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

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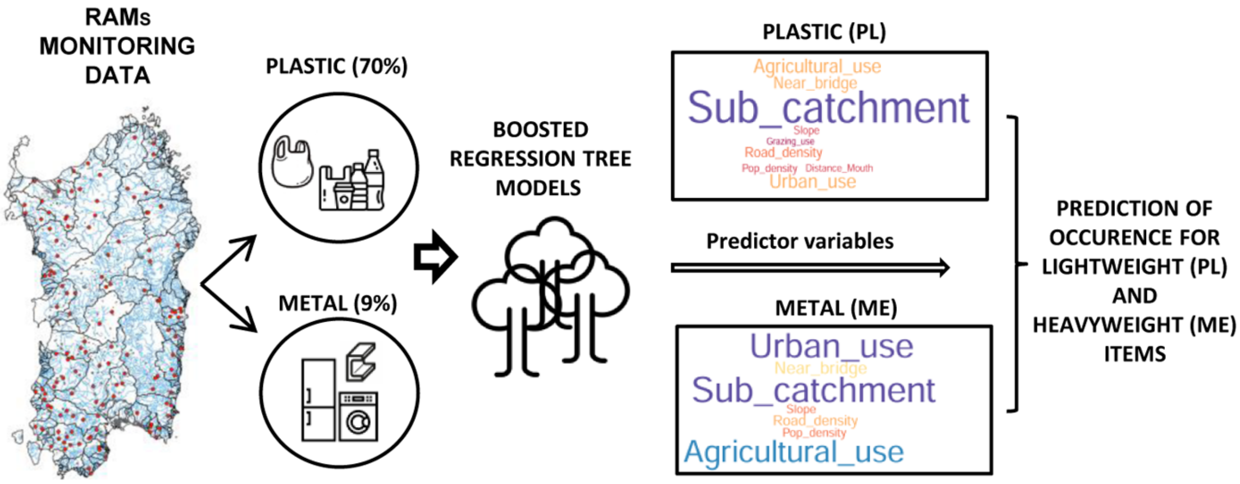
Highlights

- Macrolitter (RAM) contamination was studied in Intermittent riverbanks.
- Collected RAM was dominated by Plastic (PL) and Metal (ME) items.
- The presence of PL items is influenced by urban and agricultural land use.
- ME occurence is linked with presence of bridges and population density.
- Littering seems to be the main source of riverbank contamination.

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. Non-linear Boosted Regression Tree models (BRTs) revealed that occurence of lightweight RAM (especially plastic) is mostly explained by levels of urban and agricultural land use of the territory, whereas the proximity of bridges to the sampling point and the local population density are best predictors of heavy weighted RAM items (i.e., large metal items, appliances) occurence. Our results confirm that RAM, especially plastics, represent an important component of riverine waste and pinpoint that actions aimed at abating litter contamination along riverbanks of intermittent rivers, apart practices put in place to decrease plastic production and waste, 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 some like 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).

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). RAM 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). RAM is typically dominated by plastics, whereas other materials such as glass, metal and paper/cardboard are relatively minor contributors (Castro-Jiménez et al., 2019; Cesarini and Scalici, 2022; González-Fernández et al., 2021; Rech et al., 2014).

Abundance, composition and distribution of RAM are influenced by the cumulative effects of an array of environmental characteristics including, among the others, the presence of floating and riparian vegetation (Cesarini and Scalici, 2022; Schreyers et al., 2021; Williams and Simmons, 1997; Windsor et al., 2019), tidal influence, seasonal changes of the water level and flow rate (Battulga et al., 2019; Vriend et al., 2020b), and 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), fluvial navigation and the presence of hydraulic infrastructures (Calcar and van Emmerik, 2019; Mihai, 2018; Schirinzi et al., 2020), 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 scant (Table S1). Intermittent rivers and ephemeral streams are common across Europe and dominate river networks in the Southern basin and islands of the Mediterranean Sea (Stubbington et al., 2018), including Sardinia and Sicily. 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.

