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Schoolchildren discover hotspots of floating plastic litter in rivers using a large-scale collaborative approach☆

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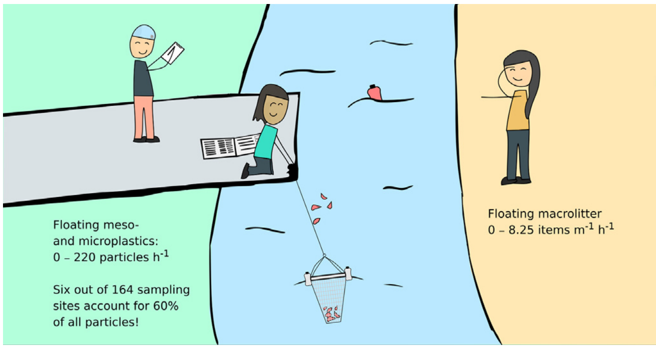
HIGHLIGHTS

- Schoolchildren investigated litter pollution of rivers at >250 sites in Germany.
- Quantities of floating macrolitter ranged from 0 to 8.25 items m^{-1} h^{-1}.
- Quantities of floating meso—/microplastics ranged from 0 to 220 particles h^{-1}.
- Six pollution hotspots accounted for 60% of meso—/microplastics found in the study.

GRAPHICAL ABSTRACT



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ABSTRACT

Rivers are an important transport route of anthropogenic litter from inland sources toward the sea. A collaborative (i.e. citizen science) approach was used to evaluate the litter pollution of rivers in Germany: schoolchildren within the project "Plastic Pirates" investigated rivers across the entire country during the years 2016 and 2017 by surveying floating macrolitter at 282 sites and taking 164 meso—/microplastic samples (i.e. particles 24.99–5 mm, and 4.99–1 mm, respectively). Floating macrolitter was sighted at 54% of sampling sites and floating macrolitter quantities ranged from 0 to 8.25 items m^{-1} h^{-1} (average of 0.34 ± 0.89 litter items m^{-1} h^{-1}). Floating meso—/microplastics were present at 57% of the sampling sites, and floating meso—/microplastic quantities ranged from 0 to 220 particles h^{-1} (average of 6.86 ± 24.11 items h^{-1}). As only particles >1 mm were sampled and analyzed, the pollution of rivers in Germany by microplastics could be a much more prevalent problem, regardless of the size of the river. We identified six plastic pollution hotspots where 60% of all meso—/microplastics collected in the present study were found. These hotspots were located close to a plastic-producing industry site, a wastewater treatment plant, at and below weirs, or in residential areas. The composition of the particles at these hotspots indicates plastic producers and possibly the construction industry and wastewater treatment plants as point sources. An identification of litter hotspots would enable specific mitigation measures, adjusted to the respective source, and thereby could prevent the release of

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☆ Main finding: Citizen scientists investigated > 250 river sites for floating macrolitter and meso-/microplastics in Germany and discovered pollution hotspots

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large quantities of small plastic particles in rivers. The adopted large-scale citizen science approach was especially suitable to detect pollution hotspots by sampling a variety of rivers, large and small, and enabled a national overview of litter pollution in German rivers.

1. Introduction

Rivers transport large amounts of plastic litter to the sea (Gasperi et al., 2014; Morritt et al., 2014; Mani et al., 2015; Lebreton et al., 2017), contributing to the profound environmental, economic, and social problem of marine litter pollution (see Kühn et al., 2015 for an overview). It is estimated that up to 2.8 million tons of plastic litter enter the sea annually by rivers, transporting litter from inland sources to the coast (Lebreton et al., 2017; Schmidt et al., 2017). In recent studies, an extensive impact of anthropogenic litter on the riparian environment has been shown, e.g. by the ingestion of microplastics by freshwater fishes (e.g. Roch et al., 2019), or by plastics being used for nest-building by birds living in wetlands (Jagiello et al., 2018; Blettler et al., 2020). Further, litter at and in rivers presents a hazard to human health, for example by the presence of sharp litter objects or by bacteria developing antibiotic resistance on the surface of microplastics (Kiessling et al., 2019; Parthasarathy et al., 2019).

Sources of anthropogenic litter at riversides are diverse: litter, large or small, can originate from people using the riverside as a recreational area (Gasperi et al., 2014; Carpenter and Wolverton, 2017; Kiessling et al., 2019), residents without access to adequate waste infrastructure or people illegally depositing litter (Franz and Freitas, 2012; Rech et al., 2015; McCormick and Hoellein, 2016; Michiani and Asano, 2019), outlets of wastewater treatment plants or sewage overflow (Williams and Simmons, 1999; Di and Wang, 2018; Magni et al., 2019), and plastic-producing or plastic-processing industry (Lechner et al., 2014; Klein et al., 2015; Lechner and Ramler, 2015; Tramoy et al., 2019). Many of these sources are linked to densely populated areas (i.e. cities or urban spaces) and several studies found an increase in litter quantities downstream of larger urban areas (van Emmerik et al., 2019a; Wagner et al., 2019; Grbić et al., 2020).

In general, it can be expected that the litter load in rivers increases from the spring to the river mouth as it passes additional pollution sources. Some studies have found such an increase in litter quantities along a river course (Mani et al., 2015; Su et al., 2020), coinciding with an increase in population density in one case (Mani et al., 2015). Other studies have not found the same and litter concentrations varied across the length of a river (e.g. Barrows et al., 2018; Forrest et al., 2019).

Once plastic litter is located in a river, transport processes are complex and floating plastic litter can have several fates. It can sink, be deposited on the river banks, float downstream, and/or fragment into smaller pieces (Gasperi et al., 2014). The resulting particles are classified according to size and in the present study we follow the definition of GESAMP (2019), defining macroplastics as those >25 mm, mesoplastics as those 5–25 mm, and microplastics as 1–5 mm in size. Litter floating downstream can reach the marine environment but is likely retained on several occasions (Kole et al., 2017), and can accumulate, for example, at dams (Zhang et al., 2015; Shumilova et al., 2019), designated litter collection booms (Gasperi et al., 2014), or at the riverside due to flow reduction (Watkins et al., 2019; Zhang et al., 2019). This can lead to hotspots of litter pollution, i.e. sites with an extraordinary load of plastic litter (see e.g. Kapp and Yeatman, 2018 for microplastic hotspots and Tasseron et al., 2020 for macroplastic hotspots in waterways).

