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Riparian vegetation entraps macroplastics along the entire river course: Implications for eco-safety activities and mitigation strategies

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ABSTRACT

Macroplastic litter causes detrimental effects on freshwater biota affecting human health. Despite the significant role of rivers in transporting plastic waste, most plastics remain in fluvial ecosystems, accumulating in infrastructure, river sediment, and (riverbank) vegetated areas. However, the entrapment of plastics by riparian vegetation was overlooked, particularly in upper and middle river courses. For the first time, we aimed to quantify the entrapment of plastics by riparian vegetation along the entire river course. Sampling riparian areas in the upper, middle, and lower river courses in central Italy, we found 1548 macrolitter items, with vegetation entrapping 93.9% of total litter. Riverbank and riparian plastics acted as long-term indicators of river plastics. We emphasized the trapping efficiency at the species level highlighting that the best plastic trapper species were trees, shrubs and reeds (*Populus* spp., *Salix* spp., *Rubus ulmifolius*, *Phragmites australis*, and *Ficus carica*), blocking 85.4% of the total macrolitter entrapped by plants. Plastic pieces, bags, bandages, sanitary items, and packaging were among the most trapped types. Furthermore, vegetation in the lower river course exhibited greater plastic entrapment compared to the upper and middle courses, following the fact that all the river courses contribute to plastic pollution. Recognizing the potential of riparian vegetation as a valuable ecosystem service in trapping macroplastics, further research should explore the characteristics and structures of riparian communities involved in this process. By developing eco-safe practices and mitigation strategies based on these findings, we might contribute significantly to managing, conserving, and restoring riverine ecosystems.

1. Introduction

Plastics represent a new widely distributed global concern, affecting aquatic ecosystems (Blettler and Mitchell, 2021; Azevedo-Santos et al., 2021). Macrolitter, with a focus on plastics, can cause detrimental effects on freshwater biota and also affect human health (Thompson et al., 2009; Eerkes-Medrano and Thompson, 2018; Waring et al., 2018; Agathokleous et al., 2021; MacLeod et al., 2021; Kukkola et al., 2021). Plastics are widespread across the globe occurring from the aquatic to atmospheric ecosystems, representing a well-studied hot topic and a growing concern threatening biodiversity and ecosystem services (Windsor et al., 2019a; Blettler and Mitchell, 2021; Azevedo-Santos et al., 2021). In aquatic ecosystems, most of the studies focused on marine environment rather than freshwater (Blettler et al., 2018; Eerkes-Medrano and Thompson, 2018; Cera et al., 2022; Battisti et al., 2023a), thus research in inland waters is only recently underway. Despite this, it has been highlighted that rivers are among the main pathways of plastic release to the oceans (Crosti et al., 2018; Gallitelli et al., 2020; González-Fernández et al., 2021; Palmas et al., 2022; Cesarini et al., 2023). The large items of plastics, called macroplastics (MA>5 mm, *sensu* Gallitelli and Scalici, 2022), can be degraded into small and microscopic particles, known as microplastics (1 μm < MP < 5 mm) due to environmental factors such as wind, UV radiation, and waves. MP have a negative impact on aquatic ecosystems with potential risk to human health. As MP originated from MA and studies on macroplastics are recently underway (Blettler et al., 2018; Eerkes-Medrano and Thompson, 2018; Cera et al., 2022), future research must focus on macroplastics in freshwaters. Among freshwater systems, rivers are of particular interest as they carry the majority of macroplastic litter from the land to the seas (Gallitelli et al., 2020; González-Fernández et al.,

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2021; Cesarini et al., 2023). However, most plastics remain stuck in the fluvial ecosystem, accumulated in infrastructure, river sediment, aquatic plants, and riverbank vegetated areas (Liro et al., 2020; Gallitelli et al., 2022; van Emmerik et al., 2022; Gallitelli and Scalici 2024). Recently, many studies quantified riverine macroplastic litter transport. Extreme events, such as floods, tsunamis, and storms might significantly affect MA transport and seasonality, but more research is needed (van Emmerik et al., 2019; Lechthaler et al., 2020; Roebroek et al., 2021). Riverine macrolitter transport depends on several factors, such as river hydrology, riverbank alteration, and riparian vegetation occurrence. However, together with riparian vegetation, floods may also increase plastic sink on the riverbanks (Liro et al., 2020; Roebroek et al., 2021). Although plastic transport depends on river hydrometeorological factors (e.g., river discharge, wind speed) and geomorphological characteristics (e.g., meanders, river width), several studies highlighted macrolitter accumulation courses in riverbank vegetated areas (Liro et al., 2020; van Emmerik et al., 2020; de Lange et al., 2023; Nguyen and Bui, 2023). However, although previous observations in rivers (Williams and Simmons, 1998), only few studies investigated the role of vegetation in entrapping macrolitter on riverbanks (Rech et al., 2014; Hoellein et al., 2014; McCormick and Hoellein, 2016). Literature highlighted the importance of the entrapment of MA by mangroves (Ivar do Sul et al., 2014; Martin et al., 2019; Luo et al., 2021; De et al., 2023; Okuku et al., 2023), dunal plants (Gallitelli et al., 2021; Andriolo et al., 2021; Ben-Haddad et al., 2023; Battisti et al., 2023b; Menicagli et al., 2023) and aquatic macrophytes (Castrop et al., 2020; Schreyers et al., 2021; Gallitelli et al., 2023). Given the importance of rivers as carriers of MA to the sea (González-Fernández et al., 2021), it is surprising that MA trapping by freshwater riparian vegetation has not been well investigated (Williams and Simmons, 1998; Cesarini and Scalici, 2022; Gallitelli et al., 2024).

Riparian vegetation is a type of plant community growing close to riverbanks and it is part of the riparian course, a transitional area between land and freshwaters that is a key element for stream ecosystem functioning (Cole et al., 2015, 2020). Particularly, riparian habitats play many ecological roles and provide ecosystem services (e.g., corridor, food and shelter for threatened species, buffer for water temperature changes, filter for organic matters, pollutants, fertilizers, and also for plastics, see Cole et al., 2015, 2020).