To address this gap of knowledge, 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. Bi-seasonal climatic features, with hot arid summers and smoothed rainy autumn/winter seasons 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 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 (> 15 m) (Marchetto et al., 2009; Montaldo and Sarigu, 2017), that, interrupting the rivers' continuity, have strongly influenced their annual hydrological cycle (Moccia et al., 2020; Naselli-Flores et al., 2014).

RAM 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. Briefly, macro-litter items (>5 mm) on 100-m long stretches of riverbanks parallel to the waterline, from the waterline itself and the maximum level of flood plain landward, were counted 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). The frequency of occurrence for each litter category was estimated as the percentage of stations containing items over the total number of stations.

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; 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, 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. In addition, since the presence of weirs and dam 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 Hack method's (Hack, 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 (De'ath, 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).

Overall, the mean litter density for all investigated riverbanks was 156±19 items km^{-1} (median value of 90 items km^{-1}). This absence of significant differences was observed using both aggregated data and dominant categories, treated singularly. 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 S1). 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), 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) and agricultural use (Agricoltural_use) (ρ = -0.9) and sub-catchment area (Sub_catchment) and number of larger dams above the sampling station (Dams) (ρ = 0.7) (Figure S2). After removing Natural_use and the Dams varaiables, the VIF values did not exceed 3.0 (Table S4).

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, Agricoltural_use, and Road_density (Figure 4). 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 4). The PL litter is most found also 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 4).

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).

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 and Conclusions

Our study provides evidence that a high frequency (~ 86%) of intermittent rivers in Sardinia is 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 tips (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., 2019; 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, 2020b). 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 synergic 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, 1997).

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. Moreover, 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 (Williams and Simmons, 1997b; Rech *et al.*, 2014; Mihai, 2018; Kiessling *et al.*, 2019; Cowger *et al.*, 2019).

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.

At a regional scale, our study highlights that the occurrence of light (plastics) and heavy (metal) waste materials largely depends upon the combined effects of river natural geomorphology, the presence of bridges and the land use. 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). 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). 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).

Finally, we contend here that, 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, always considering the complex array of factors influencing litter sources, distribution, accumulation, and transport (van Emmerik et al., 2020b; Vriend et al., 2020a).