The present study addresses the pollution of rivers in Germany and is part of the citizen science project “Plastic Pirates” (“Plastikpiraten” in German). The project involves schoolchildren investigating litter pollution of rivers in a large-scale, nationwide approach. This approach allowed us to (i) estimate quantities of floating macrolitter and meso—/microplastics at more than 250 sampling sites, (ii) identify hotspots of meso—/microplastic pollution, and (iii) evaluate the relationship between quantities of floating macrolitter and floating meso—/microplastics with macrolitter at the riverside. Regarding the latter, we expected that a higher density of macrolitter at the riverside leads to a higher density of macrolitter and meso—/microplastics within the river because of the dispersal (by people or weather-driven) and the fragmentation of larger litter objects located close to the river.

2. Materials and methods

2.1. Study area

Germany has several major river systems, which drain into the North Sea, the Baltic Sea, and, via the Danube, into the Black Sea. Almost the entire population is located close to rivers or streams; the most populated area of Germany with large industrial activity (the Ruhr region) is located along a river that is part of the Rhine watershed. Rivers, therefore, play an important role, e.g. as a recreational area, for tourism, as a transport route, and as recipients of effluents from a large share of the population and industrial activity.

The participants of the present study sampled rivers throughout the entire country, including all sixteen federal states of Germany. We categorized the sampled rivers and streams either according to the larger river system they belong to (i.e. Rhine, Weser, Elbe, or Danube) or collectively as smaller rivers flowing into the North Sea or the Baltic Sea (following Kiessling et al., 2019). Sampling sites considered in the present study ranged from small streams and channels to major rivers; 34% of the sites were located at rivers <10 m wide, 34% at rivers from 10 to 50 m widths, and 32% at rivers >50 m width.

2.2. Citizen science approach

The present study is part of the citizen science project “Plastic Pirates”, examining various aspects of anthropogenic litter pollution in riparian environments in Germany. The project was developed by the *Kieler Forschungswerkstatt* (“Kiel Science Factory”, Germany, https://www.forschungs-werkstatt.de/) and the *Científicos de la Basura* program (“Litter Scientists”, Chile, www.cientificosdelabasura.cl), and is being coordinated by the *Kieler Forschungswerkstatt*. Teachers or leaders of youth organizations served as local supervisors and contact persons, e.g. to organize shipping of material and answering questions regarding sampling methodology and data. A guidebook with sampling instructions was created for participants (Supplement S1) as well as a booklet with background information about environmental litter pollution for local supervisors. The material was distributed free of charge. Participants came mainly from secondary schools (but several elementary schools and members of youth organizations participated as well), receiving an insight into an environmental research project, expert knowledge about the litter pollution of the ocean and rivers, and a stimulus for further engagement as a citizen scientist. Approximately 5500 schoolchildren participated in the sampling, forming 408 project groups from about 340 schools and youth organizations (Fig. 1, Supplement S2). Sampling sites were not predetermined, and instead each project group chose their sampling site according to the ease of access and interest. As a result of this liberty to choose their site, some groups sampled at open sections of a river whereas others sampled near river infrastructure (e.g. bridges or weirs). The project groups organized themselves into several subgroups to investigate different aspects of litter pollution (some of which have been published by Kiessling et al., 2019).

