Current Plant Biology 41 (2025) 100450

Contents lists available at ScienceDirect

Current Plant Biology

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

Plastic hotspot areas in riverine habitats: Riparian vegetation diversity and structure entrap riverine plastics[☆]

Luca Gallitelli[a,*], Maurizio Cutini[a], Giulia Cesarini[a,b], Massimiliano Scalici[a,c]

[a] *University of Roma Tre, Department of Sciences, Viale Guglielmo Marconi, 446, Rome 00146, Italy*
[b] *National Research Council – Water Research Institute (CNR-IRSA), Corso Tonolli 50, Verbania 28922, Italy*
[c] *National Biodiversity Future Center (NBFC), Università di Palermo, Piazza Marina 61, Palermo 90133, Italy*

ARTICLE INFO

Keywords:
Riverine macrolitter
Plastic trapping
Riparian macroplastics
Riparian community
Plant morphological structure
Ecosystem services

ABSTRACT

Plastics are a significant environmental problem, accumulating in ecosystems and causing harmful effects. While macroplastics in rivers have only recently gained attention, most studies focus on their transport to the sea, neglecting the fact that plastics often remain within fluvial systems. Previous research has primarily considered abiotic factors in this transport process. However, recent findings indicate that vegetation plays a crucial role in trapping plastics in urban and lowland watercourses. The role and structure of riparian vegetation in plastic entrapment are poorly understood. This study investigates the relationship between vegetation structure and plastic entrapment applying the 3D Vegetation Index (3DVI) to quantify vegetation complexity and its capacity to trap plastics. Field data on plastics and vegetation were collected from six rivers in central Italy across three riverine zones. Results show a significant correlation between macroplastics trapped in vegetation and vegetation structure, with denser and more diverse plant communities trapping more plastics. Particularly, a significant regression between 3DVI and plastics in vegetation was observed only in the lower river zone. The higher the 3DVI value, the more complex the vegetation, indicating greater plastic trapping efficiency. These findings suggest that biotic factors, particularly vegetation structure, are important variables for driving riverine plastic entrapment at local scales. This study is the first to apply a vegetation index to describe the complexity and diversity of plant communities related to plastic entrapment. Future research urgently needs to unveil this *phenomenon* at a global scale as well as to focus on the interactions and effects of macroplastics on plants. Understanding plant structures and 3DVI usage in retaining plastics can help identify plastic hotspot areas and inform mitigation and clean-up efforts to address plastic pollution effectively.

1. Introduction

Macroplastic litter is one of the most challenging global concerns, actually still affecting ecosystems and human health [5,10,22]. Given its wide distribution across the globe, macroplastic litter represents a growing threat with observed detrimental effects in aquatic ecosystems and, for that, it has been a well-studied hot topic in the last decades [32, 23]. In aquatic ecosystems, most of the studies focused on the marine habitat, highlighting the entanglement and suffocation of bird, fish, and mammal species by dumped plastics and fishing gear for many years [1–3,15,25,24]. These lethal effects have been observed only recently in freshwater riverine habitats [4,14]. Here, macroplastics (plastics $>$ 5 mm, *sensu* Gallitelli and Scalici [15]) are responsible for ingestion and entanglement in aquatic fish, reptiles, birds, and mammals, as well as for the construction of bird nests [4,6,13,30]. Moreover, macroplastics fragment into smaller particles called microplastics (1 μm $<$ plastics $<$ 5 mm), being more easily ingested and have ecotoxicological effects on aquatic biota [9,27]. Among freshwater systems, rivers are of particular interest as they carry most of the macroplastic litter from the land to the seas [18,33]. To date, plastics in rivers have been recently documented [15,20,21]. Several research emphasized the riverine transport of plastics to the sea, with rivers as the main carriers of plastics [18,19]. However, most plastic litter remain blocked in the fluvial ecosystems due to different causes. Among these, sediments and infrastructure (e.g., dams) may interfere with plastic transport, temporarily blocking plastic litter [17]. Moreover, vegetation along the riverbank has a high

---

☆ VSI:Plants and plastics.
* Corresponding author.
E-mail address: luca.gallitelli@uniroma3.it (L. Gallitelli).

https://doi.org/10.1016/j.cpb.2025.100450
Received 1 August 2024; Received in revised form 23 January 2025; Accepted 26 January 2025

potential to retain plastics [14,17,38]. In this view, plastics from riverine habitats are retained in the riverbank habitats, and, here, the characteristics of the riverbank together with the vegetation help to entrap floating plastics carried from the river. Although several studies highlighted macrolitter accumulation zones in riverbank vegetated areas and few studies observed the role of vegetation in entrapping macrolitter on riverbanks [17], the retention and release process of this plastic entrapment should still be investigated. Until now, research focused on river plastic transport, highlighting the hydrometeorological factors (e.g., river discharge, wind speed) and geomorphological characteristics (e.g., meanders, river width) as the hydrology is pivotal in plastic transport [29]. Moreover, hydrology is the main force that brings floating plastics from the river to the riverbank and riparian vegetation. Given that riparian vegetation is a plant community that grows close to riverbanks along watercourses, when floods increase the water level reaching the bank, an unknown percentage of floating plastics are transported to the riverbank and trapped by riparian vegetation [14,38]. However, apart from the hydrological feature, the plastic entrapment by vegetation depends largely on the structure of each plant species and community. In the literature, it has been highlighted that more branched and dense vegetation may block a higher quantity of plastic litter [3,12,16]. Regarding riparian vegetation, until now generic studies assessed litter in riverine riparian habitats simply by providing quantification of vegetation occurring in the study area [38]. As recent research discovered that plants may block plastics providing an ecosystem service for plastic accumulation [17], more emphasis has been placed on standardising a method to sample plastics in vegetation by considering the riparian zone and assessing in detail the three-dimensional vegetation structure [14,16]. These studies provided field observations of plastic entrapment in the lowland and mouth zones of rivers in Mediterranean areas. Particularly, these previous studies tested an index for vegetation tridimensionality (i.e., 3DVI), to better understand the plastic entrapment related to the structure of vegetation. With the aim of applying the structural index along the river watershed to understand if a high concentration of plastics might be entrapped by a more structured and dense vegetation community, we aimed to focus on the three-dimensionality structure of the riparian community with the plastic entrapment. Precisely, we applied the structural vegetation index to plastics entrapped by vegetation. Our main hypothesis was that the three-dimensional structure due to the presence of a well-established riparian community might allow the most efficient plastic entrapment. To do it, we will use throughout the paper two different names: (i) plant morphological structure to refer to the single species and (ii) riparian vegetation community to indicate the association of species.

2. Material and methods

2.1. Study area

We applied the vegetation structure index (i.e., 3DVI) along the three riverine zones sampling field data from central Italy rivers. To do that, we considered riparian vegetation to river width following standardised methods reviewed in Gallitelli et al. [16]. Data on plastics within vegetation has been recollected after setting plots on the riparian area. Also, data on plant structures (i.e., the number of individuals and the number and height of branches per species) was sampled and then used to develop the 3D vegetation index (i.e., 3D Vegetation Index, 3DVI) considering the tridimensionality and diversity index. Regarding the 3DVI index, we followed the protocol developed by Gallitelli et al. [16] to sample vegetation branches and species. At the end, we related the 3DVI index to plastic occurrence in vegetation.

