frontiers | Frontiers in Sustainability

TYPE Original Research
PUBLISHED 17 August 2022
DOI 10.3389/frsus.2022.866982

Plastic pollution on Durance riverbank: First quantification and possible environmental measures to reduce it

Tosca Ballerini[1,2*†], Nathalie Chaudon[3], Marc Fournier[1], Jean-Paul Coulomb[4], Bruno Dumontet[1], Eléonore Matuszak[5] and Justine Poncet[6]

[1]Association "Expédition MED" – Mer En Danger, Questembert, France, [2]Department of Integrative Marine Ecology, Stazione Zoologica Anton Dohrn, Fano Marine Centre (PU), Fano, Italy, [3]France Nature Environnement Provence-Alpes-Côte d'Azur, Marseille, France, [4]Ligue pour la Protection des Oiseaux Provence Alpes Côte d'Azur, Hyères, France, [5]Société Alpine de Protection de la Nature – France Nature Environnement Hautes-Alpes, Gap, France, [6]France Nature Environnement Alpes de Haute-Provence, Les Mées, France

Plastic pollution is one of the most pressing issues of our time, with negative impacts on natural ecosystems, human health, and the climate system. The identification of top litter items discarded in the environment is essential to prioritize environmental policies to prevent plastic leakage and promote a circular economy. Here, we present the first quantification of macrolitter on three sites along Durance riverbank and one site on Lake Serre-Ponçon's beach, in the Région SUD–Provence-Alpes-Côte d'Azur, southeastern France. Data were collected through citizen science between 2019 and 2020 in three sampling occasions (autumn, winter, spring) on Durance riverbank and in 22 occasions on Lake Serre-Ponçon. A total of 25'423 litter items were categorized, of which 82% were plastics. Single-use plastic items correspond to 8.13% of total, while single-use plastic bottles are among the top 10 litter items at each site. Median litter abundance across all samples is 2,081 items/100 m survey, two orders of magnitude higher than European precautionary threshold value for marine litter (20 items/100 m survey). The majority of items (74.83%) were small and non-identifiable. Pieces of polystyrene, soft plastics and rigid plastics represented the majority of litter items in total (56.63%) and at S1 (89.28%), S2 (58.95%) and S3 (79.60%). Glass pieces corresponded to 15.83% of total litter items. Soft plastic pieces are the most abundant litter category overall and correspond to 58.85% of litter items at sampling site along Durance riverbank located in an agricultural zone, suggesting their source from agricultural plastic mulch films. Among the identifiable items, the most abundant were plastic biomedia used in waste water treatment plants and single-use beverage bottles in plastic and in glass. The development of extended producer responsibility schemes for plastic mulch films and plastic biomedia and of deposit return schemes for single-use beverage bottles is suggested as a way to prevent leakage in the environment.

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EDITED BY
Tomaso Fortibuoni,
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REVIEWED BY
Tim van Emmerik,
Wageningen University and Research, Netherlands
Paul Vriend,
Independent Researcher, The Hague, Netherlands
Gabriel Enrique De-la-Torre,
Saint Ignatius of Loyola University, Peru

*CORRESPONDENCE
Tosca Ballerini
tosca.ballerini@thalassa.one

†PRESENT ADDRESS
Tosca Ballerini,
Thalassa - Marine Research and Science Communication, Marseille, France

SPECIALTY SECTION
This article was submitted to Waste Management, a section of the journal Frontiers in Sustainability

RECEIVED 31 January 2022
ACCEPTED 22 July 2022
PUBLISHED 17 August 2022

CITATION
Ballerini T, Chaudon N, Fournier M, Coulomb J-P, Dumontet B, Matuszak E and Poncet J (2022) Plastic pollution on Durance riverbank: First quantification and possible environmental measures to reduce it. *Front. Sustain.* 3:866982. doi: 10.3389/frsus.2022.866982

This work confirms the opportunity to use citizen science to gather relevant data on macrolitter items and to monitor the effectiveness of environmental regulations to reduce plastic pollution.

KEYWORDS

plastic pollution, marine litter, extended producer responsibility (EPR), plastic policy development, single-use packaging, citizen science, deposit return systems (DRS), circular economy

Introduction

Plastic waste accumulation in the natural environment is one of the most pressing issues of our time with wide-reaching consequences on natural ecosystems, impacts on human health, contribution to climate change (United Nations Environment Programme, 2021b). From 9 to 23 million metrics tons of plastic waste are emitted yearly on rivers, lakes, and the ocean, while from 13 to 25 million metrics tons per year are emitted on terrestrial ecosystems (Borrelle et al., 2020; Lau et al., 2020). According to several authors, plastic pollution can be considered a planetary boundary threat (Galloway and Lewis, 2016; Jahnke et al., 2017; Villarrubia-Gómez et al., 2018; Arp et al., 2021; MacLeod et al., 2021; Persson et al., 2022). Rillig et al. (2021) have suggested that we are already living through a period of "toxicity debt," related to longer-term consequences of plastic degradation such as the release of toxic additives associated with plastics and the fragmentation to nanoplastics, which can themselves give rise to toxic effects.

Plastic waste enter the natural environment mainly as the result of mismanaged municipal solid waste (Lebreton and Andrady, 2019) and several initiatives have been taken at the international and national level to reduce plastic emissions and associated chemicals (United Nations Environment Programme, 2021b). In order to estimate the effectiveness of interventions to reduce marine plastic pollution, Lau et al. (2020) modeled stocks and flows of municipal solid waste and four sources of microplastics through the global plastic system for five scenarios between 2016 and 2040. They found that under a business-as-usual (BAU) scenario, mismanaged plastic waste leaking to the environment would increase by almost 3-fold by 2040 and that if all current major industry and government commitments were met, the world would see a reduction in annual rates of plastic pollution flowing into the ocean of only 7 per cent in respect to BAU. If all countries worldwide implemented the EU Single-Single Use Plastics Directive (SUPD, 2019/904/EU), one of the most ambitious regulations to tackle marine litter and plastic pollution, plastic waste emissions would be reduced by only 15 percent in respect to BAU (Lau et al., 2020). Further regulatory action is clearly needed and in March 2022 the Fifth United Nations Environment Assembly (UNEA-5.2) adopted a resolution for a mandate for an internationally legally binding agreement by 2024 to end plastic pollution both in the marine and in the terrestrial environment considering the whole life cycle of plastics.

Initially, most of the attention has been given to plastic waste in the marine environment (Blettler et al., 2018). Rivers were recognized for their role as a major source of macroplastic litter to the ocean (Wagner et al., 2014; Jambeck et al., 2015; Blettler et al., 2018; van Emmerik and Schwarz, 2020) and riverine inputs to the global ocean are estimated to range between 0.8 million and 2.7 million MT (Meijer et al., 2021), while at the European level they range between 1,600 and 5,000 tons per year (González-Fernández et al., 2021). However, recent studies suggest that the majority of macroplastic pollution never leaves rivers (Meijer et al., 2021; Tramoy et al., 2022; van Emmerik et al., 2022). These long residence times of plastic litter in rivers increase the negative effects that plastic waste has on the riverine environment.

Studies on macrolitter on rivers have increased in recent years. In Europe, plastic items were predominant in sub-surface garbage on River Thames in UK (Morritt et al., 2014) as well as in floating macrolitter on the Seine (Gasperi et al., 2014; Tramoy et al., 2020) and the Rhône (Castro-Jiménez et al., 2019) in France, on the Tiber in Italy (Crosti et al., 2018), and the Rhine in the Netherlands (Vriend et al., 2020b). A study of 42 rivers and streams in 11 EU and non-EU countries confirmed that plastic litter items are the major fraction (82%) of floating macrolitter and showed the importance of smaller streams in contributing plastic litter items from the whole catchment of a river to the sea (González-Fernández et al., 2021). Measurements on riverbanks showed that plastic litter items represent 94% of macrolitter on the Adour River in France (Bruge et al., 2018), 81% on the Rhine-Meuse River delta in the Netherlands (van Emmerik et al., 2020a), between 87.5 and 100% on the Ems, Weser and Elbe rivers (Schöneich-Argent et al., 2020), 31% on many large and small rivers in Germany (Kiessling et al., 2019) and 81% in 8 rivers in central Italy (Cesarini and Scalici, 2022). Plastic debris were 150% heavier in mass than organic debris on Seine riverbank, in France (Tramoy et al., 2019). Outside of Europe, plastics were the prevailing macrolitter items on riverbanks in Chile (Rech et al., 2014), were found in all sampled sites on the Selenga River system in Mongolia (Battulga et al., 2019) and the Lower Citarum River in Indonesia (Hidayat et al., 2022), represented 88.4% or more of macrolitter on the Tukad Badung River, in Bali, Indonesia, and 80.7% of riverbank macrolitter in the Karamana River, Kerala, India (Owens and Kamil, 2020).

The identification of top litter items discarded in the environment is essential to understand what needs most attention and to prioritize specific measures to prevent further inputs and reduce their abundance in natural ecosystems (Joint Research Centre, Institute for Environment and Sustainability, 2014; Addamo et al., 2017). In France, alongside the reception of EU SUPD and the national action plan "Zero Plastic Waste at Sea" (French Ministry for the Ecological Transition, 2020), several other initiatives have been proposed to reduce plastic waste, such as the "Chart for plastic free beaches" by the Ministry of the Environment, the "Zero Plastic Chart" by the Region SUD Provence-Alpes-Côte d'Azur (https://www.arbe-regionsud.org/1375-2-chartes-pour-zero-dechet-plastique.html), and the "Charter of Plastic Free Rivers," presented to France city majors in November 2021 (https://www.fleuve-sans-plastique.fr/). Despite these initiatives, baseline data on litter items are missing for most rivers.

Here, we present for first time results on macrolitter occurrence, with focus on macroplastics, from the Durance riverbank and the Lake Serre-Ponçon beach gathered through the citizen science project "Stop plastiques in the Mediterranée". The project was developed and carried out under the supervision of NGO Expédition MED and FNE PACA and involved volunteers from several environmental NGOs that are active in the Durance watershed.

Materials and methods

Study sites

The Durance is the largest watershed in the Région SUD–Provence-Alpes-Côte d'Azur, south-eastern France, with a length of 324 km and drainage basin of 14,472 km (Figure 1). It crosses several departments including a population larger than 1 million inhabitants and it is the second longest and third largest in terms of flow of the Rhône tributaries. The Rhône River has the largest watershed of rivers in the Northwestern Mediterranean, where it delivers 2–10 Mt of sediments and ~50 × $10^9 m^3$ of freshwater annually (Sempéré et al., 2000; Eyrolle et al., 2012). It also delivers mismanaged plastic waste, estimated at ~0.7 t per year as floating plastic debris (Castro-Jiménez et al., 2019) and 900 tons, considering both floating and non-floating debris (Boucher and Billard, 2020). The Mediterranean Sea, in turn, is one of the most affected seas by marine litter and plastic pollution (Eriksen et al., 2014; Cózar et al., 2015; Suaria et al., 2016; Boucher and Billard, 2020).