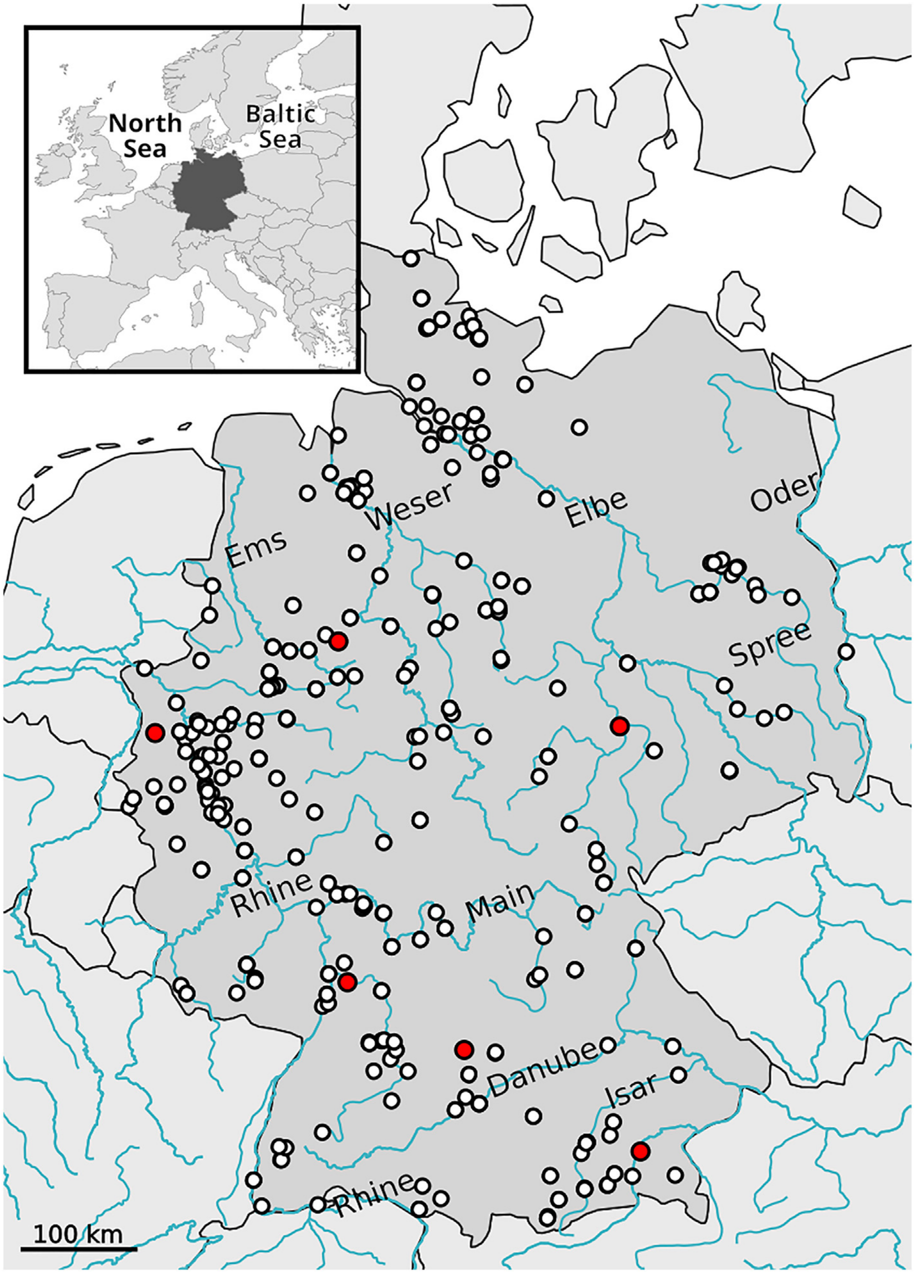

Fig. 1. Map of Germany with major rivers and sampling sites of the Plastic Pirates in 2016 and 2017. Red circles represent sites with many meso—/microplastics (more than 50 particles h^{-1}). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Data for the present study were collected in boreal autumn (16th September to 30th November 2016) and spring (8th May to 17th July 2017).

2.3. Sampling of floating macrolitter

Macrolitter items (> 25 mm) floating along the river surface were monitored from a vantage point or the riverside. Participants were asked to count floating litter passing by their observation point for at least 30 min or more; we also recommended taking photos of the floating litter items whenever possible. Items were ranked according to size (small: the size of an apple, medium: the size of a football, large: the size of a bucket), but for analysis, all recorded items were considered regardless of their size classification. Along with the litter data, participants submitted a measurement of the river width at their sampling spot, either based on estimating the width in the field or using satellite imagery services. This measurement was corrected if necessary (using the ruler tool in Google Earth Pro 7.31.4507). As wide rivers could not be surveyed across the entire width, the maximum observable distance of the schoolchildren was set to 20 m for analysis (Fig. 2A), which is in line with another river study in which floating macrolitter has been monitored (Schöneich-Argent et al., 2020). Using this information, the amount of floating macrolitter was standardized according to river width (or 20 m maximum observable distance, respectively) and observation time (for the 282 groups considered, the observation time ranged from 30 to 188 min).

2.4. Sampling of floating meso- and microplastics

Mesoplastics (24.99–5 mm) and microplastics (4.99–1 mm) were sampled by participants with custom-built nets (Device number 438215 HydroBios Kiel, Germany; Fig. 2B). The net had an opening of 35 × 11 cm, of which approximately 35 × 9 cm (0.0315 m^2) were submerged during sampling with two empty plastic bottles attached at

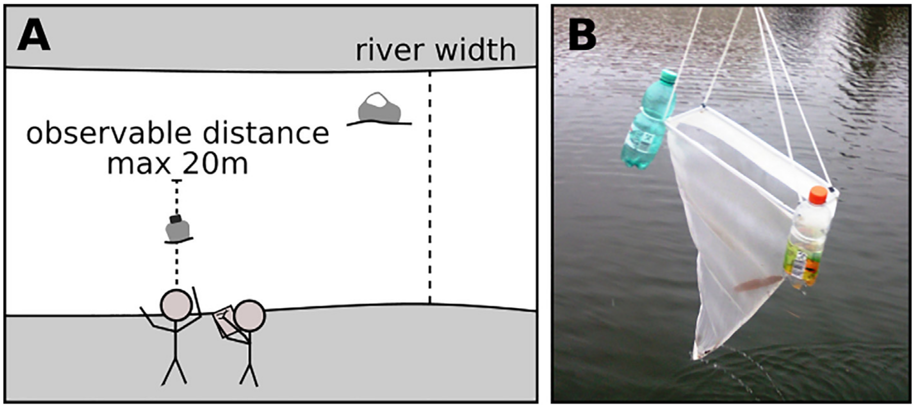

Fig. 2. (A) Survey method for floating macrolitter: litter passing by the observers was counted. For wide rivers a maximum observable distance of 20 m was assumed (see text for details). (B) Sampling net for small plastic particles, equipped with two 0.5 L plastic bottles for buoyancy. © Europaschule "Marie & Pierre Curie" Guben.

the side of the net for buoyancy. The mesh size was 1000 μm. The net was attached to jetties, pillars, or bridges with a rope and set up where feasible and permitted (i.e. sometimes closer to the riverside, other times closer to the mid-section of a river). It was deployed for 60 min, afterward hauled in, closed, and dried at the respective school or organization. Subsequently, the content of the net was emptied into a tray and analyzed by participants for meso−/microplastics (using tools available to them, e.g. dissecting microscopes, magnifying glasses, or the naked eye).

Participants were further asked to measure the flow velocity of their river within the vicinity of the site of net deployment. For that, an accessible stretch of 20 m at the riverside was chosen and three sticks were thrown into the river water, approximately at the height where the net was deployed. The time each stick needed to pass the distance of 20 m was recorded and an average flow velocity was calculated based on these three measurements. Participants submitted an estimate of the count of meso−/microplastic fragments as well as pellets in their sample (although more detailed categories were used to describe the types of plastic particles found – see result section below), and calculated the number of meso−/microplastics m^{-3} of river water, according to the following formula (Moore et al., 2011; *fv* = flow velocity of river, *noa* = area of net opening submerged in river, *dt* = deployment time of net):

$$\text{Particles } m^{-3} = \frac{\text{number of particles in net}}{(fv[m\,s^{-1}] \times noa[m^2] \times dt[s])}$$

Not all participants submitted an estimate of the meso−/microplastics contained within their samples (e.g. because of a lack of time or an adequate method to analyze the sample). Once done, the entire sample, including all other materials, e.g. organic matter, captured in the net, was packaged and sent to the coordinating laboratory (Kiel Science Factory) for more detailed analyses (see below).

2.5. Sampling of litter at riversides

For analysis of the relationship between different litter samplings, data published by Kiessling et al. (2019) were used for the litter pollution on the riverside. These data originate from the same samplings (place and time) as the data for floating macrolitter and meso−/microplastics and were collected by the same schools and organizations (albeit not the same participants as these were different subgroups). The riverside sampling comprised two groups that analyzed anthropogenic litter (not only plastics): (i) one group that classified and quantified macrolitter within sampling circles along transects, and (ii) another group that recorded and counted larger accumulations of litter within an area of at least 1000 m^2 on the riverside (see Kiessling et al., 2019 for details).