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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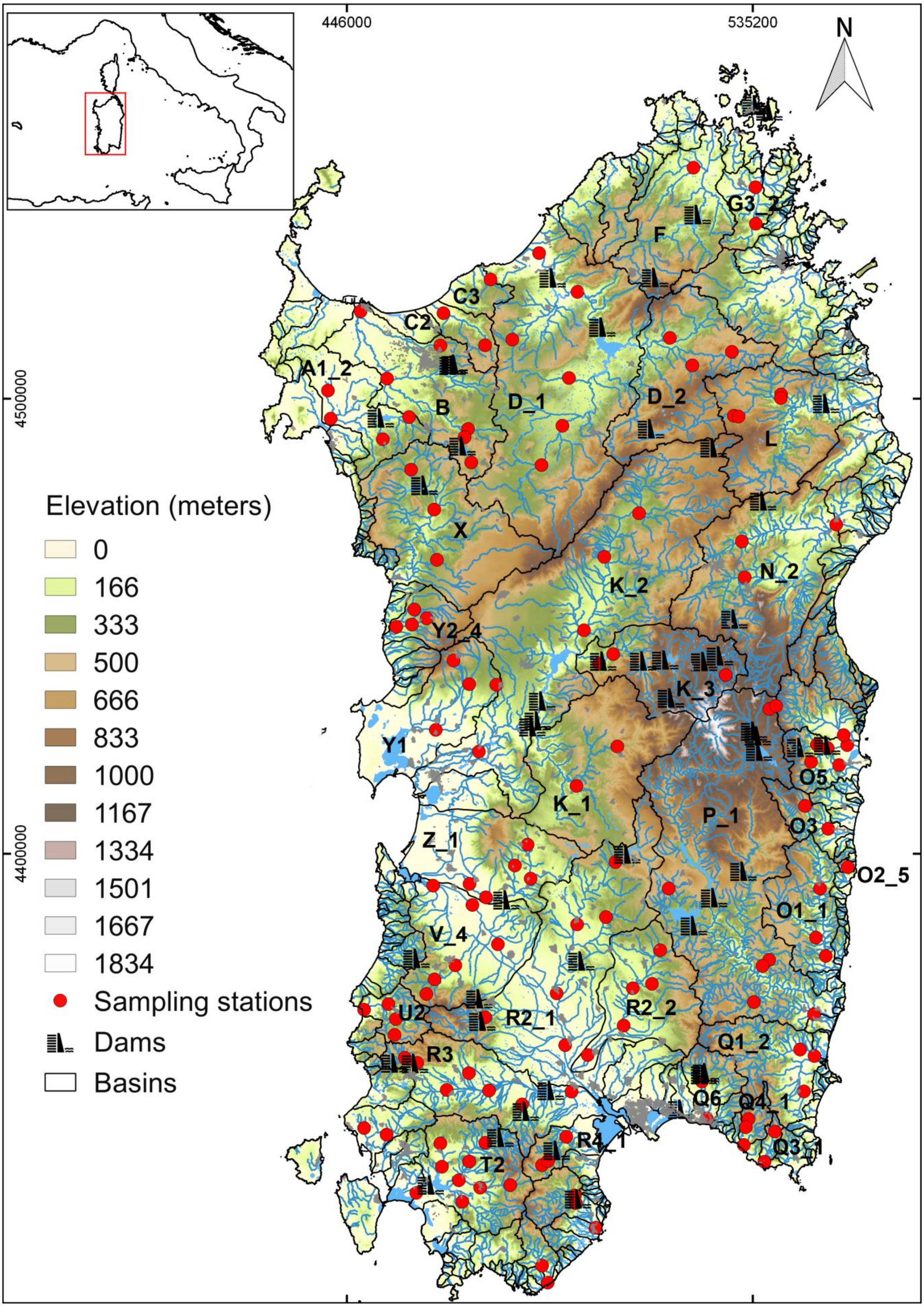

Figure 1. Study area and sampling stations of the investigated rivers. Upper case letters indicated the codes of rivers basins.