Considering that plastic accumulates along the river course and that trees and shrubs trapped efficiently plastic litter (Gallitelli and Scalici, 2022), here we hypothesise that the downstream river course may accumulate more plastics following the River Continuum Concept (see Vannote et al., 1980). Furthermore, a riparian community composed by trees and shrubs might be more apt at blocking macroplastics, following literature studies. Although studies on macrolitter mainly focus on the lower river course and given that plastics sources are located along the whole river (Gallitelli and Scalici, 2022; Liro et al., 2023), it is important to investigate the distribution of plastics along the entire river rod, highlighting the role of vegetation in entrapping macrolitter on riverbanks, until now neglected. Thus, for the first time, we aimed at investigating the distribution of macroplastics and their accumulation areas along rivers. We explored the entrapment of plastics by riparian vegetation considering the three river courses along the entire river rod. We quantified for the first time the riparian plant diversity in relation to plastic occurrence and plastic entrapment. We expected that a higher number of species should block more plastics as vegetation can act as a net for litter.

To analyse the gradient of plastic along the river course, the highest and the lowest courses of watercourses were selected. As most of the research focused on the river's lower course (Gallitelli and Scalici, 2022) and MA were also observed in the upstream part of some rivers (Gallitelli and Scalici, 2022; Liro et al., 2023), we decided to investigate plastic distribution along the three river courses. As river courses change according to abiotic and biotic factors (Vannote et al., 1980), we expected that macroplastic litter distribution may vary due to the different characteristics of each river course. Indeed, we should consider that the river is getting larger going from the upper to the lower course (Vannote et al., 1980).

2. Material and methods

2.1. Study area

To achieve our aims, we sampled sites along the three river course (i.e., upper, middle, and lower courses) of six rivers in central Italy. As rivers, we selected the Tiber River, the 2nd longest river in Italy (so its plastic output to the sea might be fundamental, according to González-Fernández et al., 2021), then Farfa and Aniene rivers as the main tributaries of the Tiber River, and finally Marta, Mignone and Arrone Rivers, as more pristine and agricultural areas. According to Fig. 1, each sampling site shows different terrain characteristics as expressed by the land use (see Table S1). Indeed, the upstream courses of the Tiber watershed (including Farfa and Aniene rivers, see FAR1, ANI1, and TIB1) flow in pristine and natural areas, while the Marta, Mignone and Arrone rivers flow entirely in agricultural areas (see Fig. 1). Moreover, the downstream courses of the Tiber and Aniene rivers (i.e., TIB3 and ANI3, Fig. 1) flow in the urban area of Rome.

We performed fieldwork along rivers sampling MA in each river in riparian habitats considering the number of items, litter type, item type, size, and colour. The number of items is visually counted after removal of litter collected (check Galgani et al., 2013). The litter type refers to the category of items collected, such as plastic bags, plastic items, polystyrene items, and so on (following González-Fernández et al., 2021). The item size is approximated by visual census considering size of the real objects and using six classes, such as 2.5–5 cm, 5–10 cm, 10–20 cm, 20–30 cm, 30–50 cm, >50 cm (González-Fernández et al., 2021). For instance, a plastic bottle is about 33 cm and so it goes in the class 30–50 cm. For more information on litter and item type, we followed Galgani et al. (2013) and González-Fernández et al. (2021), while for the specific sampling and plastic standardisation see Gallitelli and Scalici (2022) and Gallitelli et al. (2023).

2.2. Sampling approach

Regarding the study area (Fig. 1), we sampled riparian habitats along rivers, containing riparian vegetation communities with several dominant species, such as maple (*Acer* spp.), willow (*Salix* spp.) and poplar (*Populus* spp.). To investigate macroplastic distribution along rivers concerning the riparian vegetation to trap macroplastics, surveys of riverine macroplastic litter entrapped in riparian vegetation were conducted in the middle-end of June 2021 considering the low water level (mean of Tiber river water level: 5.3 m, min-max = 4.9–7.2 m). To quantify the trap efficiency of macroplastics by riparian plants, we selected random plots considering the river width and the riparian course width, thus standardising the sampled area. Considering that some riparian areas are so narrow, we set a *minimum* of 5 m^2 area to consider small-sized rivers and to allow comparisons with medium and big-sized European rivers (Fig. 2, according to Gallitelli et al., 2024). A standardised approach was then carried out in each plot, analysing the *habitus* - or 'spatial organization' - of the riparian local communities. In each plot, dominant species were investigated to evaluate their ability as mechanical traps for plastics. To define a species dominant, we considered the minimum of 5% coverage in a plot, adapting it from phytosociological methods (Braun-Blanquet, 1932). More information on the vegetation in these rivers is reported in Ceschin and Salerno (2008), Fratarcangeli et al. (2022), Gallitelli and Scalici (2023), and Gallitelli et al. (2024) (see Fig. 2).