2.6. Stepwise verification of submitted citizen science data and samples

2.6.1. Selection and verification of citizen science datasets

Participants were asked to self-report problems they experienced during the sampling. Of the 390 groups attempting to observe floating macrolitter or sample meso−/microplastics, 284 groups rated the severity of the problems they encountered on average with a score of 1.79 on a scale of 1 to 5 (1 = no problems, 5 = sampling had to be canceled). In addition, 52 groups further specified their problems; most of these problems were related to the accessibility of the sampling site, the weather, and social or motivational problems within the groups. More specific problems were reported mainly about the measurement of the flow velocity (being influenced by ship traffic, the flow of the river, or waves), and the calculations of flow velocity and the quantity of meso−/microplastics within the samples (Supplement S3–1). Most of the time, as few problems were severe, these self-reported problems did not influence the subsequent selection of datasets but helped to get a better understanding of obstacles encountered by the participants during the field sampling.

For macrolitter, a total of 347 groups conducted the observation. Of those, data from 282 groups were considered for analysis (Fig. 1). Results from 65 groups were excluded because the sampling site was not specified (17 groups), datasheets were missing or incomplete (8 groups), litter was not quantified (9 groups), it remained unknown how long the river surface was surveyed or it was surveyed for less than 30 min (15 groups). Data from some samplings could unfortunately not be used because the observation took place from a moving kayak and not a fixed position from the riverside (3 groups). For datasets reporting 10 or more observed litter items ($n = 20$ groups), the coordinator was contacted to reconfirm the results. This was mainly done to exclude datasets were much macrolitter was located within the river but immobile, i.e. stuck at the riverside or barriers. Only if the coordinators replied that they themselves had observed much floating litter, the respective dataset was considered for analysis. A total of 13 groups did not reconfirm the results this way or did not respond to the inquiry, and data were therefore excluded.

For meso−/microplastics, overall 384 groups conducted the sampling and data from 164 of those groups were considered (Fig. 1). Results from 220 groups were excluded because no or only partial samples were sent in for revision in the laboratory (123 groups), no information about the sampling location or sampling date was submitted (56 groups), the sampling took less time than the required sampling time of 60 min (18 groups), or no information about the sampling time was supplied (6 groups). Data from further 17 groups could unfortunately not be used because the samples were not taken according to the protocol (some motivated groups sampled by kayak or used self-made nets with other dimensions). The measurement of flow velocity of each group was considered valid if (i) the average flow velocity was between 0.1 and 1.0 m s^{-1} (a flow velocity < 0.1 m s^{-1} frequently indicated that the sticks floated in circles or got stuck repeatedly, while a flow velocity > 1.0 m s^{-1} usually resulted from an obvious mistiming or individual fast measurements), and (ii) if the standard deviation from replicates divided by the average of the three measurements was <0.3. This way, for 121 of the 164 groups (74%) a measurement of flow velocity could be associated with the sample.

2.6.2. Revision of meso- and microplastic samples and FTIR analysis

Samples sent to the laboratory varied largely in terms of volume, dependent on the amount of organic matter they contained. All samples were reviewed by visual inspection in the coordinating laboratory with a dissecting microscope (Wild Heerbrugg M3B, 10× – 40× magnification), scanning all materials, turning organic matter over to not miss particles, and extracting particles considered to be plastics with tweezers. The bags (resealable polyethylene freezer bags) in which the samples were sent to the laboratory were checked for holes to avoid that plastic pieces from the sample container or the surroundings contaminated the sample. All extracted particles were photographed (BMS Microscopes XCAM4K8MPA), measured, and subsequently analyzed with attenuated total reflection Fourier transform infrared (ATR-FTIR) spectrometers, in order to confirm whether the particle in question was a plastic particle and, if so, to identify the polymer composition (for this, particles were wiped with 95% ethanol if they appeared dirty). During ATR-FTIR analysis an infrared light beam passes through a crystal and is reflected by the sample surface back into the sampling device (see e.g. Käppler et al., 2016 for a comparison of microplastic FTIR verification methods). Due to logistical reasons, an ALPHA FT-IR Spectrometer (Bruker, Germany) was used for some particles, while the remaining particles were analyzed using a Cary 630-FTIR (Agilent, Germany). In order to avoid analyzing the output of the devices with two different programs by the respective manufacturer, the freeware siMPle 1.0.1 (Primpke et al., 2020) was used, a program to analyze microplastics in environmental samples (https://simple-plastics.eu/). The database used within siMPle was the siMPle ATR single spectra IR library 1.0.2 (Primpke et al., 2018). Output files from the Cary 630 were transformed using SpectraGryph 1.2.13 (Menges, 2019) for analysis in siMPle. All particles were analyzed this way, except for samples that contained more than 10 visually identical items (i.e. items that were identical to other particles based on the shape, color and surface structure). In this case, only the first 10 particles were analyzed with FTIR and if all items were identified as the same polymer, all other visually identical items were categorized as the same polymer (this inference was done for 30% of particles, while 70% were analyzed with FTIR). Each particle was analyzed three times with the FTIR (each time shifting the particle position to analyze a different surface area). In siMPle, the option to use the first derivative of the output by the spectrometers was used (rather than the raw data), and particles were accepted as microplastics if the match of the resulting spectrum and a database spectrum (i.e. the hit quality indicating the correlation of the measured spectrum with a database spectrum) was at least 0.7 for all three FTIR-measurements. Particles identified as natural materials or particles to which no database spectrum could be assigned were excluded. The estimation of meso—/microplastics submitted by the participants was not used as most groups under- or overestimated the quantity of meso—/microplastics in the samples (Supplement S3–2).

2.7. Collection of population and river infrastructure variables

In addition to the data collected by the participants, further data were collated to predict litter quantities: the population density around each sampling site was considered in circular zones with a radius of 1 km and was based on a 10,000 m^2 population grid (Statistische Ämter des Bundes und der Länder, 2015), using QGIS 3.4.4 (QGIS Development Team, 2018). The population densities per circle (3.14 km^2) were grouped into four categories: < 5,000 inhabitants, 5,000–20,000 inhabitants, 20,001–100,000 inhabitants, and > 100,000 inhabitants, following the classification by the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR, 2020). The presence or absence of artificial barriers (e.g. dams, water gates) and natural retention basins (e.g. lakes, shallow water) was assessed up to 2 km upstream of each sampling site, mostly by revising satellite imagery (Google Earth Pro 7.3.3.7786 and Google Maps). The width of the river at the sampling site was also considered for analysis (grouping river widths into six categories: 0–3 m, 4–10 m, 11–25 m, 26–50 m, 51–100 m, and > 100 m; following Kiessling et al., 2019) as well as the river system.

