisions in China. Sci. Total Environ. 761, 144093. doi:10.1016/j.scitotenv.2020.144093

Weiss, L., Ludwig, W., Heussner, S., Canals, M., Ghiglione, J.F., Estournel, C., Constant, M., Kerhervé, P., 2021. The missing ocean plastic sink: Gone with the rivers. Science (80-.). 373, 107–111. doi:10.1126/science.abe0290

Williams, A., Simmons, S., 1997. Estuarine Litter at River/Beach Interface in the Bristol Channel, United Kingdom. J. Coast. Res. 13, 1159–1165.

Williams, A.T., Simmons, S.L., 1996. The degradation of plastic litter in rivers: Implications for beaches. J. Coast. Conserv. 2, 63–72. doi:10.1007/BF02743038

Windsor, F.M., Durance, I., Horton, A.A., Thompson, R.C., Tyler, C.R., Ormerod, S.J., 2019. A catchment-scale perspective of plastic pollution. Glob. Chang. Biol. 25, 1207–1221. doi:10.1111/gcb.14572

Winton, D.J., Anderson, L.G., Rocliffe, S., Loiselle, S., 2020. Macroplastic pollution in freshwater environments: Focusing public and policy action. Sci. Total Environ. 704, 135242. doi:10.1016/j.scitotenv.2019.135242

Yun, K., Kwon, Y., Oh, S., Moon, J., Park, J., 2019. Vision-based garbage dumping action detection for real-world surveillance platform. ETRI J. 41, 494–505. doi:10.4218/etrij.2018-0520

Zeri, C., Adamopoulou, A., Koi, A., Koutsikos, N., Lytras, E., Dimitriou, E., 2021. Rivers and Aastewater-Treatment Plants as Microplastic Pathways to Eastern Mediterranean Waters: First Records for the Aegean Sea, Greece. Sustainability 13, 5328. doi:10.3390/su13105328

Zuur, A.F., Ieno, E.N., Elphick, C.S., 2010. A protocol for data exploration to avoid common statistical problems. Methods Ecol. Evol. 1, 3–14. doi:10.1111/j.2041-210X.2009.00001.x

Zylstra, E.R., 2013. Accumulation of wind-dispersed trash in desert environments. J. Arid Environ. 89, 13–15. doi:10.1016/j.jaridenv.2012.10.004