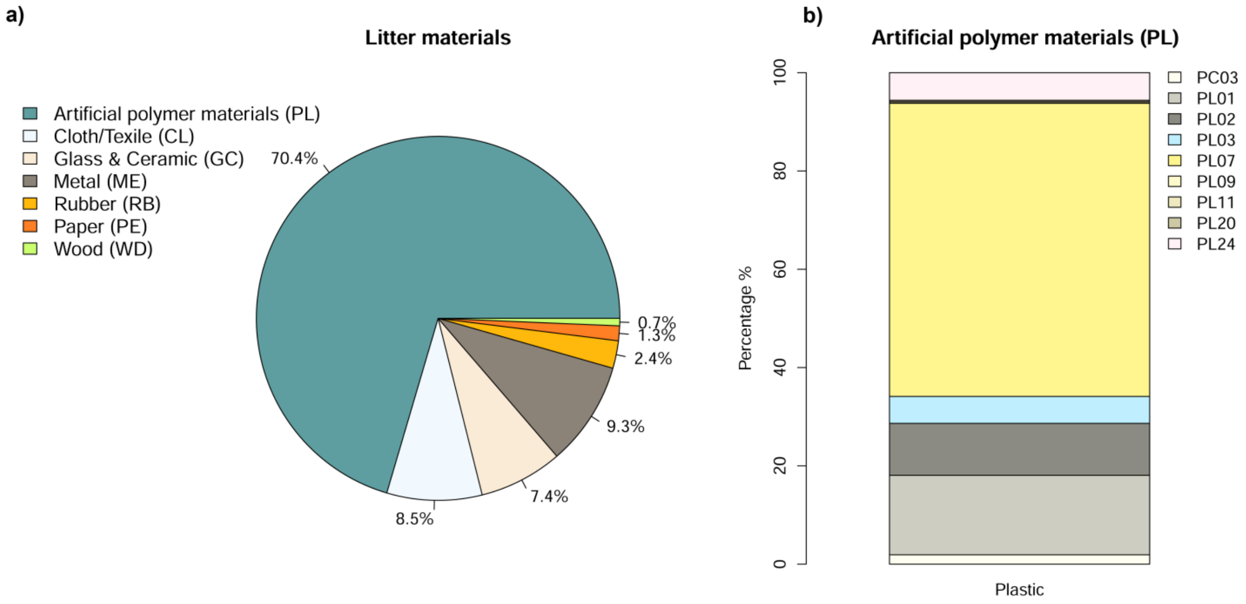

Figure 2. (a) Percentage of anthropogenic litter materials in Sardinian rivers. (b) Percentage of artificial polymer materials (PL). UNEP code sub-categories: PC03 (Cups, food trays, food wrappers, cigarette packs, drink containers), PL01 (Bottles caps and lids), PL02 (Bottles < 2 L), PL03 (Bottles,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