For exploratory analyses, two additional variables were collected for the Rhine river system only (as it was the river system with the most datasets): the distance from each sampling site to the stream source of each river was evaluated by importing the river courses from OpenStreetMap (OpenStreetMap contributors, 2019) into QGIS, using the QGIS plugins QuickOSM (Trimaille, 2019) and Topology Checker, and subsequently calculating distances with the R package riverdist 0.15.0 (Tyers, 2017). The total population upstream of sampling sites was summed up based on the same 10,000 m^2 grid for a 1 km wide stretch on both sides of the river, following each upstream tributary to its source (excluding very small streams which we did not map) and using the same four population categories as above.

2.8. Statistical analyses

Statistical analyses were conducted with R 3.4.1 (R Development Core Team, 2017). For the analyses of the macrolitter and meso—/microplastics, models with a zero-altered gamma distribution were built using the gamlss package 5.1–7 (Rigby and Stasinopoulos, 2005). Variables included were the sampling year, width of river at the sampling site, population density at the sampling site, and presence of artificial barriers and natural retention basins. For analysis of the variables “distance of sampling site to source of river” and “total population upstream of sampling site”, data from sampling sites of the Rhine only were considered ($n = 132$) as the collection of these two variables was more time-consuming than for other variables. Each model was built using the stepGAIC procedure within gamlss, stepwise adding the variable that lowers the Akaike information criterion (AIC) of the resulting model most. The AIC evaluates the quality of a model; the lowest AIC among a set of models identifies the best-fitting model. The procedure was repeated until the addition of a variable would not further reduce the AIC of the resulting model. The model with the overall lowest AIC was retained for each analysis. For post-hoc tests the package emmeans 1.5.1.0006 (Lenth, 2020) was used. For correlation analysis of different litter samplings conducted at the same sites, including the data published by Kiessling et al. (2019), the package Kendall 2.2 (McLeod, 2011) was used. The *p*-value was set at 0.05 for all analyses. For data exploration and visualization the packages fitdistrplus 1.1–1 (Delignette-Muller and Dutang, 2015) and ggplot2 3.3.2 (Wickham, 2016) were used.

3. Results

3.1. Floating macrolitter

In total, 533 floating macrolitter items were observed across all 282 sampling sites. Standardized to 1 m of river width, 0 to 8.25 items m^{-1} h^{-1} were found (the maximum number of items m^{-1} h^{-1} was found in the Panke in Berlin, which has a river width of 8 m), with an overall average of 0.34 ± 0.89 litter items m^{-1} h^{-1} for all 282 sampling sites (median of 0.05, interquartile range IQR 0.30). 151 of 282 groups (54%) recorded at least one floating litter item. Of those, most groups observed five or fewer items (129 groups), seven groups observed ten or more items (see Supplement S4 for the results for each sampling site). Regarding composition, only 8% of the floating litter objects ($n = 44$)

could be identified based on photos the participants sent in. Out of these 44 items, 30 consisted of plastic (68%). Further details (e.g. whether items were single-use plastics) could not be identified. There was one documented report of swans (*Cygnus olor*) trying to rip open a floating plastic bag in order to get to the content of the bag (Fig. 3A). At approximately 50% of the sampling sites of each river system floating macrolitter was observed (Table 1, Supplement S5).

The model with the lowest AIC (Supplement S6–1) considered the river system, sampling year, river width, and population density at the sampling sites as significant predictors for observed floating macrolitter quantities (Table 1, Fig. 4). For river systems, although there was a significant difference in macrolitter quantities between the river system Rhine and Weser, this difference was small (both river systems had a median of 0.05 items m^{-1} h^{-1}) and caused by many outliers in the Rhine river system. Regarding the sampling year, in the spring of 2017 significantly more floating macrolitter items m^{-1} h^{-1} were observed compared to the autumn of 2016, although likewise, the difference was small (median of 0.09 and 0.05 litter items m^{-1} h^{-1}, respectively). At sampling sites where the river width was narrow, more floating macrolitter was observed than at sampling sites with wider rivers (median of 0.59 and 0.10 litter items m^{-1} h^{-1}, respectively). Further, more floating macrolitter was observed at more densely populated places around the sampling sites (median of 0.15 litter items m^{-1} h^{-1} for most densely populated places compared to a median of 0 litter items m^{-1} h^{-1}, for least densely populated places; Supplement S6–2). There was one significant interaction in the model among the variables river system and population density (Supplement S6–3). The other variables (the presence of artificial and natural barriers) were not included in the model by the stepwise procedure as predictors for macrolitter densities. The analysis of variables that were collected for the Rhine river system only ("distance to the source of the river" and "total population upstream of the sampling site") did not lower the AIC of the model chosen for the Rhine, meaning that these variables were no significant predictors for the observed macrolitter densities in the Rhine river system.

3.2. Floating meso- and microplastics

A total of 1128 small plastic particles were retrieved from 164 sampling sites (278 mesoplastics, 5 mm to 24.99 mm; 850 microplastics, 1 mm to 4.99 mm). The minimum of particles found per hour was 0, and the maximum number of items h^{-1} was 220 meso—/microplastics (found in the Laucha river in the municipality of Schkopau; as all schools used the same net, the values are reported as meso—/microplastics h^{-1}). On average 6.86 ± 24.11 meso—/microplastics h^{-1} (median of 1, IQR 3) were sampled across all 164 sites. For the 121 datasets for which flow velocity measurements of the rivers were available, participants filtered on average 48 m^3 of water and found an overall average of 0.18 ± 0.61 meso—/microplastics m^{-3} of river surface water with a minimum of 0 and a maximum of 5.46 meso—/microplastics m^{-3} (median of 0.02 meso—/microplastics m^{-3}, IQR 0.11; Supplement S4). The average load of meso—/microplastics ranged from 0 to 0.32 particles m^{-3} of surface river water in the different river systems (Table 2). 93 of 164 analyzed samples (57%) contained small plastic particles (41% contained mesoplastics, 48% contained microplastics). 72 of those samples contained less than 10 meso—/microplastics. 15 samples contained 10 to 50 particles. Six samples contained more than 50 small plastic particles each; together these six samples had a total of 673 meso—/microplastics, i.e. 60% of the small plastic particles found in the present study. These sampling sites were defined as meso—/microplastic hotspots (Table 3, see Supplement S4 for the results for each sampling site). The most contaminated sample alone contained 220 small plastic particles (20% of all meso—/microplastic found in the entire study).