After collecting data on the species occurring in the plots, the dominant species were identified and given a percentage coverage within the plot. In addition, to link the plant morphological structure to the plastic occurrence, a coverage was assigned to the community layer

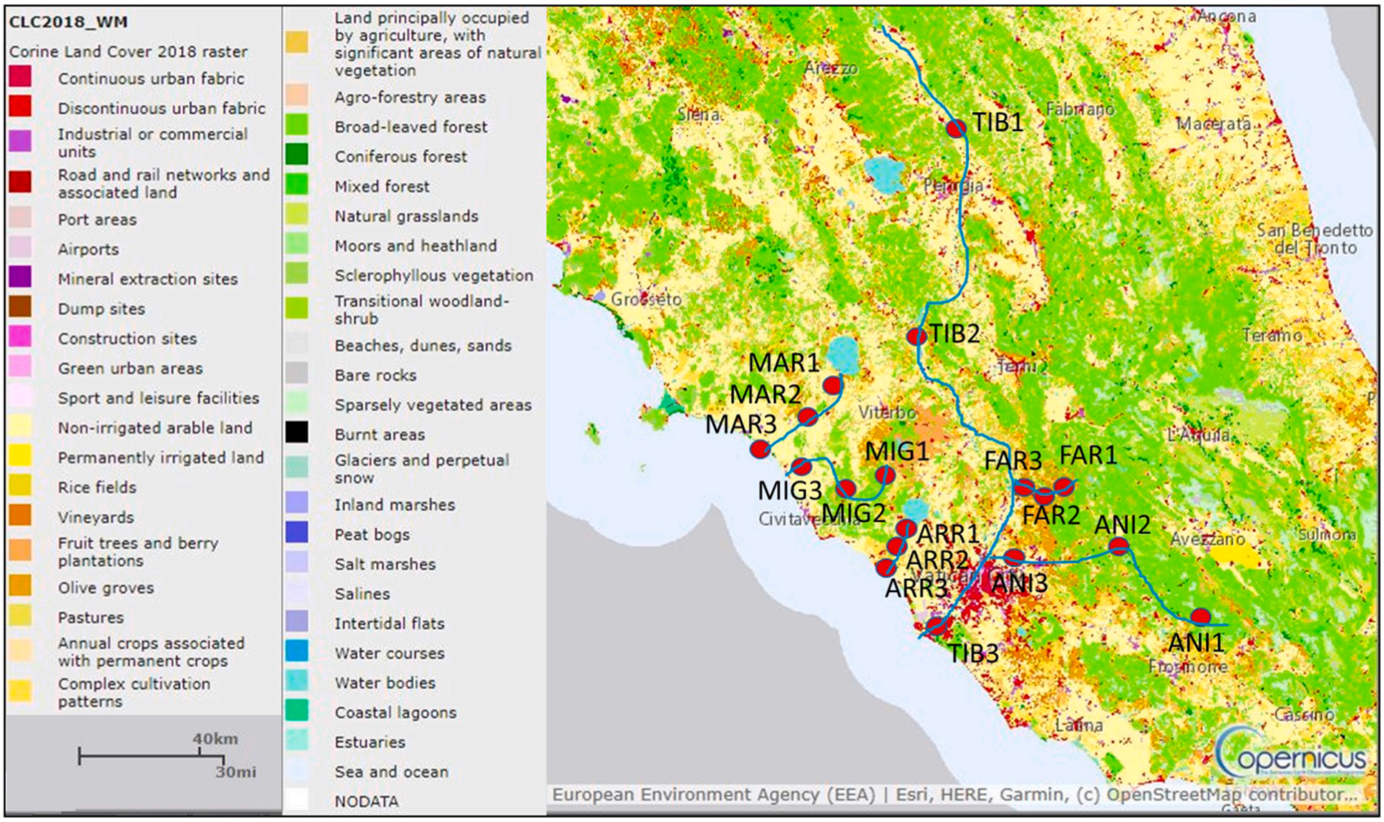

Fig. 1. Study area focusing on central Italy rivers. Each river has been sampled considering the three river courses (i.e., the number 1 after the acronym indicates the upstream, the 2 is the middle and the 3 is the lower river course). TIB = Tiber River; ANI = Aniene River; FAR = Farfa River; ARR = Arrone River; MIG = Mignone River; and MAR = Marta River. The image was taken on Copernicus and the European Environment Agency (EEA).

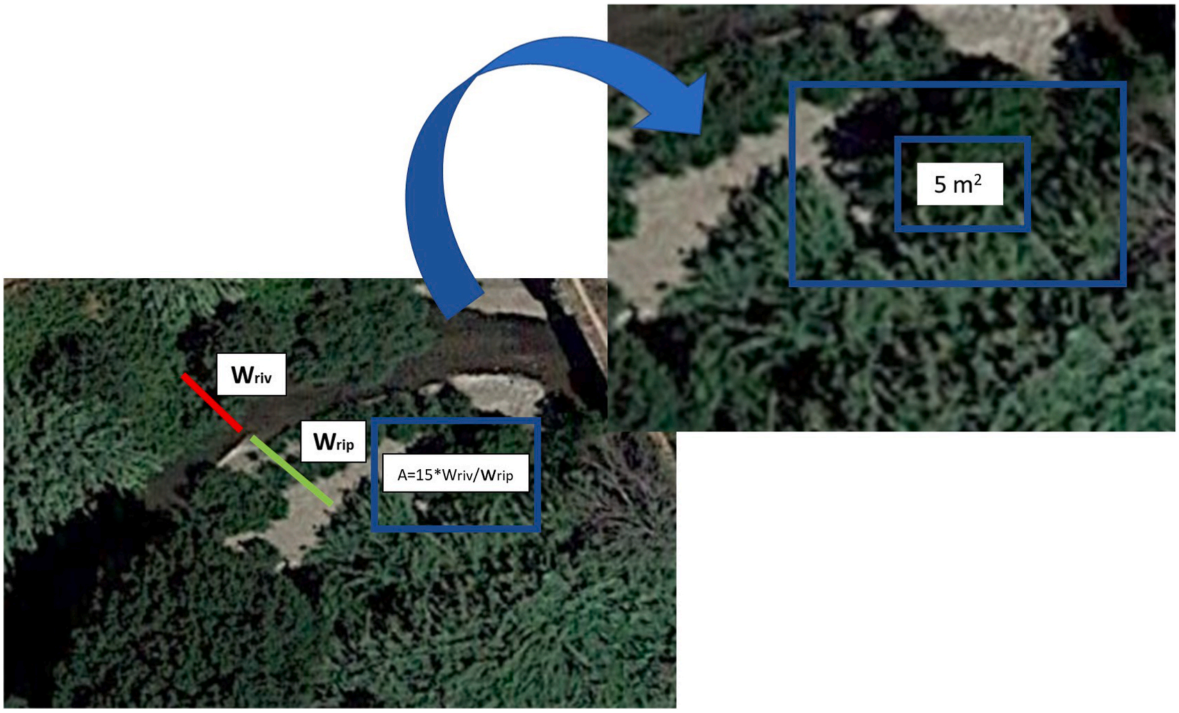

Fig. 2. Sampling plots in the study area. Plot area was calculated considering river width and riparian vegetation width. Our approach considered two important factors (e.g., river width and riparian vegetation width) for calculating the area of the plot in which we sampled plastics in riparian vegetation. rw = river width, rv = riparian vegetation width, 15 is a numerical constant allowing us to calculate a *minimum* area of 5 m^2 (according to Gallitelli and Scalici, 2023; Gallitelli et al., 2024). The image was taken from Google Earth.