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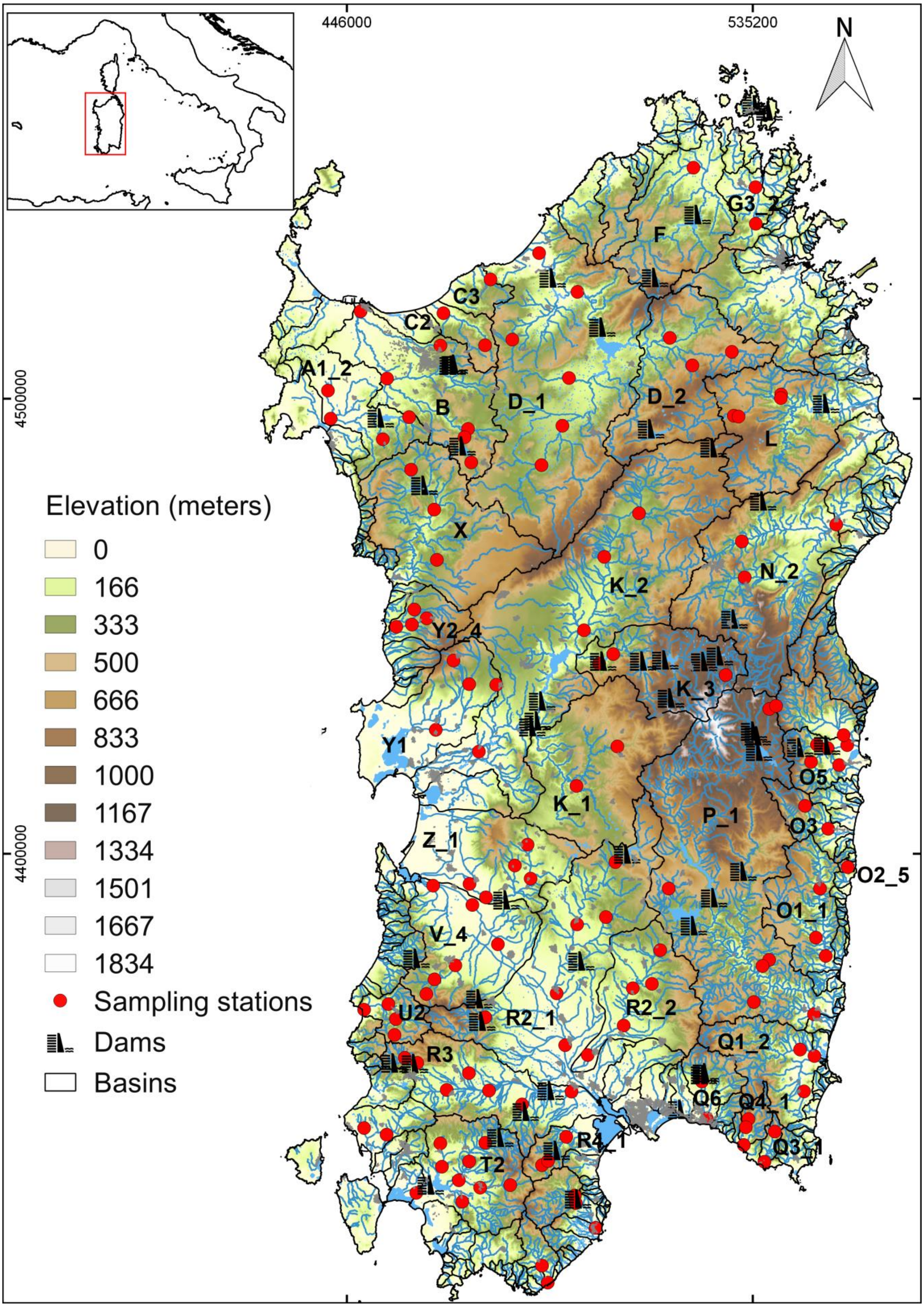


Figure 1. Study area and sampling stations of the investigated rivers (study period 2018-2020). Upper case letters indicated the codes of rivers basins.