Concerning the study area, we selected sampling sites in central Italy rivers. We considered the three river zones (i.e., up, middle, and low stream zones) as macroplastic litter can be input in the river also in the riverine parts near the spring and along the river course [15,21]. To select rivers, we considered big and small catchments, from the Tiber to the Arrone rivers, following Gallitelli et al. [16]. The Tiber River represents the second longest river in Italy, with Farfa and Aniene rivers as main tributaries. Regarding land use, the areas of the Tiber and Aniene rivers were more urban and anthropized near the city of Rome, while pristine in proximity to their spring and middle zones. Regarding Marta, Mignone and Arrone rivers, these rivers were chosen as more pristine and flowing in agricultural areas. To investigate the structure of riparian vegetation related to plastic entrapment, we followed the sampling design set in Gallitelli and Scalici [14] and Gallitelli et al. [16]. In detail, riparian vegetation was sampled by using standardised plots with a *minimum* area of 5 m^2 considering river width and riparian zone width for calculating the plot area.

2.2. Sampling design for macroplastics in vegetated riparian areas

In each sampling area, we identified and sampled dominant species, mostly dominated by riparian vegetation trees, shrubs, reeds, and grasses. In Mediterranean areas, the upstream rivers show un-typical riparian vegetation with mixed conifers and beech riparian forests covering the river catchment. Regarding the three-dimensional structure, we calculated a 3DVI index to link the structure of vegetation to plastic occurrence in the precise site [16]. The number of species and the number of branches have been used to develop the index of vegetation structure (namely 3DVI, 3D-Vegetation Index) as designed by Gallitelli et al. [16]). To understand the structure and tridimensional shape of vegetation, we counted the number of branches and the number of species in each plot. While the number of branches and individuals provides information with tridimensionality, the number of species was used to calculate biodiversity indices and have details on the role of each species in the community (see [16]). The calculation and formulas are available in the Method section in [16]. In each plot, we collected data on dominant species coverage, type of vegetation, and factors such as height, branches, and diameter species (Table 1) as a proxy of the riparian vegetation structure. Then, we collected macroplastic litter and counted and classified it for type, size, colours, and polymers. To do that, we followed the classifications by Galgani et al. [11] and González-Fernández et al. [18]. We set a protocol in Gallitelli et al. [16] to understand the provenience of vegetation plastics and to split plastics carried by river transport from land brought by wind. Following this, macroplastics in vegetation carried by the river are characterised by mud and a cup shape, as described in [16]. All these data allow us to understand the structure of the riparian vegetation in accumulating MA, considering (i) the plant morphological structure (i.e., soft traits, according to Raunkiaer [26] and (ii) the vegetation association (i.e., riparian community). Finally, to spot a correlation with plastics, this index has been related to the plastic occurrence in each site.

2.3. Statistical analyses

Normality and data distribution were checked before performing each statistical test. If data were not normally distributed, non-parametric tests were carried out. To calculate the 3DVI index we followed the calculations in Gallitelli et al. [16]. Here, we adapted the 3DVI also considering other factors. For instance, we calculated two different 3D and four different 3DVI indices. The first, the 3DVI based on $3D_1$, considered 3D as the number of branches divided by the area of plants in the plot. The second is the 3DVI based on the $3D_2$ calculated as the number of individuals of a species multiplied by the number of branches

Table 1
Characteristics of plant structure used in sampling plastics in vegetation.

Plant features	Coverage	Height	Branches	Individuals	Diameter
Sample units	Percentage (%)	meter (m)	Number (#)	Number (#)	meter (m)

and divided by the area occupied by it in the plot. These two different 3D were related to four different diversity indices: richness or number of species index (3DVI-R), Simpson index (3DVI-D), Shannon index (3DVI-H′), and Evenness index (3DVI-J). To compare data among the three river zones and stations, data of plastic entrapped within vegetation were standardised considering the coverage of each species in each plot. Also, to obtain the plastic concentration of items entrapped in plants, we standardised the number of items *per* sampling area for each plot. To obtain the source of plastics in riparian habitats, we used the land use of a 1 km × 1 km buffer area and then applied it to our study area. We calculated the percentages of each matrix (e.g., seminatural areas, artificial areas, and agricultural areas) by using the Corine Land Cover nomenclature and protocol. The results are shown in Fig. 1 with the study area map. To understand if the plastics occurring in vegetation are related to the plant structure (i.e., plant morphological structure, 3DVI), we performed correlation and regression analyses for the whole rivers and the three riverine zones. Moreover, to investigate whether the plants entrapped macrolitter mainly in upper, medium, or low height (i.e., < 0.5 m, $0.5 \text{ m} < r < 2.0$ m, > 2.0 m) to the 3DVI index, we conducted correlation and regression analyses. To investigate which environmental factors might drive the entrapment of plastics within vegetation, we performed a correlation matrix analysis. Regarding the environmental drivers that might affect the entrapment of plastics in vegetation, the number of species, number of individuals, and quantity of branches have been tested as the most influential factors.

All statistical analysis was performed using GraphPad Prism version 8.0.1, GraphPad Software, www.graphpad.com.

3. Results

Overall, we found that the river carried plastics mostly predominate than wind carried plastics (97.8 % vs 2.2 %, respectively). Here, we showed the plant structures entrapping macroplastic litter along rivers. Vegetation showed different structures per single plant (i.e., plant morphological structure) as well as per community (i.e., riparian vegetation association). Overall, trees trapped 80.0 % of the total macrolitter found, followed by *Rubus*, reeds, grasses, and shrubs trapping 7.3 %, 6.4 %, 5.3, and 1.0 % of macrolitter. Concerning vegetation types, trees efficiently blocked PO soft items (e.g., plastic bags, hygienic towels) and some hard plastic items accounting respectively for 62.8 % and 6.7 % of total macrolitter. Moreover, *Rubus* and reeds blocked mostly PO soft items respectively at 5.2 % and 3.4 % (Fig. 2, Fig. 3). Higher concentrations of macrolitter were found mostly in agricultural or artificial areas (Fig. 2B).

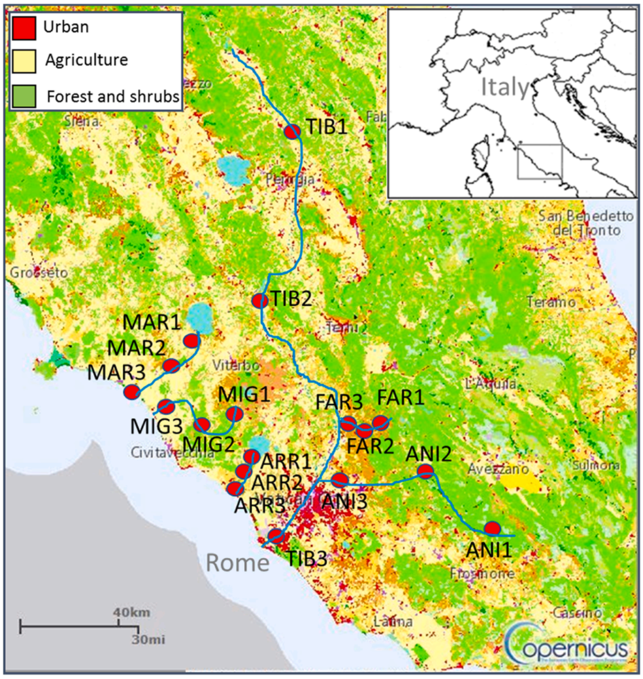


Fig. 1. Study area focusing on central Italy rivers. Each river has been sampled considering the three river zones. The image was taken on Copernicus and the European Environment Agency (EEA). ARR = Arrone river, MAR = Marta river, TIB = Tiber river, MIG = Mignone river, ANI = Aniene river, and FAR = Farfa river.