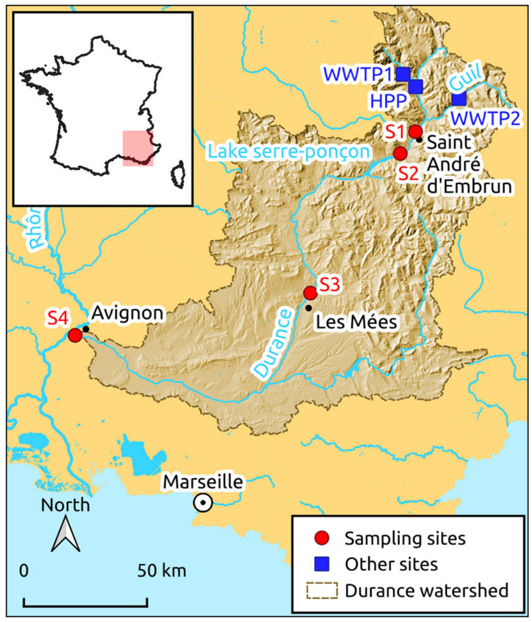

FIGURE 1
Map of Durance watershed, study sites, and other sites mentioned in the study.

The study sites in the SPEM project were selected based on three criteria: at all sites there is a stretch of riverbank or beach that can be submerged with high water levels; the sites are legally accessible by the volunteers; the sites are representative of land uses along the river (Figure 1 and Table 1). From upstream to downstream they are: Site 1 (S1), located close to the village of Saint André d'Embrun in a scarcely populated region, close to one national park and two regional parks, at 272 km from the river mouth, where the Durance flows into the Rhône River: Site 2 (S2), located on the beach of Lake Serre-Ponçon, an artificial lake and a touristic site situated at 259 km from the river mouth. The lake is closed by a dam that is operated to make electricity. Dams and other stream infrastructures are known to retain macrolitter items (van Emmerik et al., 2022); Site 3 (S3), located in a flat area where the Durance forms meanders and borders an agricultural zone close to the village of Les Mées, at 154 km from the river mouth. The width of the study area being large and characterized by different vegetation types, the site was divided into two distinct areas, a river-side area (S3 river, S3R) with no vegetation or only small bushes and a forest-side area (S3 forest, S3F) with trees; Site 4 (S4) is located in an isolated spot near the Avignon high speed train station under the bridge of national road 1,007, not far from the city of Avignon at 4 km from the river mouth and 87 km from the Mediterranean Sea.

10.3389/frsus.2022.866982

TABLE 1 Survey sites along the Durance River and on Lake Serre-Ponçon, with number of surveys conducted and a description of the site.

Site	Surveys	Description of the sampling site
S1	3	High course of the Durance River, at 15 minutes' walk from the car road, not much visited close to the village of Saint André d'Embrun. The Écrins National Park starts on the banks of the other side of the river in respect to the sampling site. Length of the transect 100 m. Width of the transect 20 m. Estimated surface of the sampling area: 2000 m^2.
S2	22	On the beach of Lake Serre-Ponçon beach, an artificial lake with important changes in water volume throughout the year. Collection of litter items on average every 10 days. Length of the transect 100 m. Width of the transect 67 m. Estimated surface of the sampling area: 6700 m^2.
S3	3	Flat area along the Durance River close to the village of Les Mées. Agriculture is the main productive activity. The sampling site was divided in two portions, based on the relative abundance of vegetation. The zone closer to the river (Les Mées River, S3R) with scarce or null vegetation, the zone further apart (Les Mées Forest, S3F) with intense shrubby and trees vegetation. Length of the transect 100 m. Width of the transect ranging from 70 to 160 m. Estimated surface of the sampling area: 7200 m^2.
S4	3	At 4 km from where the Durance River merges with Rhône River. On a white road parallel to the river, isolated, not much traffic. Close to the high-speed train station of Avignon. Length of the transect 50 m. Width of the transect 53 m. Estimated surface of the sampling area: 2650 m^2.

Sampling protocol

Macrolitter items were collected on 100 m long stretches parallel to the waterline and considering the band from the waterline to the high-water line similarly to what is done in the Beach-OSPAR method (OSPAR Commission, 2014), but differently than in the River-OSPAR method where the width of the transect from the waterline cannot exceed 25 m (van Emmerik et al., 2020c). At S4 the stretch over the riverbank was reduced to 50 m because of high density of vegetation and high density of litter items. The surface of the sampling area was estimated for each site during the first survey (Table 1).

The Beach-OSPAR method distinguishes 121 identification item categories, grouped by 11 material types (OSPAR Commission, 2014). We modified the Beach-OSPAR list of items to include litter items that were not present in the original list (ID 122 Fishing bait; ID 123 Filter media; ID 124 Twine and pieces of twine) and separated rigid plastic items from polystyrene items (ID 46 Piece of plastic/polystyrene 2.5–50 cm became ID 46 Rigid piece of plastic 2.5–50 cm; ID 47 Piece of plastic/polystyrene> 50 cm became Piece of plastic> 50 cm; ID 48 Other plastic/polystyrene object became ID 48 Other plastic object; and ID 117 Piece of plastic/polystyrene 0–2.5 became ID 117 Rigid piece of plastic 0–2.5 cm). We changed category ID 112 plastic bag end to ID 112 soft plastic pieces for a total of initial 128 litter items (see Supplementary Table 1).

The detection of litter items was carried out by visual observations and in each transect all visible litter items were collected and counted. The surveys were conducted without disturbing the upper layer of the sampling unit, i.e., without digging to release litter buried in the soil/sand, but litter items that were half under the soil/sand were retrieved.

The selection of sampling sites was done by the scientific personnel of Expédition MED and France Nature Environnement together with personnel from local NGOs, that were trained during the first survey. One or two people per site were appointed as responsible of data collection, categorization, and reporting. In addition to the authors, 36 volunteers took part in sampling and categorization of litter items. At each site, the data were validated by the trained personnel and in case of litter items difficult to classify, pictures were taken and a discussion followed up with Expédition MED scientific personnel.

At the sites on the Durance riverbank (S1, S3, S4) surveys were carried out in autumn (September–October 2019), winter (February–March 2020) and spring (June 2020). On the Lake Serre-Ponçon (S2), volunteers of the Ligue de Protection des Oiseaux (LPO–League for the Protection of Birds) carry out regular beach clean ups since January 2017. At S2 a total of 22 surveys were carried out from May 2019 to July 2020 roughly every 2 weeks distance apart following the schedule of beach clean-up activities carried out by LPO (see all the sampling dates in the Data Sheet 1 in Supplementary material).

Data analysis

Data were reported as number of litter items/100 m survey. Survey data for S3 were collected separately for the two vegetation bands and were summed up to provide a unique value of total abundance. Survey data for S4, that were collected over 50 m transect, were normalized to 100 m transect. Litter median densities at all sites were calculated as the litter median abundance over the surface of the sampling area and expressed as number of litter items/10 m^2.

The modified Beach-OSPAR list of categories was matched to the Joint List of Litter Items (Fleet et al., 2021) for harmonized comparison with other studies. In particular, the sub categories cigarette butts and cotton bud sticks, considered respectively in the material categories Paper and Sanitary items in the

OSPAR method (OSPAR Commission, 2014), where considered as Plastic and the items corresponding to Single-Use Plastic Items (SUP) were identified for subsequent analyses.

The aggregation of data at different temporal/spatial scales requires the averaging of data. The median is the calculation method that is suggested to be used to aggregate data at different temporal /spatial scales to asses EU marine beach litter baselines (Hanke et al., 2019). In this work, we have three values for S1, S3 and S4 and 22 values for S2. For each site we report the range of values (min and max) over the different surveys. We report the median value of the Durance across the 31 surveys to compare with other studies.

The top 10 most abundant litter items for each site were identified by lumping together the items over the different measurements and presenting the top 10 as fraction of the total. The top 20 litter items for the Durance were identified by lumping together the litter items over all the measurements and presented as fraction of total litter items.

The analyses were performed using R Statistical Software [v4.1.1; (R Core Team, 2021)] while the map of Figure 1 was created using QGIS (QGIS Development Team, 2021).

Results

First survey of macrolitter along Durance riverbank

Between May 2019 and July 2020, a total of 25'423 litter items were sampled at S1 ($n = 6,425$), S2 ($n = 8,984$), S3 ($n = 3,142$) and S4 ($n = 6,872$) (Figure 2) for a median litter abundance for all measurements of 2,081 items/ 100 m survey.

Of the initial 128 litter item categories considered, only 99 were found during the SPEM study. The majority of items (74.83%) were degraded to small, non-identifiable items. Pieces of polystyrene, pieces of soft plastics, and pieces of rigid plastics represented the majority of litter items both in total (56.63%) and at S1 (89.28%), S2 (58.95%) and S3 (79.60%). Glass pieces corresponded to 15.83% of total litter items and where the most abundant litter items at S4 (57.95%).

The specific litter items featuring in the top 20 for all measurement combined (93.33% of total) are plastic biomedia (small plastic cylinders used as bacterial biofilm carriers in the wastewater treatment process, also known as filter media), crisps/sweet packets and lolly sticks, glass bottles, plastic caps/lids, plastic drinks bottles, metal bottle cups, cotton bud sticks, plastic food containers, plastic cups, cigarette butts (Figure 3).

When aggregated to the 11 material categories of the OSPAR protocol, plastic items correspond to 74.76% of the total litter items, followed by glass (18.28%), paper/cardboard (1.90%), metal (1.74%) and manufactured wood items (1.22%) (Figure 4).

SUP items [*sensu* (Fleet et al., 2021)] correspond to 8.13% of the total litter items and 7 of them figure in the top 20: crisps/sweet packets and lolly sticks, plastic caps/lids, plastic drinks bottles, cotton bud sticks, food and fast-food containers, plastic cups, cigarette butts (Figure 3). Considering also glass bottles, single-use items correspond to 10.58% of total litter items.

Abundance and distribution of litter types in the four sampling sites

The highest abundance of litter items was found at S4 (range: 4,278–4,894 litter items/100 m survey), followed by S1 (range: 1,172–2,572 litter items/100 m survey), S3 (range: 460–1,092 litter items/100 m survey), and S2 (range: 8–1,798 litter items/100 m survey) (Figure 2). Data are available in Data Sheet 1 in Supplementary material.