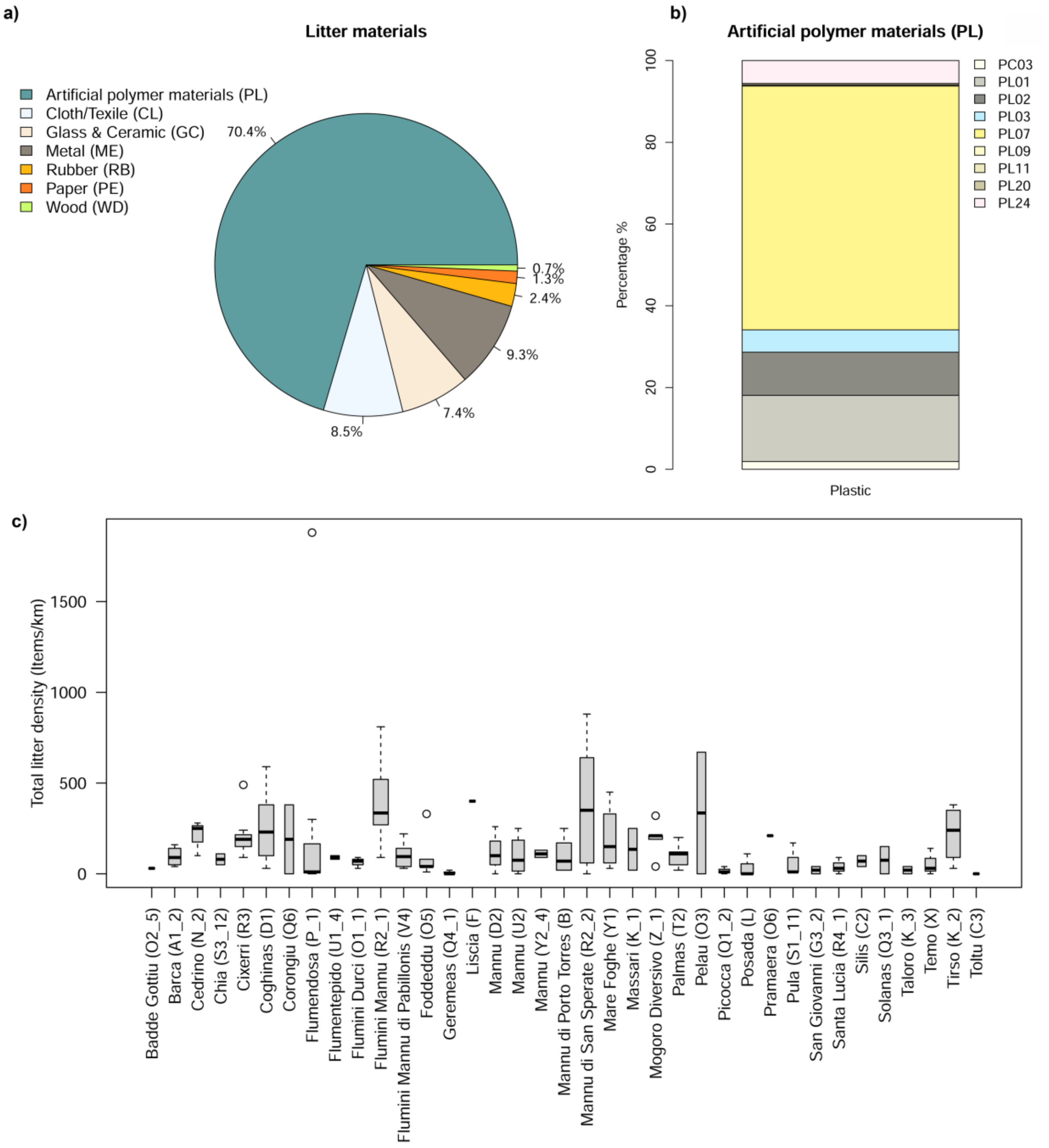