Regarding MA concentrations (Fig. 3B), we found an average of 4.3 ± 7.1 MA/m^2 on riverbanks in central Italy, with minimum-maximum ranging between 0.1 MA/m^2 in MAR3 and 28.6 MA/m^2 in ARR3. The mean MA density for urban areas was 13.9 ± 13.2 MA/m^2. Trees showed the highest trapping efficiency in the downstream river zone on a percentage average (57.2 MA/m^2), while Rubus was the lowest one in the middlestream river zone (1.2 MA/m^2). Concerning polymer concentration, PO soft was the most found in downstream river zone (72.1 MA/m^2), while multilayer was the least found in upstream locations (0.1 MA/m^2).

Concerning the structure given by the riparian community (i.e., riparian vegetation association), trees blocked more macroplastic litter. Precisely, the best combination of vegetation types for entrapping most plastics is given by the whole community. This latter showed a structure with different vegetation types of riparian vegetation, composed of trees, shrubs, and reeds (and grasses). This complete riparian community is mainly found in the most polluted stations. In those latter, riparian community characterised by trees and shrubs (i.e., *Populus* sp., *Salix* sp., and *Rubus ulmifolius* in ANI3) and by trees, shrubs and reeds (i.e., *Populus* sp., *Ficus carica*, and *Phragmites australis* in TIB3, Fig. 3) entrapped more efficiently macroplastics.

Concerning plant structure (i.e., plant morphological structure, 3DVI), high number and density of macroplastics were found in sites with medium or high vegetation structure (i.e., 3DVI) (Fig. 4). Furthermore, the vegetation community with the densest and more diverse structure blocked more plastic densities. Small-medium rivers trapped most MA (90.3 %) while big rivers 9.7 % (Fig. 4). Mean macroplastic density reached 4.7 MA/m^2 in small-medium rivers (i.e., $<$ 70 km in length), while the mean macroplastic density was 2.5 MA/m^2 for Aniene and Tiber rivers ($>$ 100 km in length) (Fig. 4).

Considering different vegetation heights in all the rivers, plants blocked macroplastics mostly below 2 m (i.e., in branches between 0.5 m and 2.0 m and below 0.5 m). Overall, there is a significant linear regression between the 3DVI in vegetation branches below and above high-water level ($0.5 < r < 2.0$ m, and $r > 2.0$ m, respectively $R^2 = 0.38$, $p = 0.007$, $Y = 0.007662 * X + 2.711$ and $R^2 = 0.45$, $p = 0.0023$, $Y = 0.2522 * X + 2.696$, Fig. 5).

With regards to the three riverine zones, plants entrapped the majority of MA in the downstream lower course near the mouth. Only in the lower river zone, there was a significant regression between 3DVI and plastics in vegetation ($R^2 = 0.94$, $p = 0.001$, $Y = 108.0 * X\text{-}143.7$; Fig. 6).

Regarding the environmental drivers that might affect the entrapment of plastics in vegetation, the number of species, number of individuals, and quantity of branches (respectively, correlation matrix, $r = 0.32$, $p = 0.535$; $r = 0.81$, $p = 0.049$; and $r = 0.30$, $p = 0.565$) resulted to be one of the most influent factors (Fig. 7). Biotic factors (i.e., such as the vegetation structure) mostly correlate with the occurrence of plastics in vegetation, driving plastic entrapment more than the environmental abiotic factors (i.e., such as hydrology).

Furthermore, to compare different kinds of structural indices, we calculated two different 3D and 3DVI. The first is the 3DVI based on $3D_1$, which provided no significant relation with the number of species (3DVI-R), Simpson index (3DVI-D), Shannon index (3DVI-H′), and Evenness index (3DVI-J). The second is the 3DVI based on the $3D_2$. This 3DVI index built with the number of species (3DVI-R), Simpson index (3DVI-D), Shannon index (3DVI-H′), and Evenness index (3DVI-J)

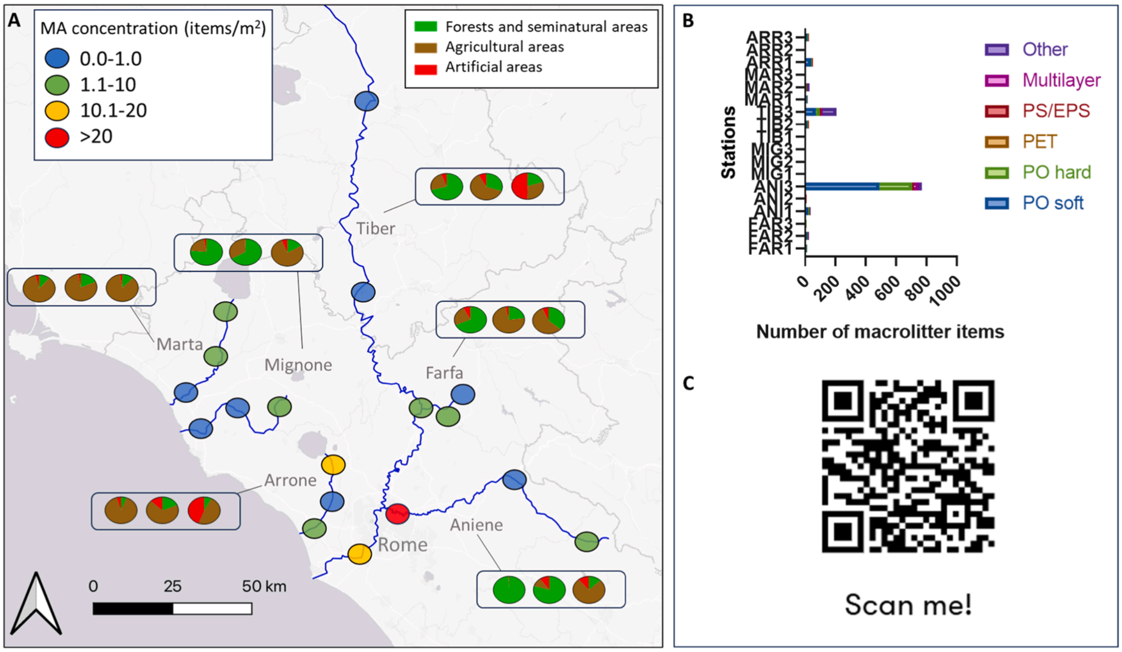


Fig. 2. (A) Macrolitter density found in each station, reporting land use for each station. (B) Number of macroplastics showing each polymer per station. (C) QR code with images of plastics entrapped by riparian vegetation along the sampled rivers. Link to the QR code: https://drive.google.com/drive/folders/174kkWKeavGmRfPvy8HME09BzCck9YJAh. ARR = Arrone river, MAR = Marta river, TIB = Tiber river, MIG = Mignone river, ANI = Aniene river, and FAR = Farfa river.