of the vegetation typology (i.e., tree, shrub, herbaceous, reed) occurring in the plot. In each plot, we collected data on dominant species coverage, type of vegetation, and factors such as height, branches, and diameter species. In particular, we collected plastics in vegetation considering all individuals of a species in a plot. When sampling an individual, we noted plant characteristic (i.e., heights) to then understand better on where plastics accumulate more in relation to the water level. The sampling effort lasts all the time necessary to remove plastics from all the individuals in the plot. Then, we collected macroplastic litter and counted and classified it for type, size, colour, and polymers. Then, the macrolitter present in vegetation species was classified by following Galgani et al. (2013) and González-Fernández et al. (2021). All these data allow us to understand if vegetation could entrap plastics along the entire river course. To understand the quantity of macroplastics carried by the river current, we split and delete the contribution by wind following the protocol set in Gallitelli et al. (2024). Precisely, all plastics carried by river current, presenting mud encrustations, and being below river water level were considered plastics carried by the river (i.e., "river plastics").

2.3. Statistical analyses

Before performing each statistical test, normality and data distribution were checked. If data were not normally distributed, non-parametric tests were performed.

To compare data among the three river courses, data on plastic entrapped within vegetation were standardised considering the coverage of each species in each plot. To obtain the plastic concentration of items entrapped in plants, we standardised the number of items by dividing it with sampling area for each plot.

To investigate if plastics in riverbank were related to and plastics in vegetation, we performed a Spearman correlation test. Similarly, to explore if there could be possible relations between the diversity (i.e., the number of species) and the number of plastic items in the six rivers and for each site, we carried out a Spearman correlation test.

Considering the riverbank as a source of macroplastics from floating litter to riparian vegetation, the source of macroplastics can be input by the river upstream course and along the watershed, following Honorato-Zimmer et al. (2021) and Gallitelli and Scalici (2022). To unravel the source of plastics in riparian habitats, land use of a 1 km × 1 km buffer area was applied along the stations in the study area. The percentages of each matrix (e.g., seminatural areas, artificial areas, agricultural areas) were calculated using the Corine Land Cover nomenclature and protocol. More information on the land use along the sampled rivers can be found in Table S1.

Furthermore, to understand if the three river courses entrapped different quantities and types of plastics, a Kruskal-Wallis test was performed. Concerning the size of macrolitter changing along the three river courses, a Friedman test was performed as data (i.e., plastic size) were matched. If the Kruskal-Wallis and the Friedman tests were significant, Dunn's post hoc test was conducted to inquire which groups showed significant differences.

To investigate the interaction of species blocking plastics and the relative station site, a co-occurrence analysis was performed following Gotelli (2000) and Gallitelli et al. (2021) who adapted co-occurrence analysis to plastics in dune vegetation. To assess if the plant species blocked similar plastics resulting in an aggregate community structure, we calculated the C-score index as well as the V-ratio by using EcoSim (Gotelli and Entsminger, 1999; Gallitelli et al., 2021). To highlight how the station sites with species grouped, a cluster analysis has been performed using Past software (Hammer et al., 2001).

All the statistical analyses were performed using GraphPad Prism version 8.0.1, GraphPad Software, www.graphpad.com.

3. Results

Overall, we found 1562 macrolitter items on ~300 m^2 of sampled riparian areas with plastics representing 96.3% of total litter. Specifically, riparian vegetation entrapped 93.9% of total litter ($n = 1466$), while 6.1% was found on unvegetated areas of the riverbank ($n = 96$). Concerning the litter blocked by vegetation, riverine and wind plastics accounted respectively for 97.8% and 2.2% of total litter. We observed a not significant correlation between plastics in riverbank and river plastics in riparian vegetation ($r = 0.24$, $p = 0.34$). Standardising the number of items per area occupied by riverbank and vegetation, the correlation resulted significant ($r = 0.61$, $p = 0.007$).

The best efficient riparian plants in entrapping macrolitter were: (i) *Populus* spp. (51.6%), (ii) *Salix* spp. (19.0%), (iii) *Rubus ulmifolius* (6.7%), (iv) *Phragmites australis* (6.3%), and (v) *Ficus carica* (1.8%), accounting for 85.4% of the total macrolitter entrapped by plants (Fig. S2, Table S2). Considering the area covered by each species in all the plots (Fig. 3), the top-5 taxa were: (i) *Populus* spp. (20.8%), (ii) *Salix* spp. (19.0%), (iii) *Parietaria* sp. (16.7%), (iv) *Rubus ulmifolius* (8.0%) and (v) *Phragmites australis* (6.6%). According to the plant type, trees blocked more macrolitter (76.3%) than grasses (9.1%), shrubs (8.2%), and reeds (6.3%), independently of the coverage covered by each species. Standardising the number of items considering the area of each species in each plot, the pattern remains similar (trees, 53.1% > grasses, 30.1% > shrubs, 10.2% > reeds, 6.6%).