Most meso—/microplastics were soft (42%) and hard fragments (28%; Fig. 3B). Pellets (including hard round or lentil-shaped pellets as well as soft, more rectangular-shaped pellets, Fig. 3C) accounted for 13% of plastic particles. Films (9%) and monofilaments (7%) were less frequent. Regarding polymer type, based on FTIR-analysis most particles were identified as polystyrene (38%), polyethylene (31%), and polypropylene (26%). Other polymers were identified for ~1% or less of all

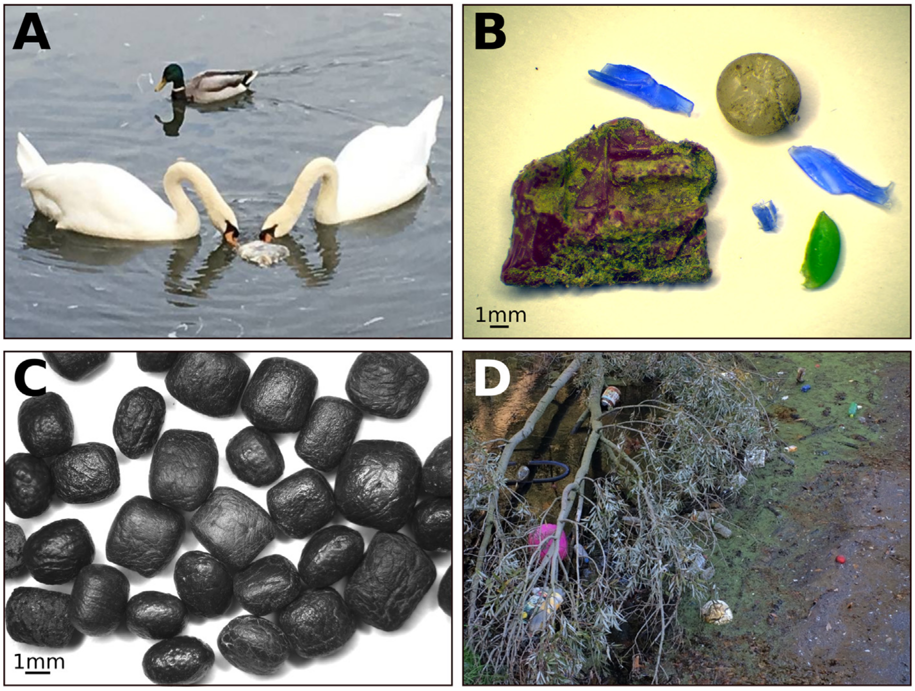

Fig. 3. (A) Swans trying to open a floating plastic bag containing old bread in the Main. © Ernst-Reuter-Schule Frankfurt am Main. (B) Meso—/microplastics found by Realschule Bissingen investigating the Enz (Rhine river system). (C) Some of the polypropylene pellets sampled by Sekundarschule Schkopau originating from the Laucha (Elbe river system). (D) Floating macrolitter temporarily stuck in branches across a tributary river of the Dinkel (Rhine river system). © Werner-von-Siemens Gymnasium Gronau. Photos (B) and (C) by Magdalena Gatta-Rosemary/Kieler Forschungswerkstatt, under Creative Commons license CC BY 4.0.

Table 1

Overview of floating macrolitter and floating meso—/microplastics for each river system as well as for significant variables.

		Percentage of sampling sites with litter findings (number of sampling sites)	Mean ± SD	Median (IQR)
Floating macrolitter m^{-1} h^{-1}				
All sampling sites		54% (282)	0.34 ± 0.89	0.05 (0.30)
River system	Rhine	45% (135)	0.38 ± 0.90	0.05 (0.46)
	Weser	46% (39)	0.15 ± 0.38	0.05 (0.15)
	Elbe	44% (54)	0.38 ± 1.22	0.10 (0.20)
	North Sea, other	50% (6)	0.15 ± 0.18	0.08 (0.24)
	Baltic Sea	59% (17)	0.48 ± 0.88	0 (0.50)
	Danube	48% (31)	0.31 ± 0.69	0.05 (0.21)
Sampling year	Autumn 2016	50% (141)	0.20 ± 0.41	0.04 (0.20)
	Spring 2017	43% (141)	0.48 ± 1.17	0.09 (0.40)
River width at sampling site	0–3 m	47% (34)	1.10 ± 1.69	0.59 (1.33)
	4–10 m	57% (60)	0.47 ± 1.18	0 (0.43)
	11–25 m	44% (57)	0.16 ± 0.23	0.05 (0.21)
	26–50 m	45% (42)	0.15 ± 0.27	0.05 (0.20)
	51–100 m	45% (33)	0.20 ± 0.58	0.05 (0.16)
	> 100 m	39% (56)	0.15 ± 0.20	0.10 (0.20)
Population density around sampling site	< 5,000	51% (159)	0.28 ± 0.80	0 (0.23)
	5,000–20,000	41% (111)	0.40 ± 0.99	0.10 (0.40)
	20,001–100,000	33% (12)	0.61 ± 1.07	0.15 (0.49)
Floating meso—/microplastics h^{-1}				
All sampling sites		57% (164)	6.86 ± 24.11	1.00 (3.00)
River system	Rhine	68% (74)	5.11 ± 10.85	1.00 (4.75)
	Weser	58% (26)	8.59 ± 26.82	0.99 (2.00)
	Elbe	44% (32)	10.56 ± 38.79	0 (7.00)
	North Sea, other	75% (4)	4.00 ± 6.06	1.50 (4.00)
	Baltic Sea	25% (8)	0.49 ± 1.07	0 (0.23)
	Danube	45% (20)	8.30 ± 32.68	0 (2.00)
River width at sampling site	0 – 3 m	48% (21)	12.00 ± 47.74	0 (2.00)
	4–10 m	69% (36)	9.94 ± 23.38	1.00 (6.75)
	11–25 m	49% (37)	1.97 ± 3.59	0 (2.00)
	26–50 m	57% (23)	4.48 ± 12.78	1.00 (3.00)
	51–100 m	57% (14)	1.70 ± 2.42	1.00 (2.58)
	> 100 m	58% (33)	9.56 ± 27.04	1.00 (8.00)
Population density around sampling site	< 5,000	61% (92)	8.56 ± 28.60	1.00 (6.00)
	5,000–20,000	51% (65)	3.87 ± 16.00	0.80 (2.00)
	20,001–100,000	57% (7)	12.29 ± 22.10	3.00 (11.50)
Upstream artificial barrier	No	56% (102)	6.34 ± 22.98	1.00 (6.00)
	Yes	58% (62)	7.69 ± 26.03	1.00 (2.00)