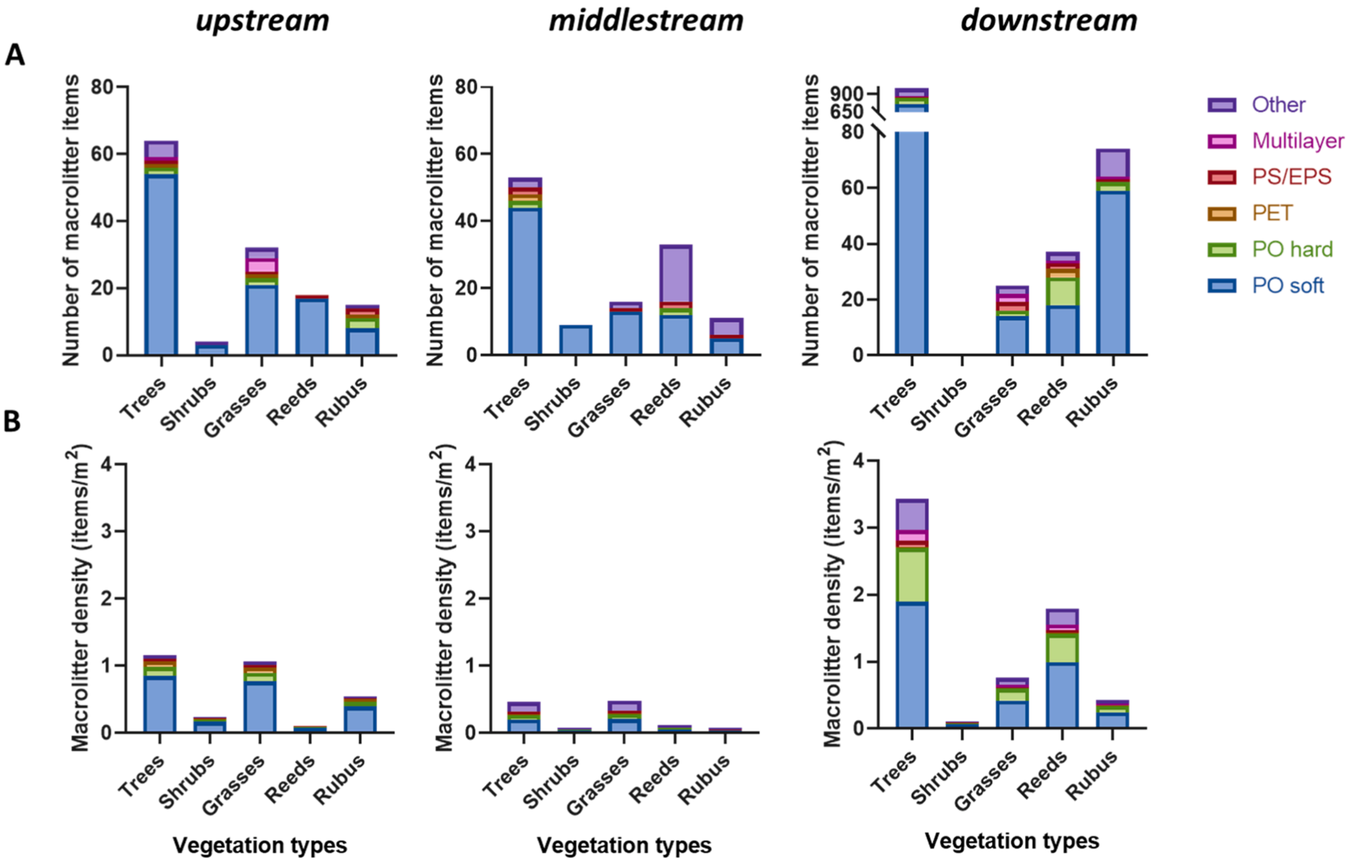


Fig. 3. Macrolitter items trapped by vegetation types (i.e., trees, shrubs, grasses, reeds, and Rubus) expressed as (A) number of items and (B) density (items/m^2) across the upstream, middlestream, and downstream zones of rivers. Note the different values for x-axes among river zones in panel A (downstream).

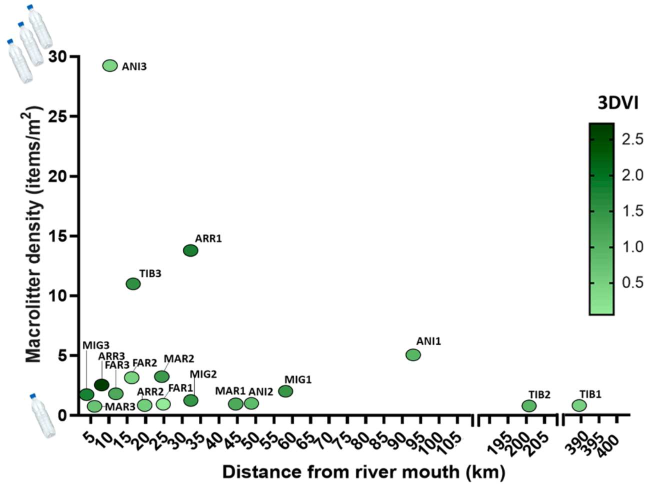


Fig. 4. Macroplastic density (items/m^2) trapped by vegetation highlighting tridimensional vegetation structural index (3DVI) in each site considering the distance from river mouth (km) in all sampled rivers. The green dots represent the 3DVI value and their position the microplastic density per site. ARR = Arrone river, MAR = Marta river, TIB = Tiber river, MIG = Mignone river, ANI = Aniene river, and FAR = Farfa river.

correlates significantly with both plastics' occurrence and concentration in rivers (Table 2).