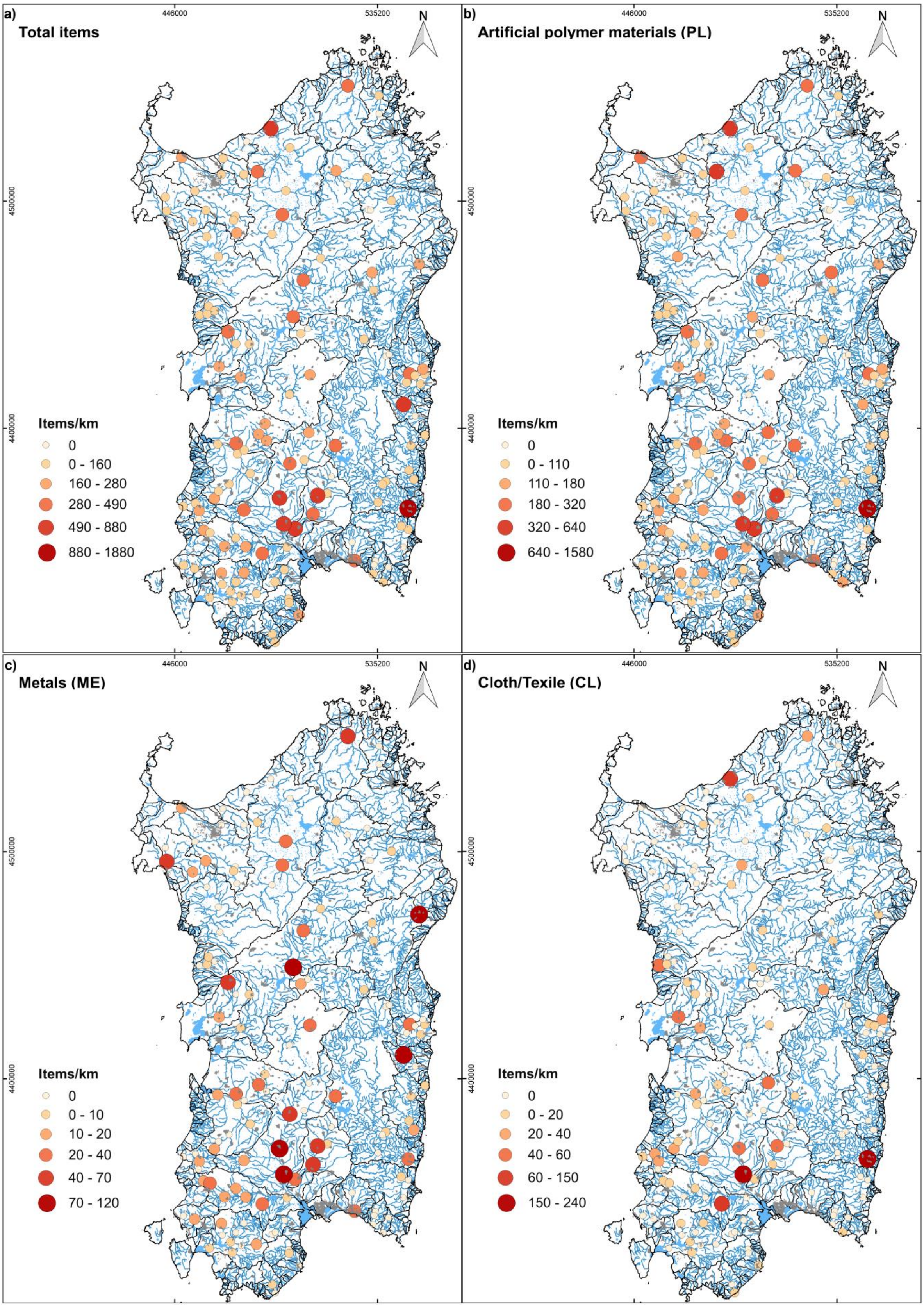

Figure 3. **Geographical distribution and number of items km^{-1} of the total and of the most abundant litter materials.**