At S1, the top 10 litter items (96.22% of the total) included polystyrene pieces, rigid plastic pieces, other wood, soft plastic pieces, metal corks and plastic drinks bottles (Figure 5). Plastic items represented 94.38% of the total. Despite their removal during sampling, pieces of polystyrene were found at each survey. At the first survey, polystyrene pieces smaller than 2.5 cm ($n = 1,222$) contributed to 58.72% of total litter items, while polystyrene pieces larger than 2.5 cm ($n = 459$) contributed to 22.06%; in the second survey, polystyrene pieces smaller than 2.5 cm ($n = 1300$) contributed to 73.36% of the total litter items while polystyrene pieces larger than 2.5 cm ($n = 279$) represented 15.74% of the total; at the third survey, polystyrene pieces smaller than 2.5 cm (1546) were 60.11% of the total, while pieces larger than 2.5 cm ($n = 590$) were 22.94% of the total litter items. SUP items were found at each sampling occasion, and in particular plastic drinks bottles were always present.

At S2, the top 10 litter items (90.27% of total), include soft plastic pieces, plastic biomedia, plastic pieces and polystyrene pieces, and four SUP items (crisps/sweets packets, plastic caps and lids, cotton bud sticks and plastic drinks bottles) (Figure 5). Plastic biomedia were recorded in 21 surveys over 22. The biggest occurrence was at time 19 with 121 items, time 20 with 860 items and time 21 with 147 items. Overall, 1,461 plastic biomedia were collected at S2 in the 22 surveys and they were of two types: white flat disks known as "biochips" and black cylinders in the shape of a helix known as Gamme Hel-X [numbers 13 and 16 in the categorization of (Bailly et al., 2018), respectively]. The overall abundance of litter items varied greatly, also as a function of river discharge. For example, from survey S2-time 17 (14/05/2020) and S2- time 18 (25/05/2020) the total number of litter items went from 8 to 330 (Figure 6).

At S3 the top 10 litter items (88.19% of total) include soft plastic pieces, rigid plastic pieces, textiles, construction material, polystyrene pieces, plastic drinks bottles, pieces of metal. The soft plastic pieces are 58.85% of the total. Litter items in the denser vegetation band farther from the river were almost twice

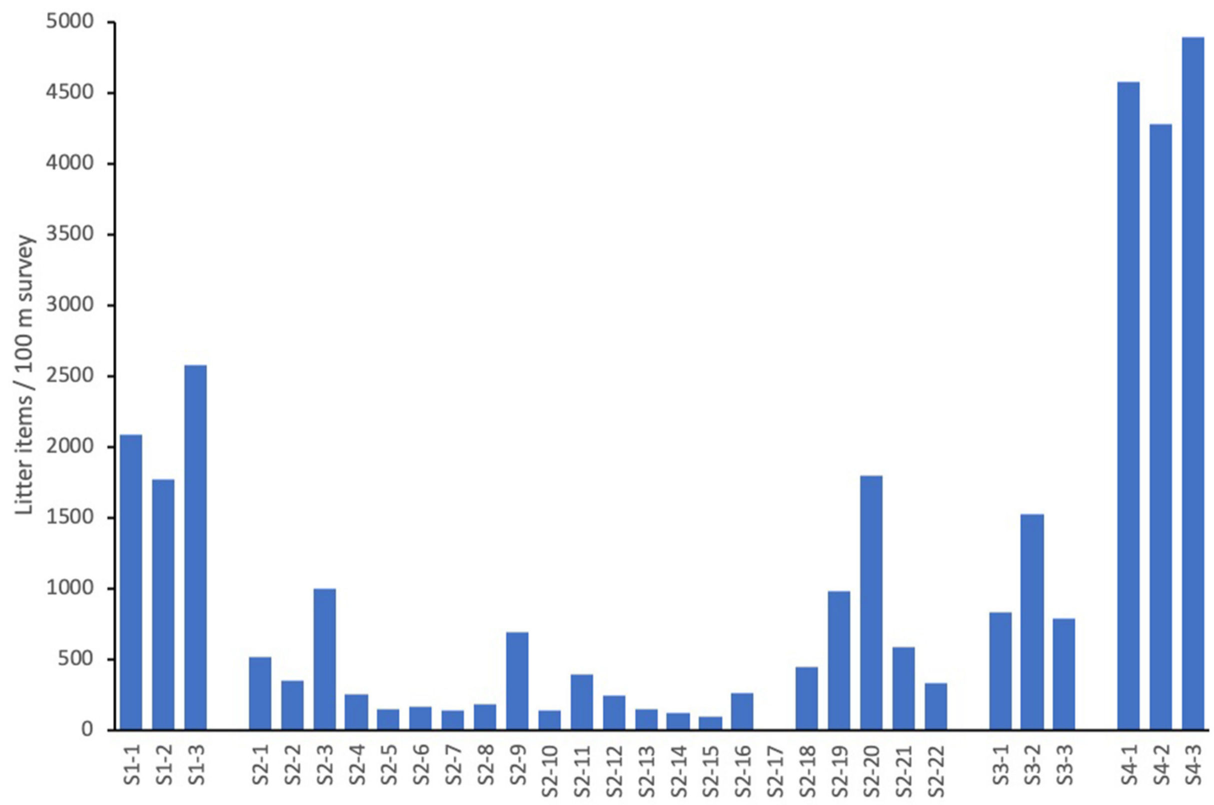

FIGURE 2
Abundance of litter items at each site and for each sampling occasion. Data for S4 were collected over a 50 m transect and here were standardized to 100 m transect.

more abundant (range: 460–1,092 litter items/ 100 m survey) than litter items in the sparser vegetation band closer to the river (range: 279–436 litter items/100 m survey) and soft plastic pieces were the most abundant litter type at each sampling occasion in both vegetation bands (ranging from 29.62 to 75.64% of the total litter items). SUP items such as plastic drinks bottles were in the top 10 in all three sampling occasions in the denser vegetation band. A full plastic film was found at the second sampling occasion (10/02/2020), as well as other pipes used in agriculture.

At S4, the top 10 litter items (90.69% of the total) include glass pieces, rigid plastic pieces, glass bottles, paper items, metal bottle caps, rigid and soft plastic pieces, plastic drinks bottles, cigarette butts, plastic cups (Figure 5). Of the 10 top litter items, three were SUP items. Glass bottles were found at each survey. At the first survey, a total of 440 bottles were found, of which 374 green bottles of 25 cl of Heineken beer brand and 66 other glass bottles; at survey 2, a total of 72 bottles, all of the type green bottles of 25 cl Heineken beer; at survey 3, a total of 58 glass bottles, of which 51 green bottles of 25 cl Heineken beer. Overall, Heineken beer bottles represented 87.06 % of all glass bottles. Green pieces of glass were found at each of the three surveys (619, 1,490, and 1,973 items, respectively).

Discussion

Abundance of litter items higher than the EU marine litter threshold at all sites

The Marine Strategy Framework Directive (MSFD, 2008/56/EC), requires that European threshold values (TVs) for marine litter (descriptor 10) be defined in order to achieve or maintain Good Environmental Status (GES). The MSFD Technical Group on Marine Litter set the TV at 20 litter items /100 m beach length, estimating that this value will be able to reduce harm from beach litter to a sufficiently precautionary level (van Loon et al., 2020). While TVs for litter have not been set specifically for rivers, the data gathered in this study show that median total abundance of litter items on Durance riverbank and Lake Serre-Ponçon beach (2,081 items/ 100 m survey) is two orders of magnitude higher than the precautionary value set by the MSFD. This threshold value was surpassed in all sampling sites, also at the S1 which is situated in a relatively isolated location, close to a national park and two regional parks.

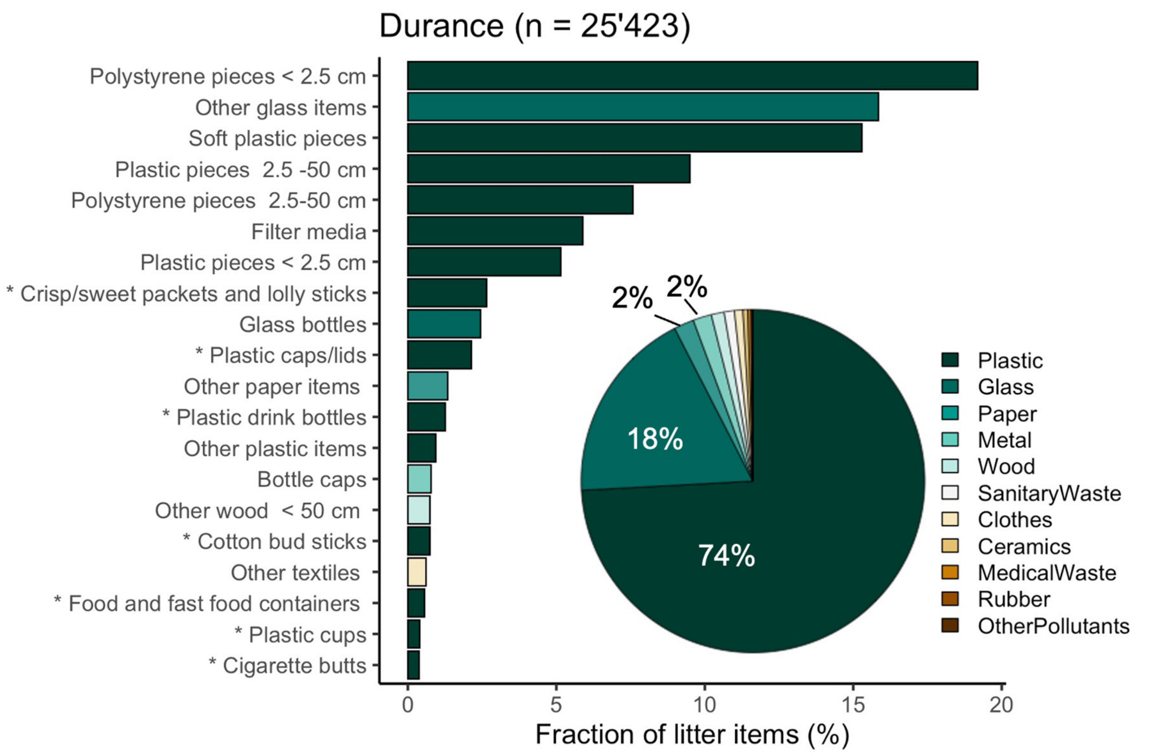

FIGURE 3
Top litter items and materials on Durance's riverbank and on Lake Serre-Ponçon's beach. Top 20 litter items are shown as fraction of the total. Percentages <2% are not shown.