4. Discussion

In this study, we showed the plant structures entrapping macroplastic litter along rivers. Vegetation showed different entrapping structures for single plants (i.e., plant morphological structure) as well as per community (i.e., riparian vegetation association). For the first time, we emphasised the structure of the riparian community (i.e., 3DVI) in relation to the plastic entrapment. We also investigated that the structure of riparian vegetation – highlighted by the 3DVI index – could drive the accumulation of plastics in vegetation more than hydrological factors. Riverine macroplastic distribution is highly driven by river currents and hydrology [17,18,36]. Consequently, plastics floating in rivers were transported to the riverbank and then on vegetation by extreme events such as floods [29]. However, when on vegetated riverbanks, plastic entrapment by plants depends highly on (1) the input of macrolitter and its abundance in the river, (2) the macrolitter type/polymer, and (3) the structure of the single plant as well as the vegetation community. Precisely, (1) regarding the abundance of litter in the river, the more macrolitter occurring in the river, the higher the probability of being trapped by vegetation. (2) Concerning the macrolitter type/polymer, soft litter items (i.e., plastic bags or PO soft packaging items) attach better to some type of vegetation structure (i.e., roots and branches), while hard items (i.e., plastic bottles or PO hard and PS items) remain stuck in the branches or the basket formed by roots. This result is in line with the global overview by Gallitelli and Scalici [17] who showed how each structure and type of vegetation traps specific macrolitter type/polymer. (3) Regarding vegetation type and structure, the effect of plant structure in entrapping litter has been highlighted by single species and communities [3,12]. According to the vegetation life form, some dune species with prostrate and more branched *habitus* entrapped more litter than not prostrate simpler *habitus* species [17]. Until now, the role of single species to entrap litter has been pointed out for dune plants, mangroves, and seagrasses (see De et al. [8], Sanchez-Vidal et al. [31], Li et al. [39], Battisti et al. [3], reviewed in Gallitelli and Scalici [17]), however the role of community vegetation has not been studied. Given the importance of riparian vegetation as an ecotone habitat, shelter and food for organisms, and filter of many contaminants [7], we started to investigate this habitat, highlighting that the whole community characterised by different types of vegetation provides the best combination of plants to entrap more plastics. As highlighted by the 3DVI index (until now tested to lowland mouth zone of rivers, see Gallitelli et al. [16]), the riparian community results have a structure efficiency in entrapping macrolitter. In this regard, when the 3DVI index accounts for the number of individuals shows a probably better representation of riparian community structure in each plot. This efficient structure of riparian vegetation in trapping plastics could be due to the different roles of each riparian species in blocking plastics. Among the different species, the alien species *Robinia pseudoacacia* block litter with spines, while trees such as *Alnus glutinosa*, *Salix* spp. and *Ficus carica* form specific branches at the top of their main trunk (i.e., called pollons) that form a sort of net, useful to entrap macrolitter [14,17]. Thus, the synergistic effect provided by the species in the riparian community might result in a higher plastic entrapment. More in detail, we found that stations with community characterised by dense and diverse species block more plastics. Plastics occurring in vegetation were significantly related to vegetation structure with the 3DVI correlated with the number of plastics. However, we should emphasise the slight correlation occurring among plastics in vegetation with the 3DVI in upper, middle, and lower riverine zones. This would highly depend on the amount of macrolitter items found on each site. Furthermore, as the 3D$_2$ index works when built with the number of species (3DVI-R), Simpson index (3DVI-D), Shannon index (3DVI-H′), and Evenness index (3DVI-J) and correlates significantly with both plastics' occurrence and concentration in rivers, thus the easiest combination of number of species (3DVI-R) or the most "ecologically" complete of evenness (3DVI-J) are recommended to be used. Those findings have been highlighted only in the lower river zone with a significant regression between 3DVI and plastics entrapped in vegetation. This result could be explained as riparian vegetation usually becomes denser in the lower river zone as the river width increases going into the lower zone (see Vannote et al. [37]). Although little research focused on investigating plastics in the river upstream zone [15,21], the importance of the lower and estuary river zone in discharging plastics into the sea is evident [18,33,34].

With regards to vegetation, we should keep in mind that plastics in

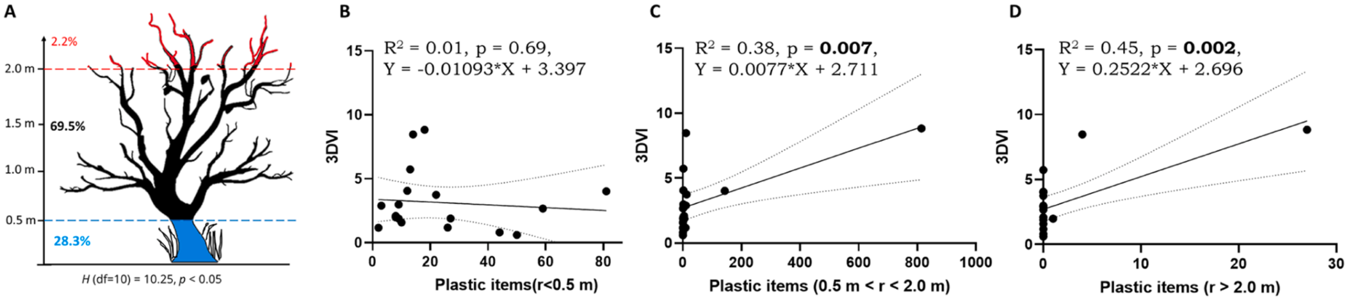


Fig. 5. Correlation between the plastic occurrence in different vegetation heights (i.e., branches) and the 3DVI in upper, middle, and lower riverine zones. The bold text indicates the significance of the results (Pearson correlations).

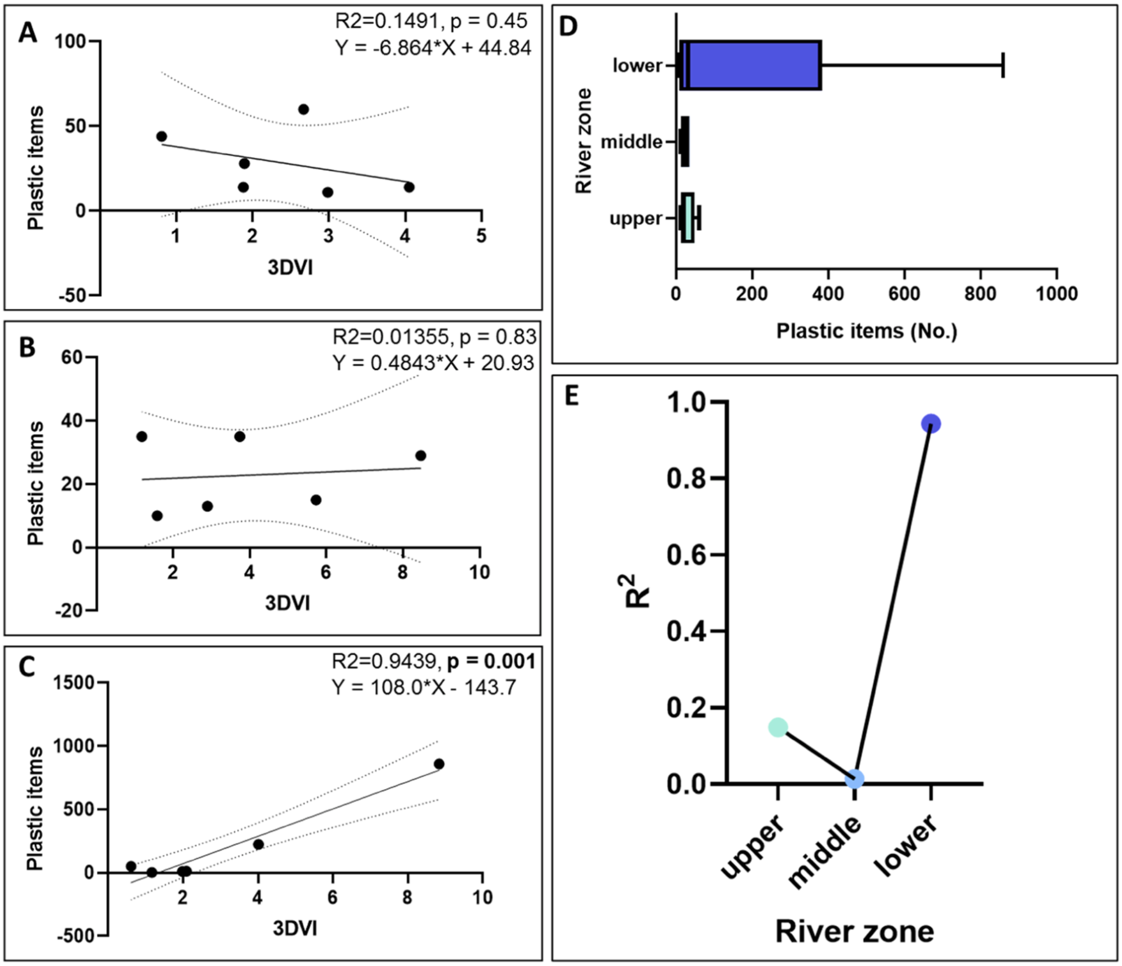
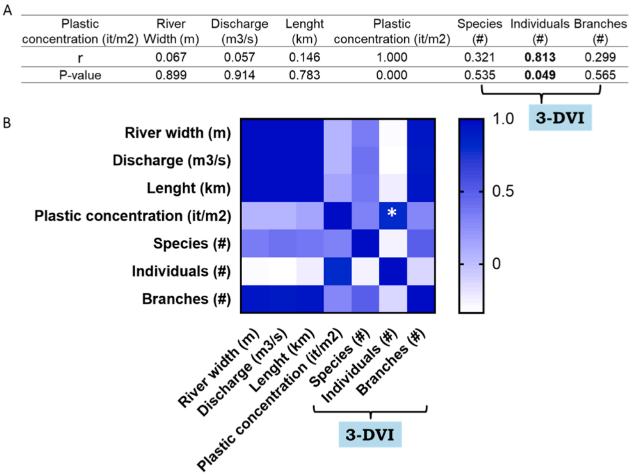