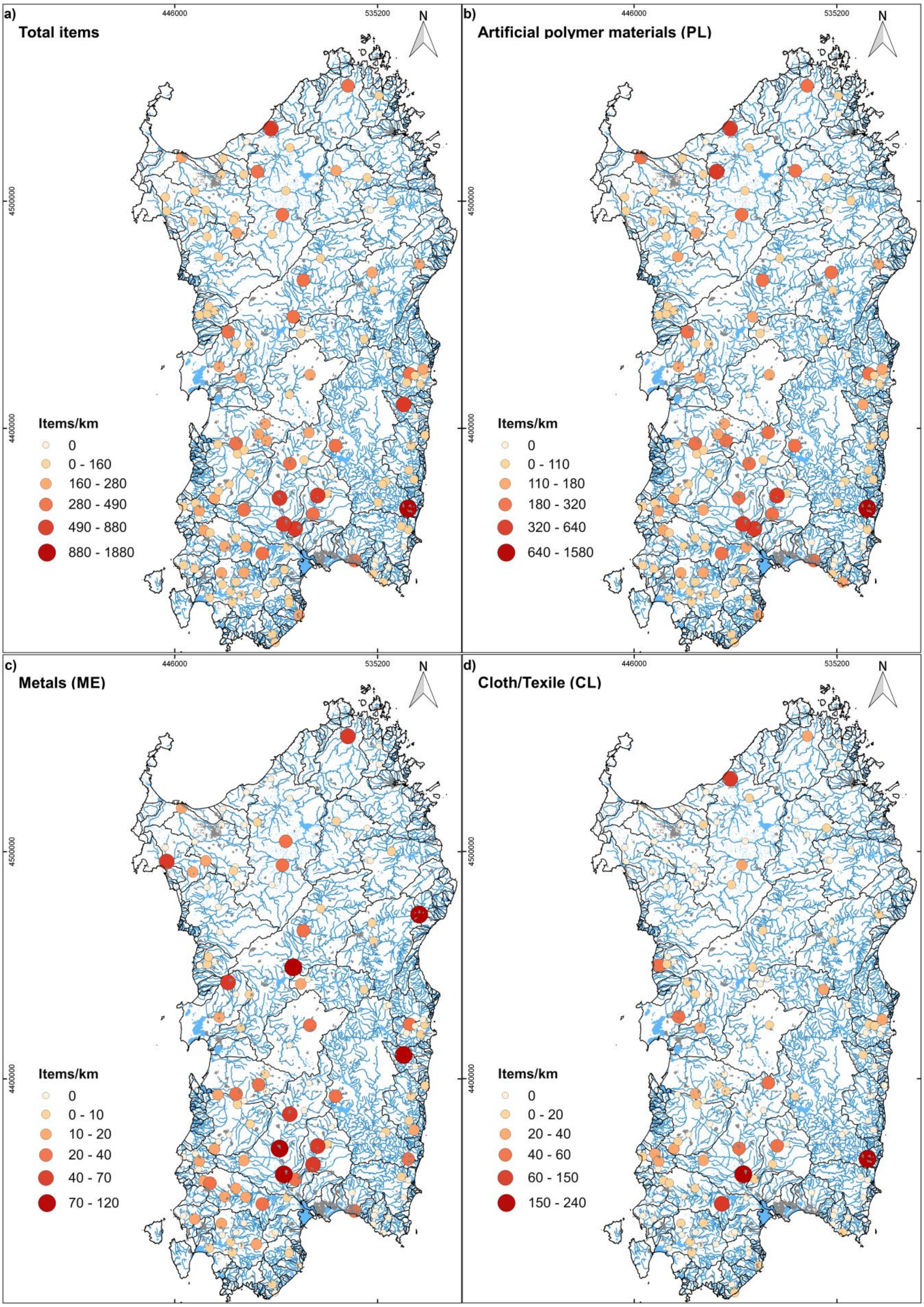