Among all the species ($n = 32$) occurring in the plots, 15.6% were alien species ($n = 5$) and, overall, they entrapped 5.6% ($n = 82$) of total macrolitter. Most of the alien species occurred in the Tiber River, specifically in the middle and lower parts. *Amorpha fruticosa* and *Acer negundo* mainly blocked plastic packaging and plastic pieces, while *Vitis riparia* blocked most hygienic/sanitary towels and pieces, *Ficus carica* mainly bandages, and *Datura stramonium* entrapped clothes, aluminium cane, and plastic cups.

Moreover, we found a not significant correlation between the diversity (i.e., number of species) and the number of plastic items for the six rivers and each site ($r = 0.35$, $p = 0.52$ and $r = 0.35$, $p = 0.16$, respectively).

Furthermore, the co-occurrence analysis revealed that species blocking plastics resulted in a random community structure (C-score index: observed > expected, $P > 0.05$; V-ratio: observed < expected, $P > 0.05$). The cluster analysis highlighted two groups: (i) the first one (MIG1, MIG2, FAR1, MIG3, and TIB1) contained few plastic-polluted stations, while (ii) the second one was represented by more polluted plastic sites (Fig. 4).

The top-5 items entrapped by plants (83.4% of total litter) were: (i) plastic pieces (74.7%), (ii) plastic bags (6.9%), (iii) plastic bandages (6.6%), (iv) sanitary and hygienic towels (4.8%), (v) plastic packaging (4.4%). Moreover, the most occurring sizes and colours were 5–10 cm and white (Fig. 5, Fig. S1).

More in detail, the most contaminated stations (i.e., ANI3, TIB3) are those with the most agricultural and artificial land use (see Table S1 in Supp. Matt.). In the sampled stations, plastic pieces were the most abundant typology, occurring mostly in ANI3 and TIB3 (75.9 % and 9.8% on total pieces). Then, plastic bags widely dominated TIB3, ARR1, and ANI3 (30.9, 12.7, and 12.7, respectively) stations. Plastic bottles accounted for TIB3, MAR2, and ANI3 (65.1%, 10.2%, and 12.0%, respectively).

Regarding the plastic distribution among the three river courses, plants in the river lower course entrapped most macrolitter (79.0%) against the upper (11.7%) and middle (9.3%) courses (Fig. 6). Standardising the number of items per sampling area, the pattern remained the same with lower course accumulating more plastics (57.1%) than the upper (30.0%) and the middle part (12.8%).

In detail, this plastic gradient showed a difference regarding (i) size and (ii) type of items with plastic size and type changing along the rivers (Fig. S2). Following the most occurring item types (i.e., plastic pieces

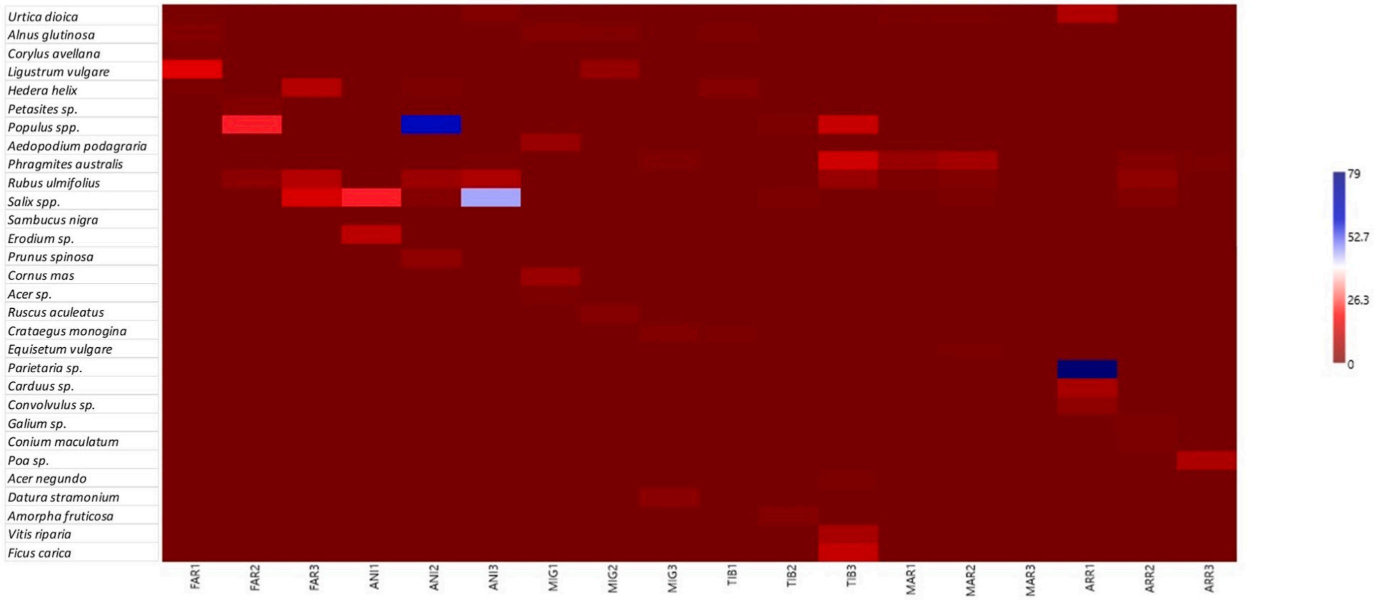

Fig. 3. Matrix plot showing the plastic density (items/m^2) in each plant species *per* station. The number 1, 2, or 3 after the station name (e.g., FAR1, FAR2, and FAR3) indicates the upper, medium, or lower river course.