Although quantitative direct comparison of abundance of litter data from other riverbanks is complicated by the fact that existing riverbank measurement methods vary greatly [see reviews in van Emmerik et al. (2020c) and in Vriend et al. (2020a)], the overall median total abundance (TA) of litter items found on the Durance in the SPEM project is higher than on riverbanks in the Dutch Rhine-Meuse delta (206 items/100 m; van Emmerik et al., 2020a), which also surpass the threshold value to achieve the GES. Median total abundance on the Durance is also higher than on beaches on the French Mediterranean coastline (214 items/100 m survey), on beaches at the level of the Western Mediterranean Sea (196 and 255 items/100 m survey in 2015 and 2016, respectively) and at the level of the whole Mediterranean basin (306 and 323 items/100 m survey, in 2015 and 2016, respectively) (Hanke et al., 2019).

The proportion of plastic litter items on Durance riverbank and on Lake Serre-Ponçon beach (82%) is comparable to riverbanks in the Netherlands (81.5 %, van Emmerik et al., 2020a) and Germany (between 87.5% and 100%, Schöneich-Argent et al., 2020), as well as to the amount of plastic litter floating at the surface of the Rhône River (Castro-Jiménez et al., 2019), at the surface of 41 rivers in Europe (82%; González-Fernández et al., 2021), and stranded on beaches in Europe (∼80%; EU, 2019).

During transport on rivers, plastic litter is broken and degraded (Tramoy et al., 2019; van Emmerik et al., 2020a). As a result, plastics in river systems are commonly fragments of soft and hard plastics or foam (Castro-Jiménez et al., 2019; Tramoy et al., 2019; van Emmerik et al., 2020a, 2022). This is true also in this study, where they represented 56.63% of total litter items. SUP items (bottles and other packaging) are usually the most abundant specific litter items in rivers in Europe (González-Fernández et al., 2021; Tramoy et al., 2022). SUP items are among the most abundant specific litter items also in this study, but here the most abundant specific litter items are plastic biomedia.

Deposits on riverbanks can be the results of different processes: they can be left intentionally such as illegal dumping, be the result of recreational activities (Kiessling et al., 2019), be transported by the wind, or be the consequence of the dynamic processes that occur in the water body (Tramoy et al., 2021). Hydrometeorology plays a role in explaining variability in macrolitter abundance on riverbanks, but a substantial part of the variability is caused by unaccounted (and often

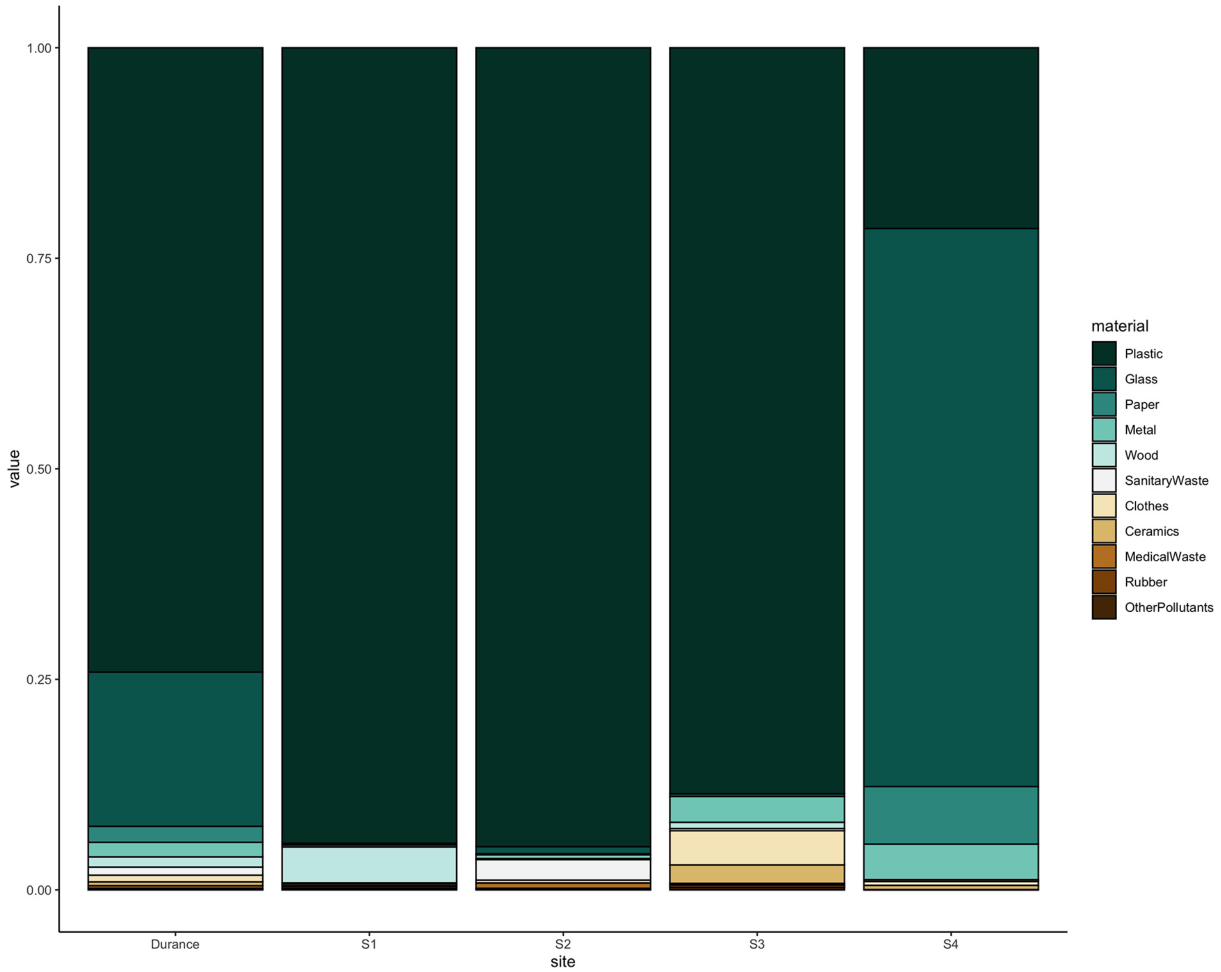

FIGURE 4
Percentage composition of materials of litter items.

fundamentally unknowable) stochastic processes, rather than being driven by the deterministic processes (Roebroek et al., 2021). Liro et al. (2021) developed a conceptual model that divides the macroplastic route into (1) input, (2) transport, (3) storage, (4) remobilization and (5) output phases. According to their model, phase 1 is mainly controlled by humans, phases 2–4 by fluvial processes, and phase 5 by both types of controls.

In the following sections we focus on three litter item categories for which we identified the possible source mechanism and for each we discuss possible environmental policies to reduce their dispersion in the environment: soft plastic pieces at S3, we supposed derived from plastic mulch films used in agriculture and the result of wind transport; plastic biomedia at S2 on Lake Serre-Ponçon beach, transported by the Durance River and accumulated by the lake; and single-use plastic and glass beverage containers at S4 and S2, caused by direct input by humans.

Plastic mulch films used in agriculture as the possible source of soft plastic pieces at S3

Unidentified soft plastic pieces represent 58.85% of total litter items at S3. While part of them might have originated from fragmentation of plastic bags or other packaging due to transport in the river and abrasion by sediments (van Emmerik et al., 2020a), we think that the high quantity of soft plastic pieces at S3 derives from plastic mulch films used in agriculture, the principal land-use type at Les Mées and have probably derived by short-distance transport by wind (Lau et al., 2020).

Statistical reporting of agriculture plastics data in Europe is still relatively underdeveloped and the proportion of conventional plastic mulch films that typically are left remaining on the soil is not known (Hann et al., 2021). In

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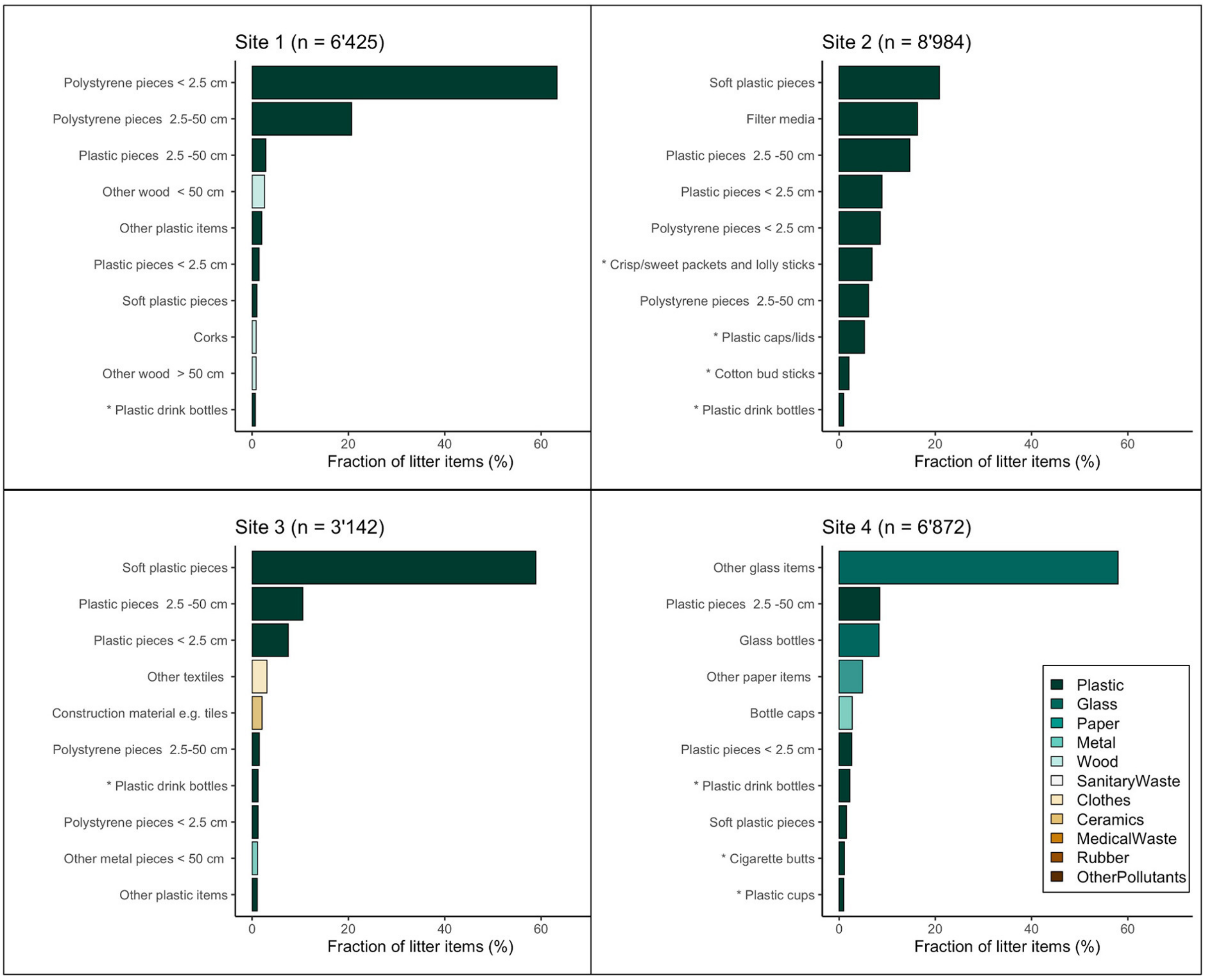

FIGURE 5
Top litter items and materials at the four sampling sites. Top 10 litter items are shown as fraction of the total. SUP items are indicated (*).