Fig. 6. Correlation of plastics in vegetation with the 3DVI in upper, middle, and lower riverine zones (A–C). Plastic occurrence is shown for each river zone (D). Pearson correlations R^2 showed for each river zone (E).


A

Plastic concentration (it/m2)	River Width (m)	Discharge (m3/s)	Lenght (km)	Plastic concentration (it/m2)	Species (#)	Individuals (#)	Branches (#)
r	0.067	0.057	0.146	1.000	0.321	**0.813**	0.299
P-value	0.899	0.914	0.783	0.000	0.535	**0.049**	0.565

Fig. 7. Plastics in vegetation are affected by environmental drivers. Results are shown in Table (A) and graphically in the heat map (B). The bold and white asterisk indicates the significance of the results (Pearson correlations).

Table 2
Regression results of the 3DVI indices, calculated with $3D_1$ and $3D_2$ and built with the four diversity indices (R, D, H', and J) related to plastics' occurrence (number of items) and concentration (number of items/area). R = number of species, D = Simpson index, H' = Shannon Index, and J = evenness index. R2 indicates the goodness of fit relative to the regression test. Significative results are shown in bold.

	3D1		3D2	
	Plastic (No.)	Plastics (it/m2)	Plastic (No.)	Plastics (it/m2)
3DVI-R	R2 = 0.05, F = 0.89, p = 0.36	R2 = 0.02, F = 0.28, p = 0.60	R2 = 0.66, F = 31.27, **p < 0.0001**	R2 = 0.60, F = 23.68, **p = 0.0002**
3DVI-D	R2 = 0.002, F = 0.03, p = 0.87	R2 = 0.0004, F = 0.006, p = 0.94	R= 0.86, F = 99.20, **p < 0.0001**	R2 = 0.61, F = 24.63, **p = 0.0001**
3DVI-H′	R2 = 0.009, F = 0.14, p = 0.72	R2 = 0.001, F = 0.02, p = 0.88	R= 0.85, F = 88.56, **p < 0.0001**	R2 = 0.61, F = 24.64, **p = 0.0001**
3DVI-J	R2 = 0.0009, F = 0.01, p = 0.91	R2 = 0.02, F= 0.34, p = 0.57	R= 0.87, F = 109.0, **p < 0.0001**	R2 = 0.61, F = 24.85, **p = 0.0001**

vegetation depend on two main factors. The first one is given by the hydrology features. Plastics in vegetation depend on the availability of macrolitter in the river as floating litter. This allows litter to be trapped by plants and, according to the river width and flow, the water level may increase with high or less intensity, bringing plastics from the river to the riverbank and riparian vegetation. In our case, plants blocked macroplastics mostly below 2 m with a slight linear regression between the 3DVI in vegetation branches below and above high-water level. This result is highly dependent on the river water level [29], thus rivers with higher flow may have greater flood events that result in plastic entrapment by plants in higher parts (see for instance big European rivers, such as the Danube and Volga Rivers). The second one depends on the land use and river zone. Specifically, urban sites and metropolises dump away great quantities of waste [34,42,43], while agriculture and forested areas show small quantities of plastics. In our study area, the most contaminated stations (i.e., ANI3, TIB3) are the ones with the most agricultural and artificial land use. Furthermore, we found that local land use around our sampling sites was mostly characterised by natural and agricultural areas near upstream zones and artificial nearer cities. Recent research pointed out that the highest density of macroplastics on riverbanks was found in urban and downstream-urban reaches, with the urban area and the number of inhabitants being good predictors of macroplastic abundance in rivers [42,43]. At our urban sites, we found an average of 13.9 macroplastics/m^2 along riverbanks. Our results are in line with the average density of macroplastics observed along rivers in Argentina (i.e., 27.5 ± 29.1 items/m^2) [42]. However, this pattern is significantly higher than reported densities in Mediterranean rivers and in some Atlantic rivers, such as the Ave River in Portugal (3.2 ± 3.2 items/m^2) [44]. This is probably because our study area comprehends the metropolis of Rome, which is highly populated and developed. Given that plastics trapped along watersheds may have a certain local source, land uses could predict the input of plastics from certain sources. In our study area, we mostly found PO soft items along the entire river course. These items could be plastic packaging, plastic foil, plastic bags and other items – mostly used for food and agriculture. In this way, polymers could be used as a proxy for plastic sources and consider land use as a proxy for certain types of plastics. Together with other factors, land use, geomorphology, hydrology and local variables were among the most important variables that resulted in being related to plastic accumulation.

Among the environmental factors, plant species, number of individuals and quantity of branches mostly drive the accumulation of plastics in vegetation. In literature, hydrological and abiotic factors were shown to be pivotal in riverine plastic transport [35], however environmental drivers showed good significance [28]. Here, our regression model found that plastics remained stuck within vegetation mostly due to biotic factors (i.e., the structural features of vegetation, in such cases). Among the factors, the number of individuals is the only one that resulted significantly, and it could provide a proxy of the vegetation density and structure. Thus, this means that vegetation characterised by dense and complex structures is able to trap more plastics retained by it. Biotic factors (i.e., vegetation structure) mostly correlate to the occurrence of plastics trapped in vegetation driving plastic entrapment more than the environmental abiotic factors (i.e., hydrology). Recent studies also confirmed that plastic entrapment is mostly driven by those factors, with geomorphological, land-use, and climatic factors shaping plastic distribution [42,44]. Furthermore, our results on plastics in vegetated riparian areas along rivers are suitable for local areas. Given this, the *phenomenon* of plastic entrapment highly depends on local conditions. As described in Gallitelli and Scalici [17], different patterns in other world regions or biomes could occur. Plastic entrapment by vegetation is mostly influenced by factors across local, catchment, and global scales [17]. At a global scale, precipitation, floods, and discharge are key drivers of plastic transport and entrapment in vegetated riverbanks [16,36,40–42]. Catchment-scale factors like river regimentation (e.g., dams, weirs) alter hydrology and plastic flow. Locally, human activities such as mowing and habitat alteration may reduce vegetation’s capacity to block plastics, while hydrological factors (e.g., water levels, meanders) and seasonal events (e.g., droughts, floods) affect plastic retention [16]. Despite these insights, research on abiotic factors across entire river catchments and riparian ecosystems remains limited.