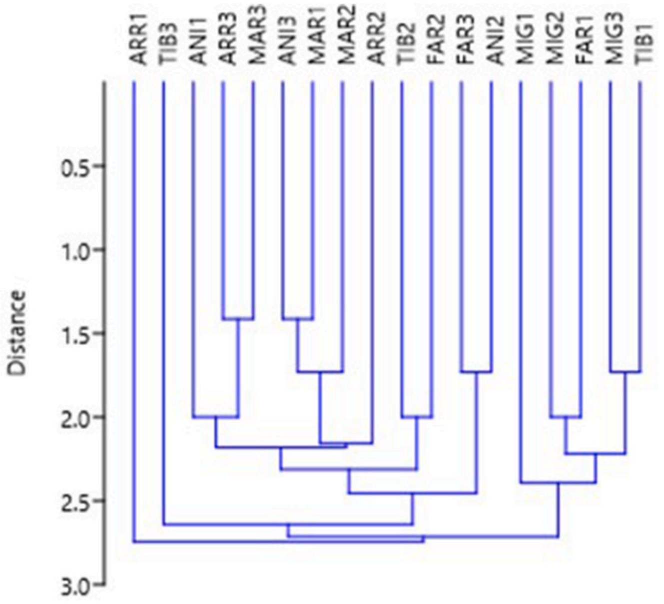

Fig. 4. Cluster analysis grouped stations with vegetation blocking few or more plastics.

and plastic bags), in the upper course, we mostly found macroplastics (i.e., plastic bags), that may undergo fragmentation originating ME and MP pieces in the river lower part. This process is also confirmed by the most found MA size (e.g., 5–10 cm, 20–30 cm). In general, there is a big process of plastic deterioration. Specifically, for the plastic distribution gradient, plastic pieces increased going to the river mouth while plastic bags dominated in the upper part (Fig. 6a). Additionally, the most occurring plastic types (i.e., plastic pieces and plastic bags) may be indicators for MA pollution along the river. In this case, plastic pieces and plastic bags may be used for making inferences on all the riverine macroplastic litter (Fig. 6b).

The size of macrolitter changes along the three river courses (F (df = 10) = 9.333, $p < 0.05$, Fig. 5a). In detail, the middle and lower river courses were significantly different (Dunn's post hoc test, $p < 0.05$). Particularly, litter distribution along watercourses showed a similar trend with major accumulation in the *potamal* lower river course (Fig. 6a). Moreover, all the macroplastic litter sizes follow this trend along stations (i.e., accumulating in the lower part, Fig. 6a).

4. Discussion

Research on plastics in rivers is only of recent investigation although the importance of rivers as carriers of plastics to the sea (González-Fernández et al., 2021). For the first time, we characterized the role of riparian vegetation in entrapping macrolitter along the river watershed, also in the up and middle river courses. Indeed, the upstream and middle stream part of rivers lacks studies on plastics (Honorato-Zimmer et al., 2021; Gallitelli and Scalici, 2022; Liro et al., 2023), while literature studies focused mainly on sampling plastics in the lower part of rivers, such as the mouth and estuaries (Gallitelli and Scalici, 2022; Tramoy et al., 2020).

We found a significant relation between plastics in the riverbank and plastics stuck in vegetation, showing that plastics occurring in vegetation reflect plastics in the riverbank. Precisely, plastics trapped in riparian vegetation indicate a long-term presence of plastics in rivers. This could be due to plastics in vegetation depending on plastics in the riverbank and, consequently, on plastics arriving with the river (i.e., floating plastics carried by hydrology). Thus, while floating plastics represent an immediate snapshot of real-time plastic pollution, riverbank and vegetation plastics represent long-term snapshots of riverine plastics transported along watercourses – that accumulated over time as rivers transport plastics downstream to the sea. In this pathway, most litter accumulates and remains in the fluvial ecosystems (van Emmerik et al., 2022; Gallitelli et al., 2022, 2024).

Concerning plastic accumulation in rivers, we emphasise plant species that are important variables for understanding the entrapment efficiency of macrolitter, highlighting that the vegetation diversity factor is key for the trapping net effect. As mangroves, macrophytes, and dune plants act as a sink for macrolitter (Gallitelli et al., 2024), at the same time riparian vegetation can filter riverine macroplastic litter (Cesarini and Scalici, 2022; Gallitelli et al., 2022, 2024). Our results are in line with other studies in literature, that showed that plastics are the main

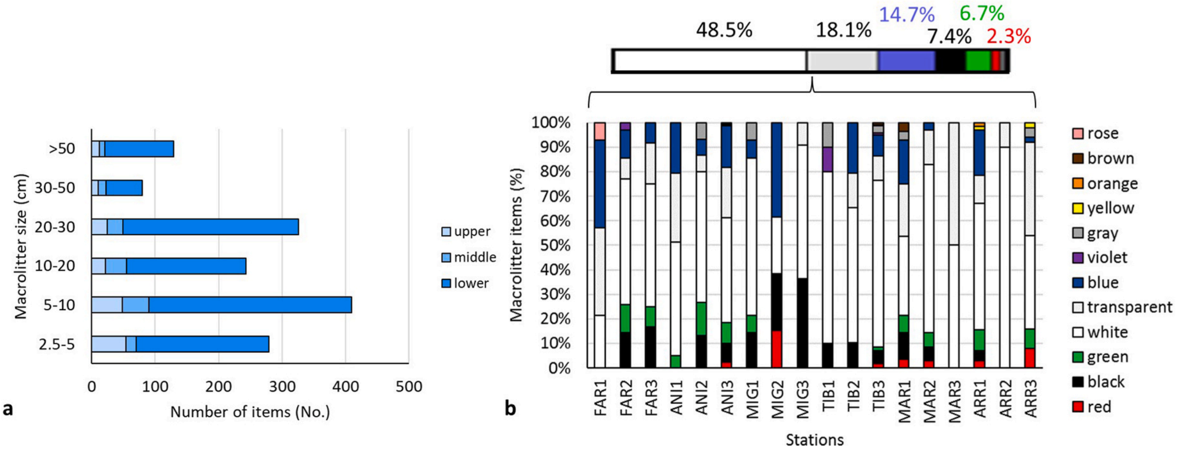

Fig. 5. Most occurring plastic size in the three river courses (a) and colours (b) along the watercourses.