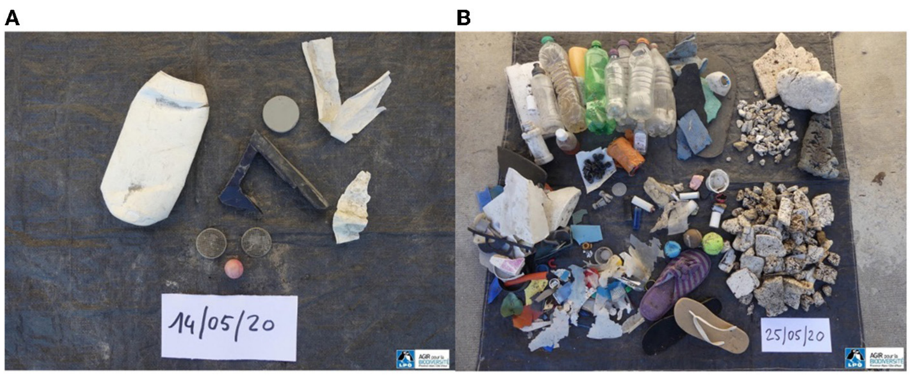

FIGURE 6
Items collected on the 100 m survey band at S2 before **(A)** and after **(B)** of a big river discharge.

France, (non-packaging) agricultural plastic waste is managed through a voluntary collection scheme operated by the producer responsibility organization (PRO) ADIVALOR and by other private companies. Using data provided by ADIVALOR, Hann et al. (2021) estimated that approximately 70,000 tons of agricultural plastic waste from mulch films were generated in France in 2019 and of these around 50% were recycled. The significant difference between the volume put on the market and the volume collected and recycled is probably due to high contamination, which is up to 50% for plastic mulch films (Hann et al., 2021).

The amount of plastic waste accumulated in world's agricultural soils is likely larger than on the ocean's surface (Hurley and Nizzetto, 2018; Galafassi et al., 2019), it is poorly reversible and can lead to long-term changes in soil properties and potentially irreversible degradation (Steinmetz et al., 2016; Bandopadhyay et al., 2018). Plastic waste accumulation in soils can have negative impacts on plant performance and diversity (de Souza Machado et al., 2019), while pathogen organisms for humans can concentrate on it (Gkoutselis et al., 2021) and plastic pieces can be transferred along the terrestrial food chain (Huerta-Lwanga et al., 2017).

The FAO identified several alternative interventions for the problem of plastic mulch films, including: adopting mulching practices that avoid the use of plastic; redesign mulching films to be biodegradable, reusable over time, and improve retrievability and reduce leakage to the environment; implementing mandatory EPR collection schemes; and redesign business models to provide agricultural plastic as a service, including retrieval and end-of life management (FAO, 2021).

In addressing the different types of plastic pollution, attention must be carried out not to shift from a source of pollution to another. While the long-term impact on soils of the use of different types of biodegradable mulch films need to be assessed (FAO, 2021), a comparison of conventional plastic mulch films and biodegradable mulch (BDM) films (i.e., plastics that passed the new EU standard EN 17033 that specifies necessary requirements and test methods for BDM to be used in agriculture and horticulture) concluded that currently there is a trade-off between plastic pollution in the environment vs. greenhouse gas emissions (as well as most other environmental impact categories) for the use of conventional vs. BDM films (Hann et al., 2021). As part of the new Circular Economy Action Plan, the EU Commission will develop a policy framework on the use of biodegradable plastics, based on an assessment of the applications where such use can be beneficial to the environment and criteria for these uses.

Litter density at S3 was higher in the zone with trees and shrubs farther from the river. This is in accordance to other riverbanks and on tidal zones were macroplastic abundance on the surface of vegetated areas is higher in comparison to the adjacent unvegetated areas (Cozzolino et al., 2020; Cesarini and Scalici, 2022). Macroplastic debris stored on the surface of alluvium, in riparian vegetation, and in river sediments can fragment and constitute the main source of secondary microplastics in river (see review in Liro et al., 2021). Taking into account the long preservation of macroplastic debris in the natural environment, the storage–remobilization cycles of macroplastic debris in fluvial systems may last for decades or centuries and this implies that the presence of riverine macroplastic and related environmental risk may continue in the future, even when the input of new plastic debris to the fluvial systems is decreased (Liro et al., 2021).

Plastic biomedia

Plastic biomedia are the most abundant specific litter item collected in this study (1,461 items) and most of them were retrieved at S2, on Lake Serre-Ponçon beach. Dams and other stream infrastructure increase the retention of litter items by removing them from the river flow (González-Fernández et al., 2021; Poletti and Landberg, 2021) and are key controls of microplastic storage and remobilization in rivers (Liro et al., 2021). Plastics on lakes may either come from local activities (e.g., littering, fishing gear, direct wastewater drainage from a nearby urban area or direct surface runoff) or have been conveyed by rivers that discharge into the lake (van Emmerik et al., 2022). This is the case for the plastic biomedia. The Serre-Ponçon dam interrupts the course of the Durance River and during normal operations the only possible exit of water and objects from the lake is situated in correspondence of the water intake for the turbines, situated at 100 meters deep. Every floating object, therefore, remains at the surface and is accumulated by the wind and the currents on the beach at north-eastern side of the lake. In addition to the plastic biomedia collected at S2 during the SPEM project, more than 60'000 black Gamme Hel-X plastic biomedia (corresponding to about 0.3 m^3) were collected by LPO in 2021 stranded on the beaches of Lake Serre-Ponçon (Ligue Pour la Protection des Oiseaux, 2021). According to an investigation by the Direction Départmental des Territoires des Hautes-Alpes (DDT 05) these plastic biomedia were accidentally released from the waste water treatment plant (WWTP) of Vallouise, the only WWTP in the Durance watershed upstream of Lake Serre-Ponçon to use the black Gamme Hel-X type. The Vallouise WWTP said to have lost 2 m^3 of plastic biomedia in the accident and currently it remains unknown where the majority of lost biomedia went, if they have been retained along Durance riverbank or if they made it to sea. The white biochips found in the SPEM project are instead probably derived from the WWTP of Molines-en-Queyras and Saint-Veran, the only WWTP upstream of the lake to use this type of plastic biomedia.

Large numbers of plastic biomedia have been found washed-up along European coasts since 2007 and since then they have been found on coastlines worldwide (Bencivengo et al., 2018). The latest reported incidents in Europe are in Denmark (2021), France (2020), and Italy (2018). Here, the public WWTP of the municipality of Capaccio Paestum, Salerno, had two consecutive accidents during which 126 million plastic biomedia of the type biochips (white disks) were released on the Sele River and arrived in the Tyrrhenian Sea. Currently, only 5.5 million of the lost biochips have been retrieved on Italian and French beaches and eight people are under criminal proceedings in to what is, according to our knowledge, the first legal process for plastic pollution at sea. Plastic biomedia are mainly made of polyethylene (PE) or high-density polyethylene (HDPE) and vary in shape and size according to the industrial application for which they are used (Bencivengo et al., 2018). Although they have been identified as a source of unintentionally released microplastics to the environment (Hann et al., 2018), currently they are not included in the EU legislation. To close this legislative hole, Surfrider Foundation and other NGOs asked for the inclusion of plastic biomedia as a source of pollution in the revised EU Urban Waste Water Treatment Directive (UWWTD, 91/271/ EEC) (Surfrider Foundation, 2020). The development of EPR schemes, the obligation for the waste water treatment industry to declare which types of biological treatment they use detailing the biomedia and models used, and the implementation of prevention measure and protocols would help to prevent losses to the environment and facilitate the identification of the source of pollution if pollution occurs (Surfrider Foundation, 2020).

Single-use litter items

Single-use plastic (SUP) items were found at all sites and seven specific items figure in the top 20 at the level on Durance riverbank (crisp/sweet packets and lolly sticks, cap lids, drinks bottles, cotton bud sticks, food and fast-food containers, cups, cigarette butts) alongside unidentified plastic pieces, similarly to what happens in other studies on rivers across Europe (González-Fernández et al., 2021). SUP items were more abundant at S2, a touristic location, and at S4, an isolated spot close to the city of Avignon. At S4 there was also a large amount of single-use glass bottles and pieces of glass bottles, abandoned in clusters alongside paper and plastic packaging related to fast food restoration and cigarette butts. These litter items derive from visitors that use the river as a leisure area and are responsible of local pollution, similarly to the case of rivers in Germany where high abundance of paper and plastic packaging related to fast food restauration, single-use glass bottles, and cigarette butts where also found (Kiessling et al., 2019).

France has transposed the EU SUPD into the Anti-waste and circular economy law (Law N. 2020-105 of 10 February 2020) and anticipated it by banning the sale of disposable tableware in batches (glass, cups, plates) and plastic cotton but sticks from January 1, 2020, 6 months prior to EU deadline and 7 months before the last litter collection and categorization in the SPEM project. Litter data collected in this study after January 1st 2020 still contain SUP items, but the time from the start of the adoption of the new law might be too short to see a difference.