Figure 2. (a) Percentage of the number of litter items in Sardinian rivers. (b) Percentage of artificial polymer materials (PL). UNEP code sub-categories: PC03 (Cups, food trays, food wrappers, cigarette packs, drink containers), PL01 (Bottles caps and lids), PL02 (Bottles < 2 L), PL03 (Bottles, drums, jerrycans and buckets > 2L, PL07 (Plastic bags (opaque & clear)), PL09 (gloves), PL11 (cigarettes, butts and filters), PL20 (fishing net), PL24 (other plastic items). (c) Box-whisker plot representation of the total litterdensity (items/km) of 37 river basins of Sardinia.



a) Total items

b) Artificial polymer materials (PL)

c) Metals (ME)

d) Cloth/Texile (CL)

Figure 3. **Geographical distribution and number of items km^{-1} of the total and of the most abundant litter materials.**

Table 1. Summary of the relative contributions (%) of predictor variables for a boosted regression tree models developed for light (PL) and heavy (ME) materials. Total deviance explained by the model (DEV %), cross-validated correlation between model prediction and observed data (R^2 of CV) and area under the curve (AUC).

Material type	Predictor	Relative contribution (%)	DEV (%)	R^2 of CV	AUC
Ligth material (PL)	Sub_catchment	34.6	40%	0.70	0.92
	Urban_use	12.4			
	Agricultural_use	12.0			
	Near_bridge	10.1			
	Road_density	7.51			
	Slope	5.91			
	Pop_density	5.45			
	Distance_Mouth	4.57			
	Grazing_use	3.68			
	River_order	2.70			
	Season	1.02			
Heavy material (ME)	Sub_catchment	22.5	16%	0.57	0.83
	Near_bridge	21.1			
	Pop_density	19.8			
	Grazing_use	9.34			
	Distance_Mouth	7.91			
	Agricultural_use	5.66			
	Slope	5.06			
	Urban_use	2.92			
	Season	2.26			
	Road_density	2.12			
	River_order	1.25			

Supplementary materials

Table S1. Overview of studies carried out to date on the occurrence and distribution anthropogenic litter in rivers flowing in the Mediterranean Sea.

Matrix	**Unit**	**Material**	**River area**	**Reference**
Water	Items m^{-3} and items km^{-2}	Microplastic and macroplastic	Po River (NE Italy)	(van der Wal et al., 2015)
Sediment	Items kg^{-1}	Microplastic, mesoplastic and macroplastic	Ombrone, Osa and Albegna Rivers (Central W Italy)	(Guerranti et al., 2017)
Sediment	Items kg^{-1}	Microplastic	Cecina River (Central W Italy)	(Blašković et al., 2018)
Water	Items km^{-2}	Microplastic	Rhone River (S France)	(Schmidt et al., 2018)
Sediment and water	Items kg^{-1} and items m^{-3}	Microplastic	Po River (NE Italy)	(Atwood et al., 2019)
Water	Items h^{-1}	Multiple macrolitter materials	Tiber River (Central W Italy)	(Crosti et al., 2018)
Water	Items h^{-1}	Multiple macrolitter materials	Rhone River (S France)	(Castro-Jiménez et al., 2019)
Sediment	Items kg^{-1}	Microplastic	Ebro River (NE Spain)	(Simon-Sánchez et al., 2019)
Water	Items m^{-3}	Microplastic	Ofanto River (SE Italy)	(Campanale et al., 2020)
Water	Items m^{-3}	Microplastic	Rhone and Tet Rivers (S France)	(Constant et al., 2020)
Sediment and water	Items kg^{-1} and items L^{-1}	Microplastic and mesoplastic	Mignone River (Central W Italy)	(Gallitelli et al., 2020)
Water	Items h^{-1}	Multiple macrolitter materials	Catalonia (NE Spain)	(Schirinzi et al., 2020)
Water	Items m^{-3}	Microplastic	Kifissos and Pinios Rivers (E Grece)	(Zeri et al., 2021)
Water	ng L^{-1}	Micro-nanoplastic	Ebro River (NE Spain)	(Llorca et al., 2021)
Water	m^{3}	Multiple macrolitter materials	Segura River (SE Spain)	(Rocamora et al., 2021)
River banks	Items m^{-2}	Multiple macrolitter materials	Latium Rivers (Central Italy)	(Cesarini and Scalici, 2022)
River banks	Items km^{-1}	Multiple macrolitter materials	Sardinian Rivers	Present study

Table S2. Summary of candidate predictor variables used in BTR models and determination methods.

	Variables	Unit	Apparatus and Methods
Geomorphology	Sub_catchment	(km^2)	QGIS; Catchment area above the sampling site
	River_Order	Classified (1-5)	QGIS; Stream order *sensu* (Strahler, 1957)
	Slope	%	QGIS; Gradient of strech
	Seasons	(Winter, Spring, Summer, Autumn)	As proxy of river runoff
Land use	Natural_use	%	QGIS; % in the catchment area above sampling site
	Agricoltur_use	%	QGIS; % in the catchment area above sampling site
	Grazing_use	%	QGIS; % in the catchment area above sampling site
	Urban_use	%	QGIS; % in the catchment area above sampling site
Human pressures	Road_density	km km^{-2}	QGIS; Length of road in the catchment area above sampling site/catchment area above sampling site
	Polulation_density	Population km^{-2}	QGIS; Population in the catchment area above sampling site/catchment area above sampling site
	River_bridge	Presence/Absence (1-0)	QGIS; Bridge immediately above the sampling station
	Dams	Count	QGIS; Number of dams above the sampling station

Table S3. Percentage of recorded items of 28 sub-categories found in Sardinian rivers.