particles. Regarding color, most particles were white (52%), followed by dark (black and brown, 21%), and transparent particles (10%). Other colors were found less frequently, most of those were red (5%), blue (4%), green (4%), or grey (4%). Very few particles were yellow or had several colors (Supplement S7). Meso—/microplastics occurred in samples from all river systems, the proportion of samples with meso—/microplastics ranged from 25% (rivers flowing into the Baltic Sea) to 75% (other rivers flowing into the North Sea), with the other river systems being located in between (Table 1, Supplement S5).

The model with the lowest AIC (Supplement S6–1) considered five variables: the river system, river width, population density at the sampling sites as well as upstream artificial barriers and natural retention basins as predictors for floating meso—/microplastic quantities, of which the former four were included as significant predictors (the variable natural retention basins lowered the overall AIC of the model but was not a significant predictor in itself; Table 1, Fig. 5). For river systems, the Elbe river system contained on average most meso—/microplastics, followed by the Rhine river system and rivers flowing into the Baltic Sea; other river systems are located in between (median values however are situated between 0 and 1.50 meso—/microplastics h^{-1}). Sampling sites with <5,000 inhabitants had significantly more meso—/microplastics (median of 1.00 meso—/microplastics h^{-1}) than sites with 5,000–20,000 inhabitants (median of 0.80 meso—/microplastics h^{-1}), but not if compared to the most populous category (20,001–100,000 inhabitants, median of 3.00 meso—/microplastics h^{-1}). Further, there was a very small but significant difference between sampling sites with and without an upstream artificial barrier (the median for both categories was the same at 1.00 meso—/microplastics h^{-1}; Supplement S6–2). Two significant interactions were present in the model between the variables river width and river system, and between the variables river width and the presence of artificial barriers (Supplement S6–3). The variable sampling year was not included as a significant predictor in the model by the stepwise procedure. The stepwise procedure for the model constructed for the Rhine river system included the total population upstream of the sampling site within the model. The variable itself was not significant but it lowered the AIC of the chosen model.

3.3. Relationship between floating litter and litter at riversides

To investigate the relationship between different litter samplings, data for floating macrolitter, floating meso—/microplastics, litter at the riverside, and litter accumulations at the riverside were considered (the data from the latter two samplings originating from Kiessling et al., 2019). Correlation coefficients were very low for all comparisons (Kendall's tau <0.15), albeit significant between floating macrolitter m^{-1} h^{-1} and floating meso—/microplastics h^{-1}, and between floating macrolitter m^{-1} h^{-1} and litter quantities at the riverside m^{-2}. For the other comparisons no significant correlation was found (Supplement S6–4).

4. Discussion

4.1. Citizen science approach

Many studies investigating environmental litter pollution have been based on data contributed by citizen scientists (e.g. Hidalgo-Ruz and