The SUPD also sets targets for separate collection of single-use plastic beverage bottles (77% by 2025 and 90% by 2029) and says that to achieve these goals, Member States may establish deposit return systems (DRS) or establish separate collection targets for relevant EPR schemes. A DRS place a small deposit on beverage purchases, which is refunded to the consumer when the empty container is returned for recycling (DRS for recycling) or for reuse (DRS for reuse). In 2011 the European Parliament proposed the implementation of an EU-wide DRS for reuse/recycling of beverage packaging with the goal to reduce the environmental impacts of packaging systems and increase resource efficiency (European Parliament, 2011). DRS are an effective way of reducing the littering of the packaging items that they target (European Commission, Directorate-General for Environment, 2018; Grant et al., 2021) and are one way to implement the EPR. The establishment of EU-wide DRS for beverage packaging would have helped the producers to optimize production and the logistics of their products, and the free movement of goods would not be restricted (Leal Filho et al., 2019). This idea was not taken further, and as June 2022 there are 13 independent DRS schemes across Europe, the ones implemented for more than 2 years all achieving collection rates higher than 80% and up to 94% (Global Deposit Book, 2020). DRS have been suggested as a tool to achieve the collection rates of the SUPD by the European Court of Auditors (ECA, 2020). The Anti-waste and circular economy law has not set a DRS in France, but says that one or more DRS for recycling and reuse will be implemented starting in 2023 if the collection rates set by the SUPD have not been achieved through the separate collection of municipal waste. European NGOs and European beverage producers also support a DRS for recycling for plastic beverage bottles (https://zerowasteeurope.eu/wp-content/uploads/2022/05/27-04-2022_Collection_Closed-Loop-recycling_Access-to-recycled-content_FINAL-Statement.pdf).

The large abundance of single-use glass bottles for beer found at S4 are also due to illicit disposal and abandonment by users, i.e., by the same littering behavior that causes dispersal of single-use plastic items, showing that the problem is single-use packaging (United Nations Environment Programme, 2021a). This suggests that the development of an "all-in" DRS which includes containers of any material (plastic, glass, metal, tetrapack) and for all kinds of drinks, so to avoid material substitutions or changes in the composition of the beverage to elude the law, would be the best strategy to reduce littering (United Nations Environment Programme, 2021a).

Municipalities can significantly limit plastic pollution on their territory through the development of integrated strategies that include public procurement and exemplarity as well as territorial animation (WWF France, 2020; Azzurro et al., 2021). For instance, they can ban the use of SUP products in public buildings and events as well as on natural tourist places (similarly to what done on the so-called "plastic free beaches"), while promoting business that voluntarily decide to reduce the use of single-use packaging (Azzurro et al., 2021).

Plastic pollution reduction strategies that can be put in place by municipalities also include the prevention of plastic waste generation and promotion of reuse; the promotion of the consumption of tap water in their territory; the improvement of wastewater and stormwater management infrastructure to preserve the water cycle from plastic pollution; the improvement of the collection and recycling of plastic wastes; the reduction of plastic pollution locally through clean ups, that event thought are not a solution to plastic pollution as they act downstream from the problem, nevertheless have the advantage of making people aware of the issues raised by plastic waste and allow collecting data useful for steering local strategy against plastic pollution (WWF France, 2020).

Citizen science and the evaluation of the effectiveness of environmental regulations

Temporal series on macrolitter abundance are important to evaluate through time the effectiveness of the implementation of existing environmental regulations such as the EU Marine Strategy Framework Directive (MSFD, 2008/56/EC) and the EU SUPD at French national level and to promote further local actions to reduce litter items dispersed in the environment. The EU MSFD requires a reduction of marine litter and the European Plastic strategy (COM/2018/028 final) has set an aspirational reduction target of 30%. In order to gather baseline value estimates with adequate precision to be able to detect changes in time, abundance of litter items shall be gathered for time periods varying from 3 to 5 years, according to the precision required (Schulz et al., 2019).

The data collected in this study represent the first available data on quantity and types of litter items for the Durance River and can be used to support the development of targeted policies in litter prevention, mitigation and reduction of most abundant litter items, as well as be used to test whether implemented measures to reduce plastic pollution are effective (van Emmerik et al., 2019; Vriend et al., 2020a; González-Fernández et al., 2021). Additional surveys on the Durance could assess if SUP items targeted by the EU SUPD and French Anti-waste and circular economy law are less prevalent after a few years of restriction from the market and the obligation of collection targets. Future studies could include a higher spatial/temporal resolution and take into consideration hydrological variations, so to account for extreme events such as floods (Tramoy et al., 2022; van Emmerik et al., 2022) and provide data useful for quantifying emission of litter items from the Durance to the Rhône River and the Mediterranean Sea.

Collecting data on macrolitter is resource-intensive and citizen science can provide a cost-effective way to do it. Citizen science has been very valuable for carrying out large scale survey of marine litter on sea beaches (Hidalgo-Ruz and Thiel, 2015; Syberg et al., 2020; Vlachogianni et al., 2020; Zorzo et al., 2021) and riverbanks (Rech et al., 2015; Kiessling et al., 2019; van Emmerik et al., 2020a,b). In the Danish Realm, it was used to carry out the first scientific survey of plastic litter to cover an entire country (Syberg et al., 2020). Comparison of data collected by citizen scientists vs. trained professionals shows that citizen scientists report a higher fraction of non-categorized items (Rech et al., 2015) and find less small or "dirty" items (Roebroek et al., 2021). However, most litter items do now show any significant bias of volunteers (Roebroek et al., 2021) and the similar values of total abundance of litter items reported by citizen scientists and professional researchers show the value of citizen science (Rech et al., 2015; Zorzo et al., 2021), especially where monitoring programs are scarce or not in place (Smail et al., 2020). As noted by van Emmerik et al. (2022), the use of citizen science mobile applications can facilitate upscaling of data collection of plastic pollution on land (Ballatore et al., 2022) in river systems (van Emmerik et al., 2020b) and in urban environments (Tasseron et al., 2020). Data collected through citizen science can assist local decision-making (Hidalgo-Ruz and Thiel, 2015; United Nations Environment Programme, 2021b).

Data collected in the SPEM project cover smaller spatial and temporal scales in comparison to other citizen science projects developed throughout Europe (Rech et al., 2015; Kiessling et al., 2019; Syberg et al., 2020; van Emmerik et al., 2020a,b; Vlachogianni et al., 2020; Zorzo et al., 2021) and in Chile (Hidalgo-Ruz and Thiel, 2015; Rech et al., 2015), that have been running for longer times and on wider spatial scales. However, even limited amount of data can be useful when no data at all is available (Owens and Kamil, 2020). Indeed, the data on litter items collected in the SPEM project allowed to suggest environmental regulations that could be put in place at EU and French level and immediate action that can be taken at municipal level to reduce plastic pollution.

Conclusions

In this study we have quantified and characterized for the first-time macrolitter items on Durance riverbank and Lake Serre-Ponçon beach using citizen science. Plastic litter items correspond to 82% of total litter items and the overall abundance of litter items is two orders of magnitude higher than the European threshold value for marine litter to achieve or maintain the Good Environmental Status.

Unidentified soft plastic films probably derived from plastic mulch films used in agriculture, plastic biomedia used in waste water treatment plants, and single-use beverage bottles in plastic and glass were among the most abundant litter items. We discussed policies that could reduce these sources of pollution. These include the expansion of extended producer responsibility (EPR) schemes for plastic mulch films, the development of new EPR schemes for plastic biomedia, and the introduction of deposit return systems (DRS) for single-use beverage bottles.

We suggest that complementary to EU and French national laws, municipalities can start immediately to address the issue of plastic pollution targeting the most abundant litter items found on Durance riverbank through green public procurement and territorial animation. The same measures can be taken by other municipalities in the whole Region SUD Provence-Alpes-Côte d'Azur. Future surveys carried out with citizen science could be carried out as a cost-effective way to monitor litter items and assess the effectiveness of environmental regulations in reducing plastic pollution.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

BD, MF, and TB contributed to conception and design of the study. MF and TB contributed to the methodology and training of citizen scientists. EM, JP, J-PC, MF, NC, and TB contributed to investigation. BD and NC contributed to resources, project administration, and funding acquisition. TB performed the formal analysis and wrote the manuscript. All authors read the manuscript, contributed to discussion, and approved the submitted version.

Funding

This work was carried out in the framework of the project SPEM - Stop Plastiques en Méditerranée supported by Région SUD Provence-Alpes-Côte-d'Azur through the fund N° DEB 19-405 DU 20/06/2019. Additional funds were provided to Expédition MED by the French Ministry for the Ecological Transition, SUEZ, Novamont, La Fondation Club Méditerranée.

Acknowledgments

We thank the volunteers from FNE Vaucluse (Alice Scotti, Alain Aubaud, Célia Desnoyes, Léo Paumard, Maxime Simon, Jean- François Sami, Jean Paul Bonneau), FNE Alpes de Haute-Provence (Thomas Husson, Caroline Guède, Mario Chabanon, Sophie Rieu, Tifène Ducottet, Elizaveta Mochalova, Janine Brochier-Marino), Colibircole (Solange Borsotto, Céline Bonnard), Société Alpine de Protection de la Nature-FNE Hautes-Alpes (Maryse Le Crom, Magalie Fournier, Sarah Haudidier, Anaïs Fleming, Koen Vuylsteke, Candice Morin, Julie Durand, Annabelle Matuszak, Caroline Guède, Laure Navoret, Léandre Navoret, Jean-François Fortin), and Ligue pour la Protection des Oiseaux (Henry Ripert, Laura Vanhaecke, Nans Denis, Roseline Coulomb, Paul Sarlin, Pierre Girard, Laurence Thibaut) who participated in field work and the Semailles association for the use of their spaces to stock litter items. JP thanks Caroline Guède for assistance in compiling data for Les Mées sampling site. TB thanks Cristina Barreau of Surfrider Foundation for information on plastic biomedia legislation and Gilles Bassière for the map of Durance watershed. We thank four reviewers that provided useful and detailed comments to improve the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2022.866982/full#supplementary-material

References

Addamo, A. M., Laroche, P., and Hanke, G. (2017). *Top Marine Beach Litter Items in Europe, EUR 29249 EN*. Luxembourg: Publications Office of the European Union, Luxembourg.

Arp, H. P., Kuhnel, H., Rummel, D., MacLeod, C., Potthoff, M., Reichelt, A., et al. (2021). Weathering plastics as a planetary boundary threat: exposure, fate, and hazards. *Environ. Sci. Technol.* 55, 7246–7255. doi: 10.1021/acs.est.1c01512

Azzurro, P., Pinca, G., Rossi, A., and Vanelli, L. (2021). *Oltre il #monouso: i modelli del #riuso. Alcune idee per un dialogo tra amministrazioni e imprese.* Available online at: http://www.anci.emilia-romagna.it/Media/Files/OLTRE-IL-MONOUSO-I-MODELLI-DEL-RIUSO (accessed January 03, 2022).

Bailly, C., Barreau, C., Bencivengo, P., and Verdet, F. (2018). *Pollution des plages et des cours d'eaux par les biomédias, supports en plastique de proliferation bactériologique utilizes dans le traitement des eaux usées. Surfrider Foundation.* Available at: https://surfrider.eu/wp-content/uploads/2020/10/surfrider_foundation_europe_biomedias-2018.pdf (accessed December 02, 2021).