UNEP-Code	General name	Percentage of recorded items
PL07	Plastic bags (opaque & clear)	42.40
PL01	Bottles caps & lids	11.50
PL02	Bottles < 2 L	7.51
CL01	Clothing, shoes, hats & towel	6.02
GC02	Bottles & jars	4.62
PL24	Other plastic items	3.99
PL03	Bottles, drums, jerrycans & buckets > 2L	3.90
ME03	Aluminium drink cans	3.56
ME10	Appliances	3.56
GC01	Construction material	1.64
CL06	Other cloth	1.54
GC08	Other glass items	1.35
PC03	Bottles, drums, jerrycans & buckets > 2L	1.35
RB04	Tyres	1.35
RB08	Other rubber items	1.06
CL04	Rope & string	0.96
ME05	Gas bottles, drums % buckets (> 4 L)	0.77
WD04	Processed timber and pallet crates	0.67
ME09	Wire, wire mesh & barber wire	0.63
ME04	Other cans (< 4 L)	0.48
ME06	Foil wrappers	0.34
PL11	Cigarettes, butts & filters	0.19
PL20	Fishing net	0.19
ME02	Bottles caps, lids & pull tabs	0.14
CL05	Carpet & furnishing	0.10
RB05	Inner-tubes and rubber sheet	0.10
CL03	Canvas, sailcloth & sacking	0.05
PL09	Gloves	0.05

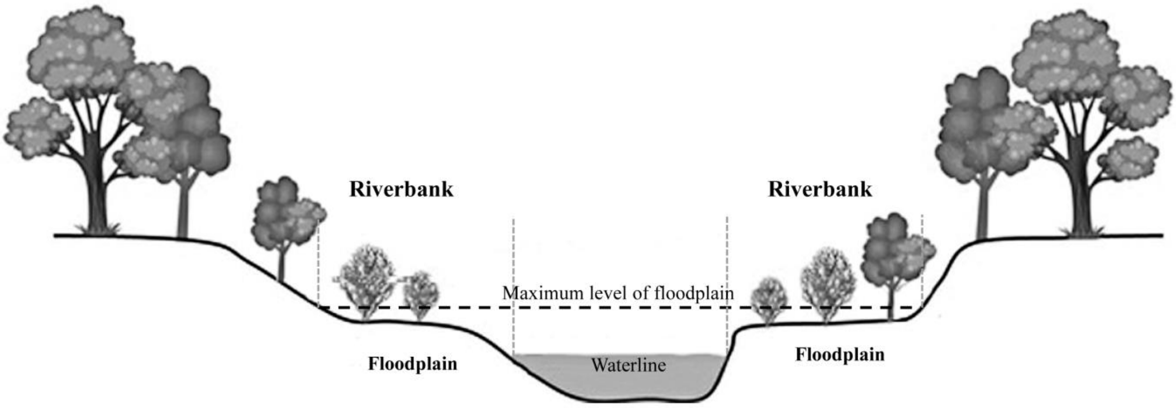


Figure S1. Diagram of a typical stream cross-section encountered across the study area, emphasizing the sampled area from the waterline to max. level of floodplain.