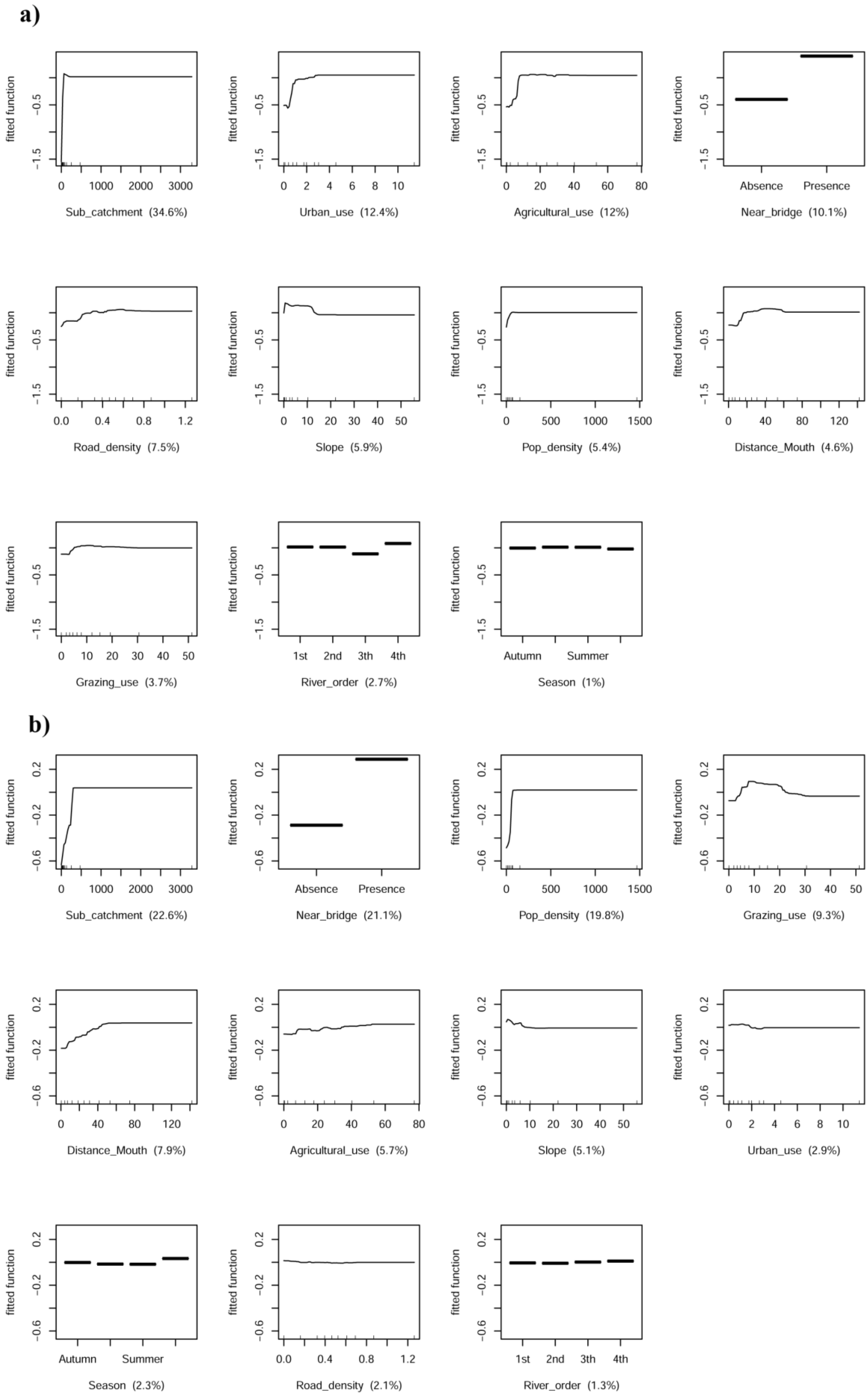

Figure 4. **Partial dependence plots of the relationship between predictive variables and occurrence of light (PL) (a) and heavy (ME) (b) materials. The percentage indicates the relative contribution of each variable in the BRTs. Black lines represent the the smoothed results.**

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

Material type	Predictor	Relative contribution (%)	DEV (%)	R^2 of CV	AUC
Ligth material (PL)	Sub_catchment	34.584	40%	0.70	0.92
	Urban_use	12.399			
	Agricultural_use	12.042			
	Near_bridge	10.132			
	Road_density	7.510			
	Slope	5.911			
	Pop_density	5.449			
	Distance_Mouth	4.572			
	Grazing_use	3.680			
	River_order	2.704			
	Season	1.017			
Heavy material (ME)	Sub_catchment	22.550	16%	0.57	0.83
	Near_bridge	21.097			
	Pop_density	19.832			
	Grazing_use	9.340			
	Distance_Mouth	7.908			
	Agricultural_use	5.663			
	Slope	5.057			
	Urban_use	2.919			
	Season	2.258			
	Road_density	2.122			
	River_order	1.255			

Supplementary materials

Table S1. Overview of studies carrier 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 Hack (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

Table S4. Result of collinearity test.

Selected variables	**Variance inflation factor (VIF)**
Sub_catchment	1.070739
Slope	1.14281
Distance_Mouth	1.163589
Agricultural_use	1.660203
Grazing_use	1.300179
Urban_use	1.848669
Road_density	1.47726
Pop_density	1.298474