Ballatore, A., Verhagen, T. J., Li, Z., and Cucurachi, S. (2022). This city is not a bin: Crowdmapping the distribution of urban litter. *J. Indust. Ecol.* 26, 197–212. doi: 10.1111/jiec.13164

Bandopadhyay, S., Martin-Closas, L., Pelacho, A. M., and DeBruyn, J. M., (2018). Biodegradable Plastic Mulch Films: Impacts on Soil Microbial Communities and Ecosystem Functions. *Front Microbiol* 9, 819. doi: 10.3389/fmicb.2018.00819

Battulga, B., Kawahigashi, M., and Oyuntsetseg, B. (2019). Distribution and composition of plastic debris along the river shore in the Selenga River basin in Mongolia. *Environmental Science and Pollution Research*, 26, 14059–14072. doi: 10.1007/s11356-019-04632-1

Bencivengo, P., Barreau, C., Bailly, C., and Verdet, F. (2018). *Sewage Filter Media and Pollution of the Aquatic Environment, Surfrider Foundation Europe Report, Water Quality and Marine Litter programme, Biarritz, France.* Available online at: https://www.surfrider.eu/wp-content/uploads/2018/08/biomedia-pollution-report.zip (accessed October 12, 2021).

Blettler, M. C., Abrial, E.l., Khan, F. R., Sivri, N., and Espinola, L. A. (2018). Freshwater plastic pollution: recognizing research biases and indentifying knowledge gaps. *Water Res.* 15, 416–424. doi: 10.1016/j.watres.2018.06.015

Borrelle, S. B., Ringma, J., Lavender Law, K., Monnahan, C. C., Lebreton, L., McGivern, A., et al. (2020). Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. *Sciecne*. 369. 1515–1518. doi: 10.1126/science.aba3656

Boucher, J., and Billard, G. (2020). *The Mediterranean: Mare plasticum*. Gland, Switzerland: IUCN.

Bruge, A., Barreau, C., Carlot, J., Collin, H., Moreno, C., and Maison, P. (2018). Monitoring litter inputs from the adour river (Southwest France) to the marine environment. *J. Mar. Sci.* 2018, 6, 24. doi: 10.3390/jmse6010024

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

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

Cózar, A., Sanz-Martí, M., Martí, E., González-Gordillo, J. I., Ubeda, B. Á., Gálvez, J., and Duarte, C. M. (2015). Plastic accumulation in the Mediterranean sea. *PLoS ONE*. 10:e0121762. doi: 10.1371/journal.pone.0121762

Cozzolino, L., Nicastro, K. R., Zardi, G. I., and de los Santos, C. B. (2020). Species-specific plastic accumulation in the sediment and canopy of coastal vegetated habitats. *Sci. Total Environ*. 723,138018. doi: 10.1016/j.scitotenv.2020.138018

Crosti, R., Arcangeli, A., Campana, I., Paraboschi, M., and Gonzàlez-Fernandéz, D. (2018). 'Down to the river': amount, composition, and economic sector of litter entering the marine compartment, through the Tiber river in the Western Mediterranean Sea. *Rendiconti Lincei. Scienze Fisiche e Naturali*. 8, 859–866. doi: 10.1007/s12210-018-0747-y

de Souza Machado, A. A., Lau, C. W., Kloas, W., Bergmann, J., Bachelier, J. B., Faltin, E., et al. (2019). Microplastics can change soil properties and affect plant performance. *Environ. Sci. Technol*. 53, 6044–6052 doi: 10.1021/acs.est.9b01339

ECA (2020). *European Court of Auditors. EU Action to Tackle the Issue of Plastic Waste.* Availabble online at: https://www.eca.europa.eu/en/Pages/DocItem.aspx?did=55223 (accessed August 31, 2021).

Eriksen, M., Lebreton, L. C. M., Carson, H. S., Thiel, M., Moore, C. J., Borrero, J. C., et al. (2014). Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. *PLoS ONE.* 9, 111913. doi: 10.1371/journal.pone.0111913

European Commission, Directorate-General for Environment. (2018). *Assessment of Measures to Reduce Marine Litter From Single Use Plastics: Final Report and Annex.* Publications Office. Available online at: https://data.europa.eu/doi/10.2779/500175

European Parliament (2011). *A European Refunding Scheme for Drinks Containers, Briefing, Paper*. Aavailable online at: http://www.europarl.europa.eu/RegData/etudes/note/join/2011/457065/IPOL-AFET_NT(2011)457065_EN.pdf. (accessed January 19, 2022).

Eyrolle, F., Radakovitch, O., Raimbault, P., Charmasson, S., Antonelli, C., Ferrand, E., et al. (2012). Consequences of hydrological events on the delivery of suspended sediment and associated radionuclides from the Rhône River to the Mediterranean Sea. *J. Soils Sediments.* 12, 1479–1495. doi: 10.1007/s11368-012-0575-0

FAO (2021). *Assessment of Agricultural Plastics and Their Sustainability - A Call for Action*. Rome: FAO. doi: 10.4060/cb7856en

Fleet, D., Vlachogianni, T., and Hanke, G. (2021). *A Joint List of Litter Categories for Marine Macrolitter Monitoring*. Luxembourg: Publications Office of the European Union. doi: 10.2760/127473

French Ministry for the Ecological Transition. (2020). *Plan d'actions "Zéro Déchets Plastique en Mer" (2020–2025)*, 16. Available online at: https://www.ecologie.gouv.fr/sites/default/files/DGALN_plan-actions-zero-dechet-plastique_web.pdf (accessed January 4, 2022).

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

Galloway, T. S., and Lewis, C. N. (2016). Marine microplastics spell big problems for future generations. *Proc Natl Acad Sci U S A.* 113, 2331–2333. doi: 10.1073/pnas.1600715113

Gasperi, J., Dris, R., Bonin, T., Rocher, V., and Tassin, B. (2014). Assessment of floating plastic debris in surface water along the Seine River. *Environm. Pollut*. 195, 163–166. doi: 10.1016/j.envpol.2014.09.001

Gkoutselis, G., Rohrbach, S., Harjes, J., Obst, M., Brachmann, A., Horn, M. A., et al. (2021). Microplastics accumulate fungal pathogens in terrestrial ecosystems. *Sci. Rep*. 11:13214| doi: 10.1038/s41598-021-92405-7

Global Deposit Book (2020). Available online at: https://www.reloopplatform.org/reloops-global-deposit-book-2020/. (accessed August 13, 2021).

González-Fernández, D., Cózar, A., Hanke, G., Viejo, J., Morales-Caselles, C., Bakiu, R., et al. (2021). Floating macrolitter leaked from Europe into the ocean. *Nat. Sustain*. 4, 474–483. doi: 10.1038/s41893-021-00722-6

Grant, A., Fletcher, D., Cordle, M., Card, D., and Ventosa, V. (2021). *Waste in the Net-Zero Century: testing the holistic resources system via three European case studies.* Available online at: https://www.eunomia.co.uk/reports-tools/waste-in-the-net-zero-century-testing-the-holistic-resources-system-via-three-european-case-studies/ (accessed December 13, 2021).

Hanke, G., Walvoort, D., van Loon, W., Addamo, A. M., Brosich, A., del Mar Chaves Montero, M., et al. (2019). *EU Marine Beach Litter Baselines, EUR 30022 EN.* Luxemburg: Publications Office of the European Union.

Hann, S., Fletcher, E., Molteno, S., Sherrington, C., Elliot, L., Kong, M. A., et al. (2021). *Conventional and Biodegradable Plastics in agriculture. Report for DG Environment of the European Commission.* Available online at: https://www.eunomia.co.uk/reports-tools/conventional-and-biodegradable-plastics-in-agriculture/ (accessed October 20, 2021).

Hann, S., Sherrington, C., Jamieson, O., Hickman, M., Kershaw, P., Bapasola, A., et al. (2018). Available online at: https://ec.europa.eu/environment/marine/good-environmental-status/descriptor-10/pdf/microplastics_final_report_v5_full.pdf (accessed January 11, 2022).

Hidalgo-Ruz, V., and Thiel, M. (2015). "The contribution of citizen scientist to the monitoring of marine litter.," in *Marine Anthropogenic Litter,* Bergmann, M., et al. (eds.), doi: 10.1007/978-3-319-16510-3_16

Hidayat, H., Aisyah, S., Rahmadya, A., Husrin, S., Hermana, I. S., Hurley, R., et al. (2022). *Quantification of Riverbank Macroplastic Contamination in The Lower Citarum River*. Available online at: https://iopscience.iop.org/article/10.1088/1755-1315/950/1/012010/meta

Huerta-Lwanga, E., Vega, J. M., Quej, V. K., de los Angeles Chi, J., del Cid, L. S., Chi, C., et al. (2017). Field evidence for transfer of plastic debris along a terrestrial food chain. *Sci. Rep*. 7, 1407.1 doi: 10.1038/s41598-017-14588-2

Hurley, R. R., and Nizzetto, L. (2018). Fate and occurrence of micro(nano)plastics in soils: Knowledge gaps and possible risks. *Curr Opin Environ Sci Health.* 1, 6–11. doi: 10.1016/j.coesh.2017.10.006

Jahnke, A., Arp, H. P. H., Escher, B. I., Gewert, B., Gorokhova, E., Kühnel, D., et al. (2017). Reducing uncertainty and confronting ignorance about the possible impacts of weathering plastic in the marine environment. *Environ. Sci. Technol. Lett.* 4, 85–90. doi: 10.1021/acs.estlett.7b00008

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

Joint Research Centre, Institute for Environment and Sustainability (2014). *Guidance on Monitoring of Marine Litter in European Seas*. Publications Office.

Available online at: https://data.europa.eu/doi/10.2788/99816 (accessed August 13, 2021).

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

Lau, W. W. Y., Shiran, Y., Baily, R. M., Cook, E., Stuchtey, M. R., Koskella, J., et al. (2020). Evaluating scenarios toward zero plastic pollution. *Science*. 369, 1455–1461. doi: 10.1126/science.aba9475

Leal Filho, W., Saar, U., Fedoruk, M., Iital, A., Moora, H., Klöga, M., et al. (2019). An overview of the problems posed by plastic products and the role of extended producer responsibility in Europe. *J. Cleaner Product.* 214, 550e558. doi: 10.1016/j.jclepro.2018.12.256

Lebreton, L., and Andrady, A. (2019). Future scenarios of global plastic waste generation and disposal. *Palgrave Commun.* 5, 6. doi: 10.1057/s41599-018-0212-7

Ligue Pour la Protection des Oiseaux (2021). *"Les biomédias, quésaco? pourquoi sont-ils là ?"* Available online at: https://paca.lpo.fr/blogs/ecrins-embrunais/2021/03/20/les-biomedias-quesaco-pourquoi-sont-ils-la/ (accessed December 08, 2021).