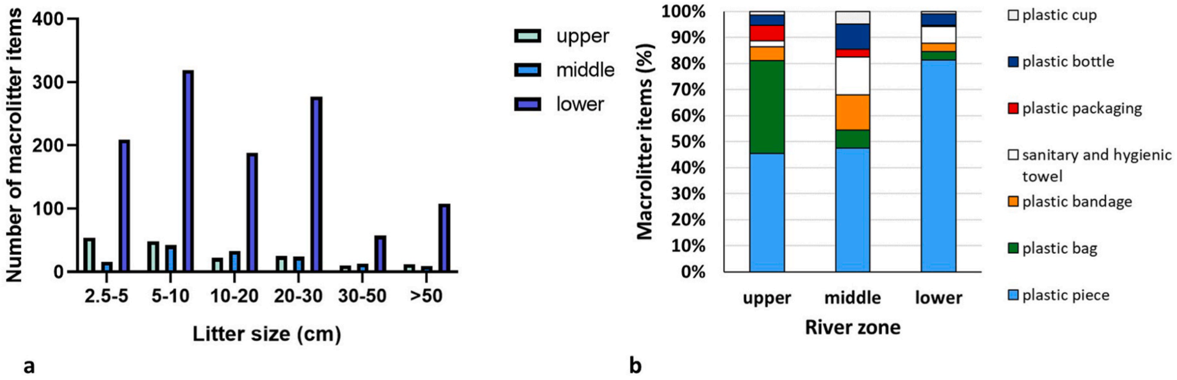

Fig. 6. Plastic size (a) and type (b) most occur in central Italy rivers considering the upper, middle, and lower courses.

litter type found in rivers (González-Fernández et al., 2021; Cesarini and Scalici, 2022; de Lange et al., 2023; Gallitelli and Scalici, 2023). Precisely, plastic size and colours might provide information about the source and sinks of riverine macrolitter (Cesarini and Scalici, 2022). Here we found plastic pieces, plastic bottles, and packaging as the most found items stuck within vegetation. In the literature, the same results are highlighted by Cesarini and Scalici (2022), who analyzed plastics in riparian vegetation occurring in the lower river courses. Thus, according to other studies investigating floating plastics in rivers (see González-Fernández et al., 2021) or riverbank plastics in rivers (Cordova et al., 2024), these are the main items transported by rivers and entrapped by vegetation.

Moreover, the highest amount of these items is found in the urban tract of rivers flowing into Rome (i.e., ANI3 and TIB3) being the most polluted stations, highlighting the influence of the metropolises in the release of litter and plastics. This is in line with other studies in the literature highlighting this process (Crosti et al., 2018; Schirinzi et al., 2020; van Emmerik et al., 2020; González-Fernández et al., 2021; Cesarini et al., 2023). Thus, it is important to point out that metropolises greatly impact macroplastic release. Furthermore, we highlighted that agricultural, urban and artificial matrices with diffuse vegetation (e.g., rows of vines, such as vineyards and olive groves), might behave differently from a (semi)natural area with vegetation. In the latter, plastics could be retained more efficiently, due to a more diverse ecosystem with a structured community. Concerning land use across rivers, Eide et al. (2022) pointed out that land cover type might influence the distribution of litter. On a larger scale, land use of riparian areas has great importance in plastic pollution detection and removal (see Cowger et al., 2019). In this regard, future research should focus on unravelling the correlation between the complexity and structure of riparian vegetation and plastic accumulation (Gallitelli et al., 2022).

Concerning the most efficient riparian plants in blocking litter, we pointed out that riparian vegetation entrapped plastics along the whole river rod, especially in the lower river course. These results follow the 'Christmas tree effect' (Williams and Simmons, 1998) where litter is blocked in the vegetation. Here, we provided the evidence that riparian vegetation affects riverine plastic transport acting as a barrier for MA. In addition, we highlighted that MA were blocked more efficiently by certain species, such as willows, poplars, and reeds, maybe due to their morphological structure (i.e., species traits and life form). Moreover, native plants entrapped most of the litter, however, we observed for the first time that alien species entrap plastic litter, as well. Given that complex undisturbed riparian areas might be resistant to colonisation by alien species (Zelnik et al., 2020), riparian forests in urban areas may be susceptible to alien species invasion (Campagnaro et al., 2022), indeed alien species have spread in the last years in Mediterranean areas (Cao Pinna et al., 2021), they could provide the ecosystem service by blocking plastics together with native plants (as found in Gallitelli et al., 2021; Gallitelli and Scalici, 2023). To potentially act with measures to deal with both issues (i.e., aliens and MA), future research on this topic should be conducted and valuable management of riparian habitats (i.e., when mowing) should be systematically applied to have stronger vegetation communities to trap more MA.

In the trapping process, we should identify two pivotal factors. The first is the diversity factor (e.g., number of species) that affects the efficiency of trapping in a precise part of the river. The abundance of the species forms a dense spot of vegetation that entraps more litter. Although we found a not significant relation between diversity and the number of plastics for each site, we suppose that, among all the occurring species, each one might have a role in the plastic entrapment process – and this should be further investigated. Our results highlighted how trees and shrubs are the most effective net plastic trappers along the whole river course. More precisely, willows and poplars (i.e., *Salix* spp., *Populus* spp.) block plastics with roots as well as aerial branches. Moreover, reeds tend to form a kind of net web that can entrap litter but can also act as a wall not allowing litter to be held in (i.e., when the vegetation is too dense). This behaviour is more likely than the one by mangroves (Martin et al., 2019). Furthermore, spiny plants (i.e., *Rubus ulmifolius*) can retain macrolitter more efficiently, although macroplastics can be fragmented into meso- and micro-plastics (Gallitelli et al., 2022; Gallitelli et al., 2024). This could be of particular concern for freshwater biota and human health (Blettler and Mitchell, 2021). Although interaction between MA and freshwaters is underestimated, at plastic accumulation areas, MA may cause detrimental effects on freshwater biota, such as ingestion, entanglement, and plastic usage (e.g., nesting material, vector for biota transport and shelter) (Blettler and Mitchell, 2021). Therefore, management authorities need to consider implementing regular removal strategies to prevent the formation of MP in these areas. In this case, clean-up activities and removal actions might mitigate the long-term ecological risks linked to plastic debris accumulation in vegetation patches.