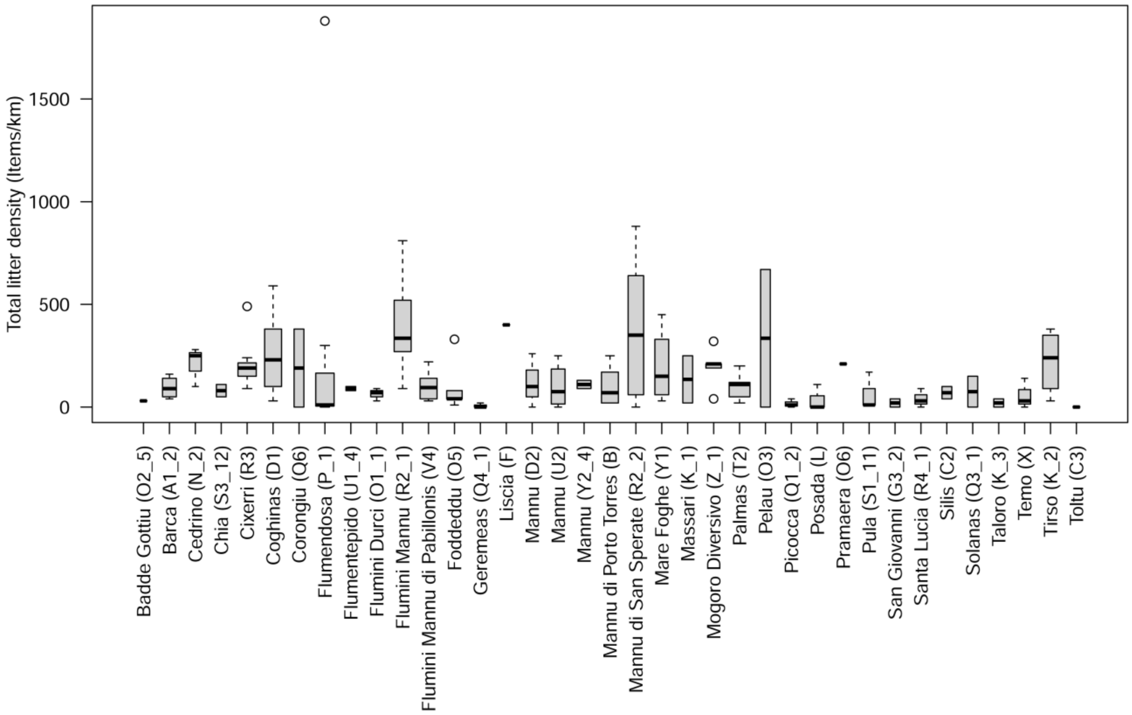

Figure S1. Box-whisker plot representation of the total litter density of 37 river basins of Sardinia.

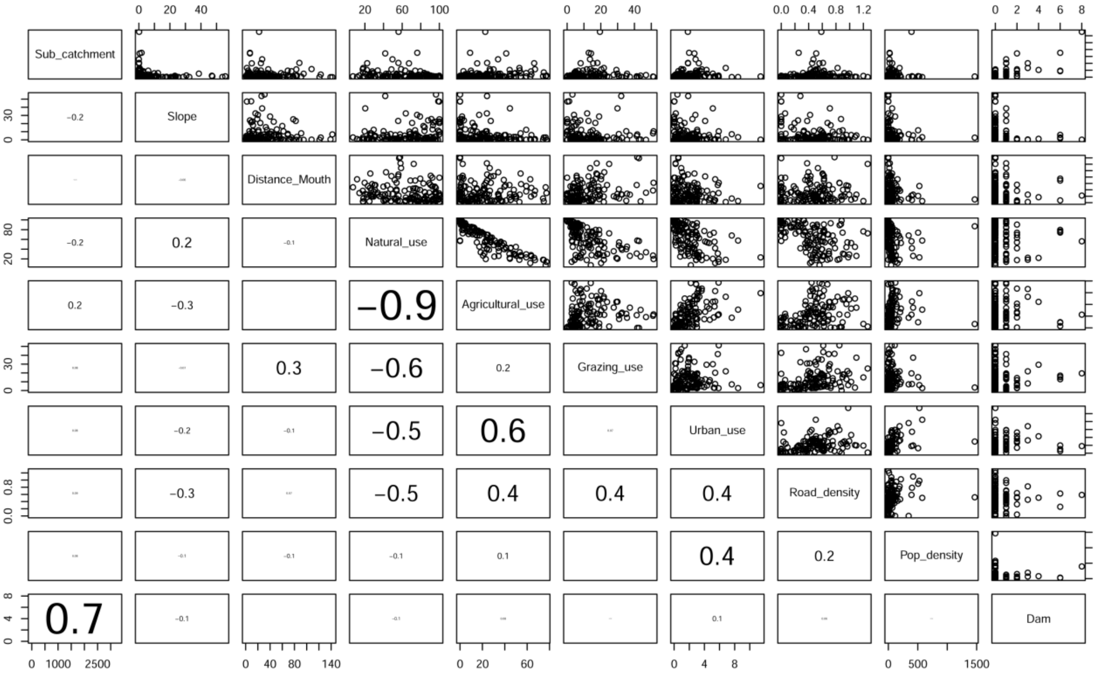

Figure S2. Scatter plot matrix depicting the bivariate relationships among potential explanatory variables. Upper diagonal: scatter plots. Lower diagonal: Spearman’s correlation coefficients among variables.

CRediT authorship contribution statement

F. Palmas: Conceptualization, Field sampling, Data curation, Software, Formal analysis, Formal Writing - Original draft. **Al. Cau**: Writing—review & editing. **C. Podda:** Field sampling, Software, Formal analysis, Writing—review & editing. **A. Musu:** Field sampling, Writing—review & editing. **A. Pusceddu:** Supervision, Writing – review & editing. **M. Serra:** Field sampling, Writing—review & editing. **A. Sabatini:** Project administration, Supervision, Writing - review & editing.