Our results highlighted how the riparian vegetation community has a three-dimensionality structure apt at blocking efficiently macroplastics. These findings might be pivotal if applied to mitigation activities. In this regard, future research should consider this parameter in studies on riverine macrolitter and transfer the current knowledge on plastics to mitigate and solve this problem. In this case, as riparian vegetation may act as a temporary filter for plastics, we should use this information to introduce riverine clean-up activities in those plastic hotspot areas. Indeed, to remove riverine macroplastic litter, plastic hotspot areas might be detected and then monitored to provide policy decisional actions. Furthermore, knowing the best species and communities able to entrap plastics, those plants could be preserved to provide this ecosystem service. Future perspectives should focus on filling these gaps and providing information for plastic removal measures and policy-making decisions.

5. Conclusions

For the first time, we applied a tridimensional index accounting for the structure of riparian vegetation with the presence of plastics in vegetation. We emphasised plant species and structures that are important variables for understanding the entrapment efficiency of macrolitter, highlighting that the complexity of riparian vegetation structure is key for plastic entrapment. The role and structure of riparian vegetation in entrapping macrolitter have recently started to be investigated, presenting a high potential to be applied. Given that much research on riverine plastic transport has been conducted, future research should deal with the fact that vegetation entraps macroplastics, providing this new ecosystem service. As riparian species provide the ecosystem service of trapping macrolitter, these findings are crucial for ecosystem restoration and sustainable requalification of the threatened freshwater habitats. Further studies should focus on riverine macrolitter to better understand the fate of plastics in rivers and seas to mitigate the problem. As vegetation retains plastics efficiently along the whole river watershed, the 3DVI index could be managed and applied for future solutions to mitigate plastic pollution. Specifically, as several types of vegetation (i.e., mangroves, macrophytes, seagrass, riparian vegetation, and dune plants) globally act as a trap for macrolitter, they could be useful to detect plastic hotspot areas during mitigation and clean-up activities. This means that the application of a vegetation structure index should be the first step to setting a protocol to tackle plastic pollution.

CRediT authorship contribution statement

Luca Gallitelli: Conceptualization, Data curation, Formal analysis, Project administration, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Maurizio Cutini:** Conceptualization, Methodology, Validation, Visualization, Writing – review & editing. **Giulia Cesarini:** Investigation, Validation, Visualization, Writing – review & editing. **Massimiliano Scalici:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

All authors read and approve the ms.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by the Grant of Excellence Departments (“Departments of Excellence 2023–27”, “Dipartimenti d’Eccellenza 2023–27”), MUR-Italy (Italian Minister of University and Research). The authors acknowledge the support of the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.4 – Call for tender No. 3138 of 16 December 2021, rectified by Decree n.3175 of 18 December 2021 of Italian Ministry of University and Research funded by the European Union – NextGenerationEU, Project code CN_00000033, Concession Decree No. 1034 of 17 June 2022 adopted by the Italian Ministry of University and Research, CUP F83C22000730006; CUP J83C22000870007 Project title "National Biodiversity Future Center – NBFC. The study was also supported by RIPARIANET (Prioritising riparian zones to sustain and connect river biodiversity and function, https://riparianet.eu/), co-funded by the EU Commission (Biodiversa+). We also acknowledge the Editor and the anonymous Reviewers who provided useful comments to improve our manuscript.

Data availability

All data are available in the manuscript and Supplementary materials.

References

[1] N. Abdelkader, S.B. Ismail, R. Zakhama-Sraieb, Macro-, meso-and microplastic debris in three sandy beaches of north-eastern Tunisian coasts, Reg. Stud. Mar. Sci. 67 (2023) 103229.

[2] A. Anastasopoulou, T. Fortibuoni, Impact of plastic pollution on marine life in the Mediterranean sea, in: F. Stock, G. Reifferscheid, N. Brennholt, E. Kostianaia (Eds.), Plastics in the Aquatic Environment – Part I. The Handbook of Environmental Chemistry, 111, Springer, Cham, 2019, https://doi.org/10.1007/698_2019_421.

[3] C. Battisti, L. Gallitelli, S. Vanadia, M. Scalici, General macro-litter as a proxy for fishing lines, hooks and nets entrapping beach-nesting birds: implications for clean-ups, Mar. Pollut. Bull. 186 (2023) 114502, https://doi.org/10.1016/j.marpolbul.2022.114502.

[4] M.C.M. Blettler, C. Mitchell, Dangerous traps: macroplastic encounters affecting freshwater and terrestrial wildlife, Sci. Total Environ., 2021.

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

[6] M.C.M. Blettler, L. Gauna, A. Andréault, E. Abrial, R.E. Lorenzón, L.A. Espinola, K. M. Wantzen, The use of anthropogenic debris as nesting material by the greater thornbird, an inland–wetland-associated bird of South America, Environ. Sci. Pollut. Res. 27 (2020) 41647–41655, https://doi.org/10.1007/s11356-020-10124-4.

[7] L.J. Cole, J. Stockan, R. Helliwell, Managing riparian buffer strips to optimise ecosystem services: a review, Agric. Ecosyst. Environ. 296 (2020) 106891.

[8] K. De, S. Sautya, G.U. Dora, S. Gaikwad, D. Katke, A. Salvi, Mangroves in the "Plasticene": high exposure of coastal mangroves to anthropogenic litter pollution along the Central-West coast of India, Sci. Total Environ. 858 (2023) 160071, https://doi.org/10.1016/j.scitotenv.2022.160071.

[9] V.N. de Ruijter, P.E. Redondo-Hasselerharm, T. Gouin, A.A. Koelmans, Quality criteria for microplastic effect studies in the context of risk assessment: a critical review, Environ. Sci. Technol. 54 (19) (2020) 11692–11705.

[10] D. Eerkes-Medrano, R. Thompson, Occurrence, fate, and effect of microplastics in freshwater systems, in: Microplastic Contamination in Aquatic Environments, Elsevier, 2018, pp. 95–132.

[11] F. Galgani, G. Hanke, S. Werner, L. De Vrees, Marine litter within the European marine strategy framework directive, ICES J. Mar. Sci. 70 (2013) 1055–1064, https://doi.org/10.1093/icesjms/fst122.

[12] L. Gallitelli, M. D'Agostino, C. Battisti, A. Cózar, M. Scalici, Dune plants as a sink for beach litter: the species-specific role and edge effect on litter entrapment by plants, Sci. Total Environ. 904 (2023) 166756.

[13] L. Gallitelli, C. Battisti, M. Scalici, Using social media to determine the global distribution of plastics in birds' nests: the role of riverine habitats, Land 12 (2023) 670, https://doi.org/10.3390/land12030670.

[14] L. Gallitelli, M. Scalici, Can macroplastics affect riparian vegetation blooming and pollination? First observations from a temperate South-European river, Ecol. Indic. 154 (2023) 110531, https://doi.org/10.1016/j.ecolind.2023.110531.