Apart from the species, the second factor is related to hydrological factors. Indeed, we highlighted that larger basins (i.e., Aniene and Tiber rivers) with floods going higher may raise the height of trapped plastics making it trappable by plants. We found that litter items accumulated on branches >2m might be carried by winds (see Gallitelli et al., 2024). In this regard, hydrology might influence riverine plastic transport and, for this reason, we noticed the first link of riverine plastics with the plastic occurrence in vegetation along watercourses. We inferred that the higher the water level and the flow rate, the higher the probability of plastics getting stuck on the riverbank and consequently entrapped in vegetation. Moreover, although the important role of the hydrological regime for macroplastic transport and deposition on the floodplain, we should talk of "channel-floodplain connectivity" that is not only related to flood pulses but also to the specific geomorphological setting of a reach or anthropogenic factors such as flood protection dykes. Following the definition of river connectivity by Wohl (2017), the river connectivity largely impacts macroplastic transport along the watershed, increasing a deposition in the dykes and dams (see Tramoy et al., 2022).

Among river courses, plants in the river's lower course entrapped most macrolitter against the upper and middle courses. This could be explained by factors such as changes in riparian vegetation characteristics and the hydrological regime, and a higher leakage rate of macrolitter in the lower course of the river. We observed a trend for macroplastic accumulation in vegetation along the river watershed. This trend can provide us with information on the source of plastic pollution. In this case, we found that mismanaged plastic waste dominated in the highest part of rivers (Liro et al. 2020, 2023).

Our findings highlighted how vegetation diversity affect the plastic transport process as a biotic factor. Future studies should deepen into biotic factors affecting plastic transport along rivers, such as (i) the plant morphology within riparian vegetation and then (ii) the structure of the entire riparian community and its complexity. Although it is expected that a higher number of species should block more plastics as vegetation can act as a net for litter, we found no correlation between the number of species and the plastic concentration in vegetation for each station. This could be explained by a more complex structure of vegetation community – not considered in this study.

In a nutshell, the role of riparian vegetation in entrapping macrolitter along river watersheds is at an early stage. Concerning the mitigation activities, as riparian species can provide us with the ecosystem service of trapping macrolitter, this topic shows a high potential that could be applied for plastic removal. This result may have future applications in monitoring the riverine plastic hotspot areas and performing mitigation and clean-up activities. In this optic, healthy plants are necessary to reach the service of plastic entrapment and removal. If the plants are in excellent health (i.e., natural status) then they can be used to accumulate and remove plastics. Sometimes pruning and mowing could damage plants as well as improve their growth (Davis and Estes, 1993; Albert et al., 2010). Further research is needed to tackle the plastic pollution threat. To remove macroplastic litter from rivers, plastic hotspot areas might be detected and monitored to provide policy decisional actions. However, future perspectives should focus on filling these gaps and mapping macroplastic litter courses to provide information for plastic removal measures. All these findings are crucial for ecosystem conservation, restoration, and sustainable requalification of threatened freshwater habitats.

5. Conclusions

Recently published models and field studies revealed the importance of small and medium-sized rivers for plastic pollution studies. Along the river watershed, we found that riparian vegetation entrapped most macrolitter in the river lower course. Although some studies observed the possibility of woody debris and riparian vegetation to trap litter (Rech et al., 2014; Hoellein et al., 2014; McCormick and Hoellein, 2016; Liro et al., 2020), here for the first time, we actively focused on vegetation role and species to trap litter along the river course. Precisely, we quantified and observed a trend for macroplastic transport and fate along river watersheds, highlighting that riparian vegetation occurring in the entire river entraps plastics influencing the riverine plastic transport. For these reasons, it is key to assess the contribution provided by small and medium-sized rivers that might play a pivotal role in leaking macroplastic litter from land to the sea and, with our findings, in being a hotspot of plastic pollution.

More studies on macroplastics in rivers are mandatory as macroplastics are a big problem *per se* (see entanglement of biota in Blettler and Mitchell, 2021, see macroplastic litter on riparian vegetation might not allow flowers to be emitted affecting pollination in Gallitelli and Scalici, 2023), but also because MA can fragment into MP that provoke large threat due to its ecotoxicological effects. Thus, it is crucial to study macroplastics because they give rise to MP. For instance, understanding how many bags are on a poplar might be crucial to knowing how many MP will be generated over time. Future studies will deal with the fact that not all the plastics are transported downstream by the rivers, a part remains in the fluvial ecosystems, trapped by vegetation, sediments, and other matrices. Also, the "global plastic treaty" (see Dey et al., 2022; Bergmann et al., 2022) should consider the inclusion of plastic monitoring into the European and global Framework Directive (see for instance, Water Framework Directive, 2000/60/CE). The transport and accumulation of macroplastics were less studied rather than microplastics, resulting in a lack of real observation data. The source, origin, transport, and accumulation of plastics need to be well studied and understood to manage plastic pollution providing managers with an educated knowledge for policy-making decisions. In conclusion, this research can contribute to filling the gap of knowledge giving possibilities to mitigate the threat and preventing detrimental effects of plastics on ecosystems' health. A valuable management of riparian habitats should be recommended, and specific plans developed and systematically applied. By proposing eco-safety activities and mitigation strategies, these advances might be key for conservation and mitigation strategies aimed at the ecological integrity of riverine ecosystems.

CRediT authorship contribution statement

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

review & editing, Visualization, Validation, Investigation. **Massimiliano Scalici:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.120224.

Data availability

All data are available in the manuscript and in Supplementary Materials.

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