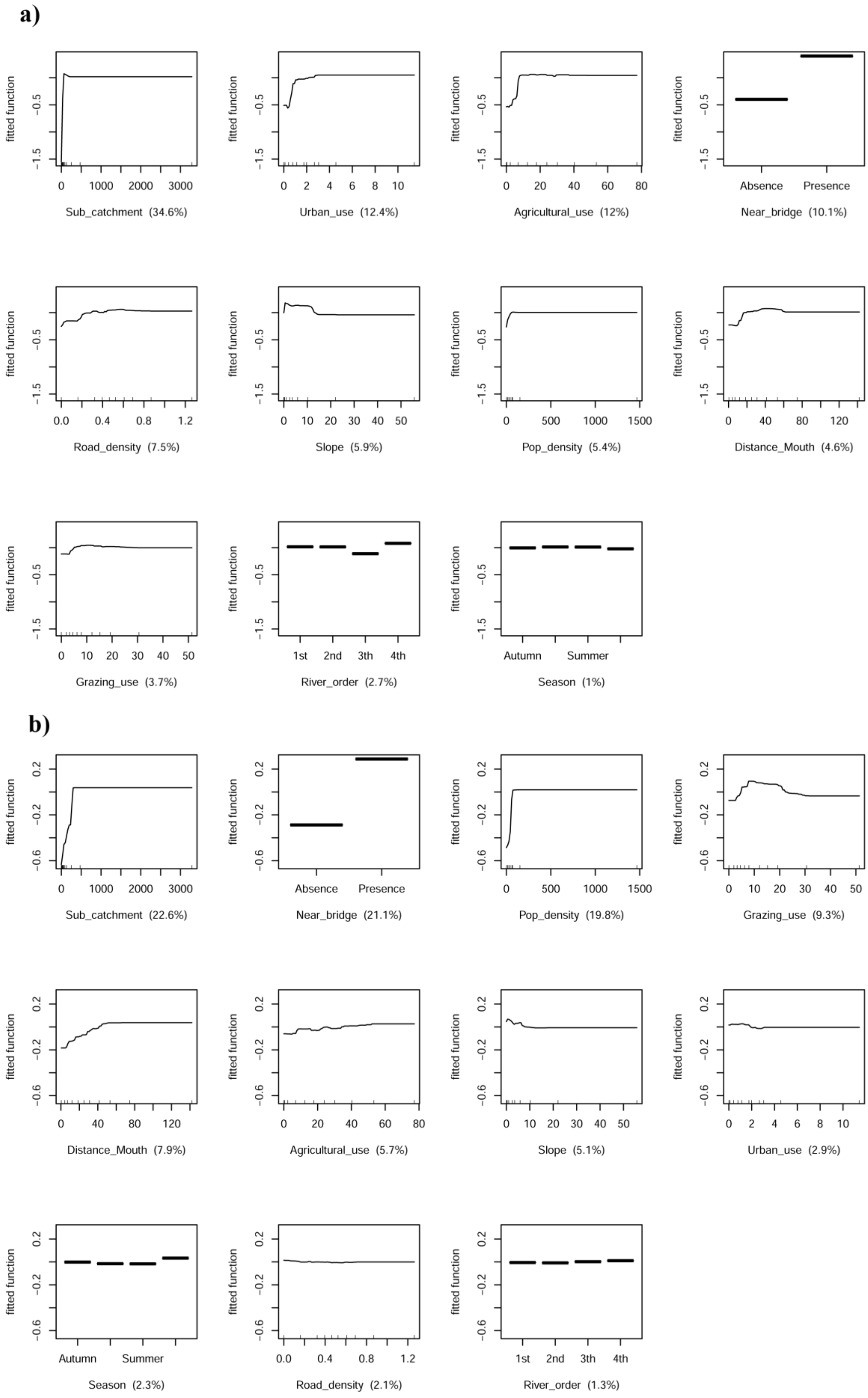


Figure S2. Partial dependence plots of the relationship between predictive variables and occurrence of light (PL) (a) and heavy (ME) (b) materials. The percentage indicates the relative contribution of each variable in the BRTs. Black lines represent the smoothed results.