[15] L. Gallitelli, M. Scalici, Riverine macroplastic gradient along watercourses: a global overview, Front. Environ. Sci. 10 (2022) 937944, https://doi.org/10.3389/fenvs.2022.937944.

[16] L. Gallitelli, M. Cutini, M. Scalici, Riparian vegetation plastic monitoring: a harmonized protocol for sampling macrolitter in vegetated riverine habitats, Sci. Total Environ. 912 (2024) 169570, https://doi.org/10.1016/j.scitotenv.2023.169570.

[17] L. Gallitelli, M. Scalici, Conceptual model of global plants entrapping plastics, Environ. Rev. (2024). ⟨https://cdnsciencepub.com/doi/abs/10.1139/er-2023-0141⟩.

[18] González-Fernández, et al., Floating macrolitter leaked from Europe into the ocean, Nat. Sustain. 4 (2021) 474–483, https://doi.org/10.1038/s41893-021-00722-6.

[19] D. González-Fernández, C.T. Roebroek, C. Laufkötter, A. Cózar, T.H. van Emmerik, Diverging estimates of river plastic input to the ocean, Nat. Rev. Earth Environ. (2023) 1–3.

[20] M. Liro, P. Mikuś, B. Wyżga, First insight into the macroplastic storage in a mountain river: the role of in-river vegetation cover, wood jams and channel morphology, Sci. Total Environ. 838 (2022) 156354.

[21] M. Liro, T.H. van Emmerik, A. Zielonka, L. Gallitelli, F.C. Mihai, The unknown fate of macroplastic in mountain rivers, Sci. Total Environ. 865 (2023) 161224.

[22] A.C. Mehinto, S. Coffin, A.A. Koelmans, S.M. Brander, M. Wagner, L.M. Thornton Hampton, A.G. Burton, E. Miller, T. Gouin, S.B. Weisberg, C.M. Rochman, Risk-based management framework for microplastics in aquatic ecosystems, Microplast. Nanoplast. 2 (1) (2022) 17.

[23] C. Morales Jiménez, F. Lango Reynoso, M. del Refugio Castañeda Chávez, G. Navarrete Rodríguez, Macroplastics in the bottom of the Veracruz reef system national park, Sustainability 15 (8) (2023) 6934.

[24] S. Nama, A. Shanmughan, B.B. Nayak, S. Bhushan, K. Ramteke, Impacts of marine debris on coral reef ecosystem: a review for conservation and ecological monitoring of the coral reef ecosystem, Mar. Pollut. Bull. 189 (2023) 114755, https://doi.org/10.1016/j.marpolbul.2023.114755.

[25] K.J. Parton, T.S. Galloway, B.J. Godley, Global review of shark and ray entanglement in anthropogenic marine debris, Endanger. Species Res. 39 (2019) 173–190.

[26] C. Raunkiaer, The Life Forms of Plants and Statistical Plant Geography, Clarendon Press, Oxford, 1934.

[27] P.E. Redondo-Hasselerharm, A. Rico, A.A. Koelmans, Risk assessment of microplastics in freshwater sediments guided by strict quality criteria and data alignment methods, J. Hazard. Mater. 441 (2023) 129814.

[28] C.T. Roebroek, S. Harrigan, T.H. Van Emmerik, C. Baugh, D. Eilander, C. Prudhomme, F. Pappenberger, Plastic in global rivers: are floods making it worse? Environ. Res. Lett. 16 (2) (2021) 025003.

[29] C.T. Roebroek, C. Laufkötter, D. González-Fernández, T. Van Emmerik, The quest for the missing plastics: large uncertainties in river plastic export into the sea, Environ. Pollut. 312 (2022) 119948.

[30] L. Roman, B.D. Hardesty, Q. Schuyler, A systematic review and risk matrix of plastic litter impacts on aquatic wildlife: a case study of the Mekong and Ganges River Basins, Sci. Total Environ. 843 (2022) 156858.

[31] A. Sanchez-Vidal, M. Canals, W.P. De Haan, J. Romero, M. Veny, Seagrasses provide a novel ecosystem service by trapping marine plastics, Sci. Rep. 11 (2021) 254.

[32] A.L.P. Silva, J.C. Prata, T.R. Walker, A.C. Duarte, W. Ouyang, D. Barcelò, T. Rocha-Santos, Increased plastic pollution due to COVID-19 pandemic: Challenges and recommendations, Chem. Eng. J. 405 (2021) 126683.

[33] R. Tramoy, J. Gasperi, L. Colasse, M. Silvestre, P. Dubois, C. Noûs, B. Tassin, Transfer dynamics of macroplastics in estuaries–new insights from the Seine estuary: Part 2. Short-term dynamics based on GPS-trackers, Mar. Pollut. Bull. 160 (2020) 111566.

[34] R. Tramoy, E. Blin, I. Poitou, C. Noûs, B. Tassin, J. Gasperi, Riverine litter in a small urban river in Marseille, France: plastic load and management challenges, Waste Manag. 140 (2022) 154–163.

[35] T. van Emmerik, E. Strady, T.C. Kieu-Le, L. Nguyen, N. Gratiot, Seasonality of riverine macroplastic transport, Sci. Rep. 9 (1) (2019) 1–9.

[36] Y. Mellink, L. Schreyers, R. Hauk, R. Pinto, K. Thi, K. Waldschläger, T. van Emmerik, Overcoming oceans of ignorance: what you should know about plastic waste before it enters the sea, in: Plastic Pollution in the Global Ocean, 2023, pp. 47–75.

[37] R.L. Vannote, G.W. Minshall, K.W. Cummins, J.R. Sedell, C.E. Cushing, The river continuum concept, Can. J. Fish. Aquat. Sci. 37 (1) (1980) 130–137.

[38] A.T. Williams, S.L. Simmons, The degradation of plastic litter in rivers: implications for beaches, J. Coast. Conserv. 2 (1996) 63–72.

[39] Q. Li, L. Su, C. Ma, Z. Feng, H. Shi, Plastic debris in coastal macroalgae, Environ. Res. 2 (2022) 112464, 205.

[40] M. Liro, P. Mikuś, B. Wyżga, First insight into the macroplastic storage in a mountain river: the role of in-river vegetation cover, wood jams and channel morphology, Sci. Total Environ. 838 (2022) 156354.

[41] Ł. Przyborowski, Z. Cuban, A. Łoboda, M. Robakiewicz, S. Biegowski, T. Kolerski, The effect of groyne field on trapping macroplastic. Preliminary results from laboratory experiments, Sci. Total Environ. 921 (2024) 171184.

[42] A.S. Andrade-Muñoz, M.L. Miserendino, C.P. Quinteros, W.M. Dromaz, E. Abrial, C. Y. Di Prinzio, Macroplastic pollution in riparian corridors of urban and pristine mountain streams in Patagonia (Argentina), Sci. Total Environ. 959 (2025) 178092.

[43] T.J. Hoellein, L.H. Kim, R.F. Lazcano, A.E. Vincent, Debris dams retain trash, mostly plastic, in urban streams, Freshw. Sci. 43 (1) (2024) 94–106.

[44] G. Pace, J. Lourenço, C.A. Ribeiro, C. Rodrigues, C. Pascoal, F. Cássio, Spatial accumulation of flood-driven riverside litter in two Northern Atlantic Rivers, Environ. Pollut. 345 (2024) 123528.