Liro, M., van Emmerik, T., Wyz ga, B., Liro, J., and Mikus, P. (2021). Macroplastic storage and mobilization in rivers. *Water.* 2020, 2055 doi: 10.3390/w12072055

MacLeod, M., Arp, H. P. H., Tekman, M. B., and Jahnke, A. (2021). The global threat from plastic pollution. *Science.* 373, 61–65. doi: 10.1126/science.abg5433

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

Morritt, D., Stefanoudis, P. V., Pearce, D., Crimmen, O. A., and Clark, P. F. (2014). Plastic in the Thames: a river runs through it. *Marine Pollution Bull.* 78, 196–200. doi: 10.1016/j.marpolbul.2013.10.035

OSPAR Commission (2014). *Marine litter regional action plan*. Available online at: https://www.ospar.org/documents?v=34422 (accessed January 10, 2022).

Owens, K. A., and Kamil, P. I. (2020). Adapting coastal collection methods for river assessment to increase data on global plastic pollution: examples from India and Indonesia. *Front. Environm. Sci.* 208. doi: 10.3389/fenvs.2019.00208

Persson, L., Carney Almorth, B. M., Collins, C. D., Cornell, S., de Witt, C. A., Diamond, M. L., et al. (2022). Outside the safe operating space of the planetary boundary for novel entities. *Environ. Sci. Technol.* 2022. doi: 10.1021/acs.est.1c04158

Poletti, S., and Landberg, T. (2021). Using nature preserve creek cleanups to quantify anthropogenic litter accumulation in an urban watershed. *Freshwater Sci.* 40, 3. doi: 10.1086/716214

QGIS Development Team (2021). *QGIS Geographic Information System*. Open Source Geospatial Foundation Project. Available online at: http://qgis.osgeo.org

R Core Team. (2021). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. Available online at: https://www.R-project.org/

Rech, S., Macaya-Caquilpán, V., Pantoja, J. F., Rivadeneira, M. M., Kroeger Campodónico, C., and Thiel, M. (2015). Sampling of riverine litter with citizen scientists — findings and recommendations. *Environ Monit Assess.* (2015) 187, 335. doi: 10.1007/s10661-015-4473-y

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

Rillig, M. C., Kim, S. W., Kim, T. Y., and Waldman, W. R. (2021). The global plastic toxicity debt. *Environ. Sci. Technol.* 55, 2717–2719. doi: 10.1021/acs.est.0c07781

Roebroek, C. T., Hut, R., Vriend, P., De Winter, W., Boonstra, M., and Van Emmerik, T. H. (2021). Disentangling variability in riverbank macrolitter observations. *Environ. Sci. Technol.* 55, 4932–4942 doi: 10.1021/acs.est.0c08094

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

Schulz, M., Walvoort, D. J. J., Barry, J., Fleet, D. M., and van Loon, W. M. G. M. (2019). Baseline and power analyses for the assessment of beach litter reductions in the European OSPAR region. *Environme. Pollut.* 248 555e564. doi: 10.1016/j.envpol.2019.02.030

Sempéré, R., Charriere, B., Cauwet, G., and Van-Wambeke, F. (2000). Carbon inputs of the Rhône River to the Mediterranean Sea: biogeochemical implications. *Global Biogeochem. Cy.* 14, 669–681. doi: 10.1029/1999GB900069

Smail, E., Campbell, J., Takaki, D., Plag, H. P., Garello, R., Djavidnia, S., et al. (2020). *A global platform for monitoring marine litter and informing action*. Available online at: https://geoblueplanet.org/wp-content/uploads/2020/03/Marine-Litter-White-Paper-Draft_07Mar2020.pdf (accessed January 20, 2022).

Steinmetz, Z., Wollmann, M., Schaefer, C., Buchmann, J., David, J., Tröger, K., et al. Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation? *Sci. Total Environ.* 550, 690–705 (2016). doi: 10.1016/j.scitotenv.2016.01.153

Suaria, G., Avio, C. G., Mineo, A., Lattin, G. L., Magaldi, M. G., Belmonte, G., et al. (2016). The Mediterranean Plastic Soup: synthetic polymers in Mediterranean surface waters. *Sci. Rep.* 6, 37551. doi: 10.1038/srep37551

Surfrider Foundation (2020). *Feedback to the EU Commission on the revision of the Urban Waste Water Treatment Directive*. Available online at: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12405-Water-pollution-EU-rules-on-urban-wastewater-treatment-update-/F550460_en (accessed December 20, 2021).

Syberg, K., Palmqvist, A., Khan, F., R., Strand, J., Vollertsen, J. et al. (2020). A nationwide assessment of plastic pollution in the Danish realm using citizen science. *Sci Rep* 10, 17773(2020). doi: 10.1038/s41598-020-74768-5

Tasseron, P., Zinsmeister, H., Rambonnet, L., Hiemstra, A.-F., Siepman, D., and van Emmerik, T. (2020). Plastic hotspot mapping in urban water systems. *Geosciences* 10, 342. doi: 10.3390/geosciences10090342

Tramoy, R., Blin, E., Poitou, I., Noûs, C., Tassin, B., and Gasperi, J. (2022). Riverine litter in a small urban river in Marseille, France: Plastic load and management challenges. *Waste Managem.* 140, 154–163. doi: 10.1016/j.wasman.2022.01.015

Tramoy, R., Colasse, L., Gasperi, J., and Tassin, B. (2019). Plastic debris dataset on the Seine River banks: Plastic pellets, unidentified plastic fragments and plastic sticks are the Top 3 items in a historical accumulation of plastics. *Data in Brief.* 23, 103697. doi: 10.1016/j.dib.2019.01.045

Tramoy, R., Gasperi, J., Colasse, L., Noûs, C., and Tassin, V. (2021). Transfer dynamics of macroplastics in estuaries – new insights from the Seine estuary: Part 3. What fate for macroplastics? *Marine Pollution Bullet.* 169, 112513. doi: 10.1016/j.marpolbul.2021.112513

Tramoy, R., Gasperi, J., Colasse, L., and Tassin, B. (2020). Transfer dynamic of macroplastics in estuaries—new insights from the Seine estuary: Part 1. *Long term dynamic based on date-prints on stranded debris. Marine Pollut. Bulletin.* 152, 110894. doi: 10.1016/j.marpolbul.2020.110894

United Nations Environment Programme (2021a). *Addressing Single-use Plastic Products Pollution Using a Life Cycle Approach*. Nairobi.

United Nations Environment Programme (2021b). *From Pollution to Solution: A global assessment of marine litter and plastic pollution reveals the impact of marine litter and plastic pollution*. Nairobi. Available online at: https://www.unep.org/resources/pollution-solution-global-assessment-marine-litter-and-plastic-pollution (accessed November 23, 2021).

van Emmerik, T., Mellink, Y., Hauk, R., Waldschläger, K., and Schreyers, L. (2022). Rivers as Plastic Reservoirs. *Front. Water*, 212. doi: 10.3389/frwa.2021.786936

van Emmerik, T., Roebroek, C., de Winter, W., Vriend, P., Boonstra, M., and Hougee, M. (2020a). Riverbank macrolitter in the Dutch Rhine-Meusa delta. *Environmental Res. Lett.* 15, 104087doi: 10.1088/1748-9326/abb2c6

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

van Emmerik, T., Seibert, J., Strobl, B., Etter, S., Den Oudendammer, T., Rutten, M., et al. (2020b). Crowd-based observations of riverine macroplastic pollution. *Front. Earth Sci.* 8, 298. doi: 10.3389/feart.2020.00298

van Emmerik, T., Tramoy, R., van Calcar, C., Alligant, S., Treilles, R., Tassin, B., et al. (2019). Seine plastic debris transport tenfolded during increased river discharge. *Front. Marine Sci.* 6, 642. doi: 10.3389/fmars.2019.00642

van Emmerik, T., Vriend, P., and Roebroek, C. T. J. (2020c). *An evaluation of the River-OSPAR method for quantifying macrolitter on Dutch riverbanks*. Wageningen: Wageningen University, Report. P. 86. doi: 10.18174/519776

van Loon, W., Hanke, G., Fleet, D., Werner, S., Barry, J., Strand, J., et al. (2020). *A European Threshold Value and Assessment Method for Macro Litter on Coastlines.EUR 30347 EN*. Luxembourg: Publications Office of the European Union.

Villarrubia-Gómez, P., Cornell, S. E., and Fabres, J. (2018). Marine plastic pollution as a planetary boundary threat – The drifting piece in the sustainability puzzle. *Marine Policy* 96, 213–220. doi: 10.1016/j.marpol.2017.11.035

Vlachogianni, S., Skocir, M., Constantin, P., Labbe, C., Orthodoxou, D., Pesmatzoglou, I., et al. (2020). Plastic pollution on the Mediterranean coastline: generating fit-for-purpose data to support decision-making via a participatory-science initiative. *Sci. Total Environ.* 816, 151638. doi: 10.1016/j.scitotenv.2019.135058

Vriend, P., Roebroek, C. T. J., and van Emmerik, T. (2020a). Same but different: a framework to design and compare riverbank plastic monitoring strategies. *Front. Water.* 2:563791. doi: 10.3389/frwa.2020.563791

Vriend, P., Van Calcar, C., Kooi, M., Landman, H., Pikaar, R., and Van Emmerik, T. (2020b). Rapid assessment of floating macroplastic transport in the Rhine. *Front. Marine Sci.* 10. doi: 10.3389/fmars.2020.00010

Wagner, M., Scherer, C., Alvarez-Muñoz, D., Brennholt, N., Bourrain, X., Buchinger, S., et al. (2014). Microplastics in freshwater ecosystems: what we know and what we need to know. *Environ. Sci. Eur.* 26, 12. doi: 10.1186/s12302-014-0012-7

WWF France. (2020). *Territoires zero pollution plastique. Guide a destination des communes françaises et leur groupements, pour stopper les rejets plastiques dans la nature d'ici à 2015*. Available online at: https://www.wwf.fr/sites/default/files/doc-2020-09/20200920_Guide_Territoires-Z%C3%A9ro-Pollution-Plastique_WWF.pdf (accessed May 10, 2022).

Zorzo, P., Buceta, J. L., Corredor, L., López-Samaniego, I., and López-Samaniego, E. (2021). An approach to the integration of beach litter data from official monitoring programmes and citizen science. *Mar Pollut Bull.* 173,112902. doi: 10.1016/j.marpolbul.2021.112902