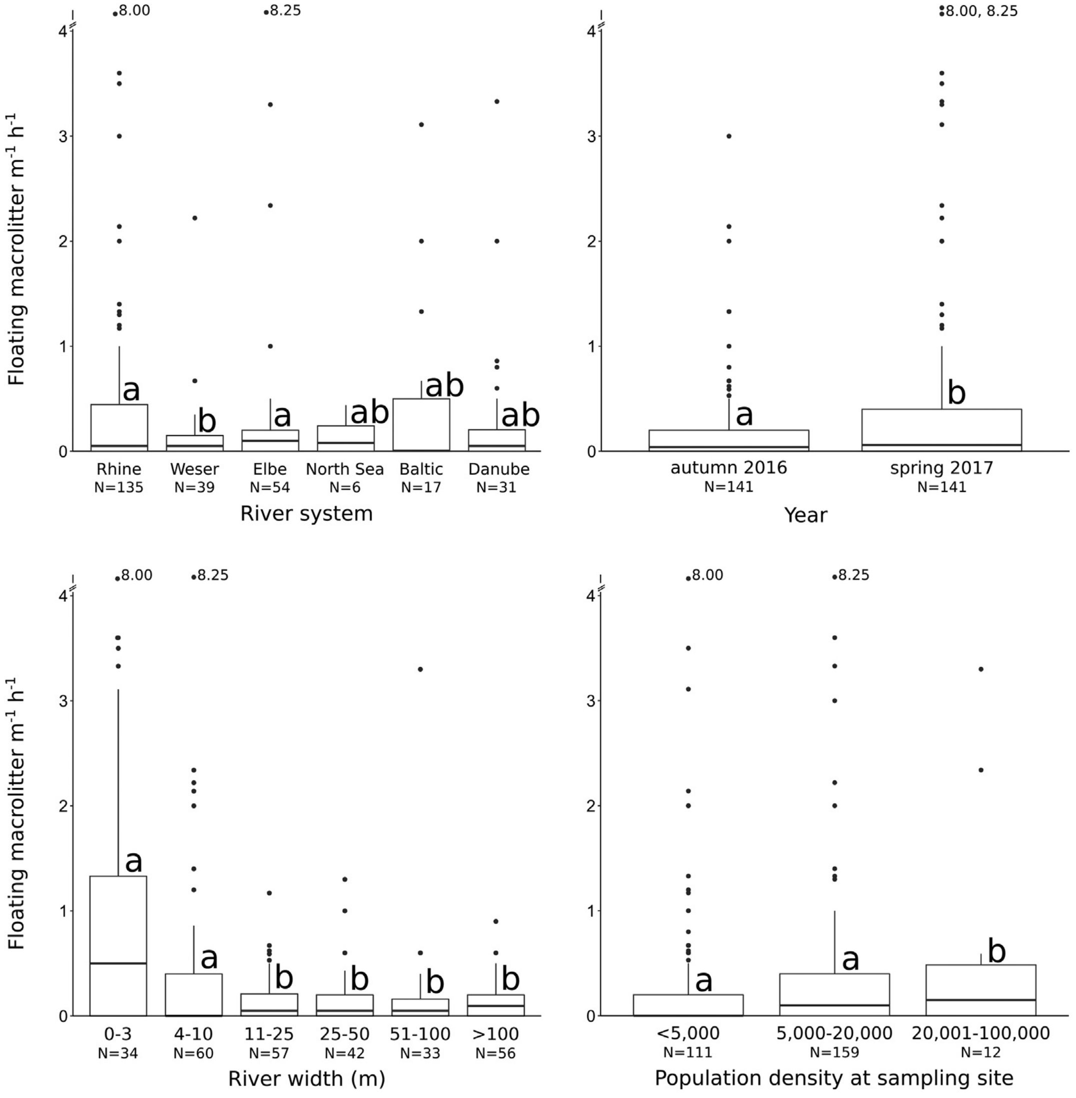

Fig. 4. Boxplot representing floating macrolitter densities for the variables that were selected by the model as significant predictors of litter quantities. The horizontal lines, from bottom to top of each box represent the first quartile, the median, and the third quartile respectively. The vertical line represents the interquartile range * 1.5. Dots represent outliers, while the values of extreme outliers are marked at the top of each chart. Letters mark significant differences. N = Number of datasets in each category.

Thiel, 2013; Rech et al., 2015; Barrows et al., 2018; Forrest et al., 2019), with the obvious advantage of obtaining observations and samples from many locations over a large spatial area, in addition to contributing to the participant's understanding of science (e.g. Kruse et al., 2020). If sampling strategies are adapted to the citizen science approach and data verification criteria are in place (Hidalgo-Ruz and Thiel, 2015), the quality of citizen science data can match that of data by “professional scientists” (Zettler et al., 2017).

Table 2
Estimation of meso−/microplastics m^{-3} of river surface water for the different river systems. Smaller rivers flowing into the North Sea and Baltic Sea were grouped. Included are only sampling sites for which a measurement of flow velocity was available (see text for details).

River system	Number of sampling sites	Mean ± SD	Median (IQR)
All sampling sites	121	0.18 ± 0.61	0.02 (0.11)
Rhine	60	0.15 ± 0.28	0.03 (0.12)
Weser	17	0.27 ± 0.83	0.03 (0.05)
Elbe	23	0.32 ± 1.13	0 (0.12)
North Sea, other	4	0.15 ± 0.25	0.04 (0.16)
Baltic Sea	5	0	0 (0)
Danube	12	0.03 ± 0.06	0 (0.04)

Missing information (e.g. unspecified sampling area, missing photos, missing replicates of samples) are a limitation in many citizen science studies (e.g. Hoellein et al., 2017; Nelms et al., 2017; Forrest et al., 2019; Kiessling et al., 2019) and likewise, our validation analysis confirmed that data from groups had to be excluded mainly because of missing information or samples, rather than because of methodological errors. In the present study, approximately half of groups that conducted the microplastic sampling could not be considered because of missing samples or missing information about the sampling. This could partly be mitigated by closer communication with the participants (which is the approach used by the *Científicos de la Basura* in Chile, Eastman et al., 2014), emphasizing the importance of the storage, labeling, and packaging of the samples. To avoid the loss of other information, a smartphone app could be useful, collecting data and files (Andrachuk et al., 2019). In order to allow for easy participation, citizen science protocols should be simple and eliminate barriers to participation (Hidalgo-Ruz and Thiel, 2015; Zettler et al., 2017; Forrest et al., 2019). In the present study, we had, for example, no pre-assigned sampling locations, anticipating that logistical constraints would limit the number of participating groups, with the caveat of not being able to formulate research questions related to site-specific criteria (see Nelms et al., 2017 and Forrest et al., 2019 for critical discussions). However,

Table 3
List of meso−/microplastic hotspots, i.e. sampling sites where more than 50 particles were found h^{-1}. The description of the sampling site is based on OpenStreetMap (OpenStreetMap contributors, 2019) and satellite imagery from Google Earth Pro 7.31.4507.

Place and year of sampling	River (river system)	Total plastic particles in sample (mesoplastics/microplastics)	Description of sample (number of particles)	Description of river and surroundings of sampling site
Schkopau 2016	Laucha (Elbe)	220 (29 / 191)	Soft, black polypropylene pellets (125; Fig. 3C); mainly spherical, often weathered polystyrene particles (95)	Small river (~ 3 m wide), sampling site within 500 m downstream of a chemical industry production site (size of industrial area ~ 4 km^2).
Wasserburg 2017	Inn (Danube)	147 (15 / 132)	Weathered, often flat polystyrene particles (119); mainly white polyethylene and polypropylene fragments (28)	Bridge at ~ 100 m wide river Inn. Residential area. Sampling site before a meander of the river, approximately 1 km downstream of hydroelectric power station with dam and subsequent shallow river section.
Bielefeld 2017	Lutter (Weser)	126 (21 / 105)	Very weathered, often flat polystyrene particles (68); hard polyethylene and polypropylene fragments, some elongated (53); hard polyethylene pellets (4); other particle	Small river (few meters wide) within the city of Bielefeld. River is artificially guided, also through underground pipes. Several small water reservoirs with dams upstream. Residential areas and garden plots at sampling site.
Hildesheim 2016	Innerste (Weser)	62 (14 / 48)	Mainly weathered, often flat polystyrene particles (34); hard polyethylene fragments of different shapes and colors (20); other particles	Bridge at ~ 20 m wide river Innerste. At city boundaries of Hildesheim, at the height of a wastewater treatment plant.
Heidelberg 2016	Neckar (Rhine)	60 (33 / 27)	Hard polyethylene and polypropylene fragments of different shapes and various colors (36); weathered polystyrene particles (24)	> 100 m wide section of the river Neckar. Residential area and park surround sampling site.
Aalen 2017	Kocher (Rhine)	58 (13 / 45)	Mainly transparent polyethylene and polypropylene film fragments or bendable, soft particles (42); other particles	Small river (~ 10 m wide), sampled right at small weir. Open farm and woodland nearby, few houses.

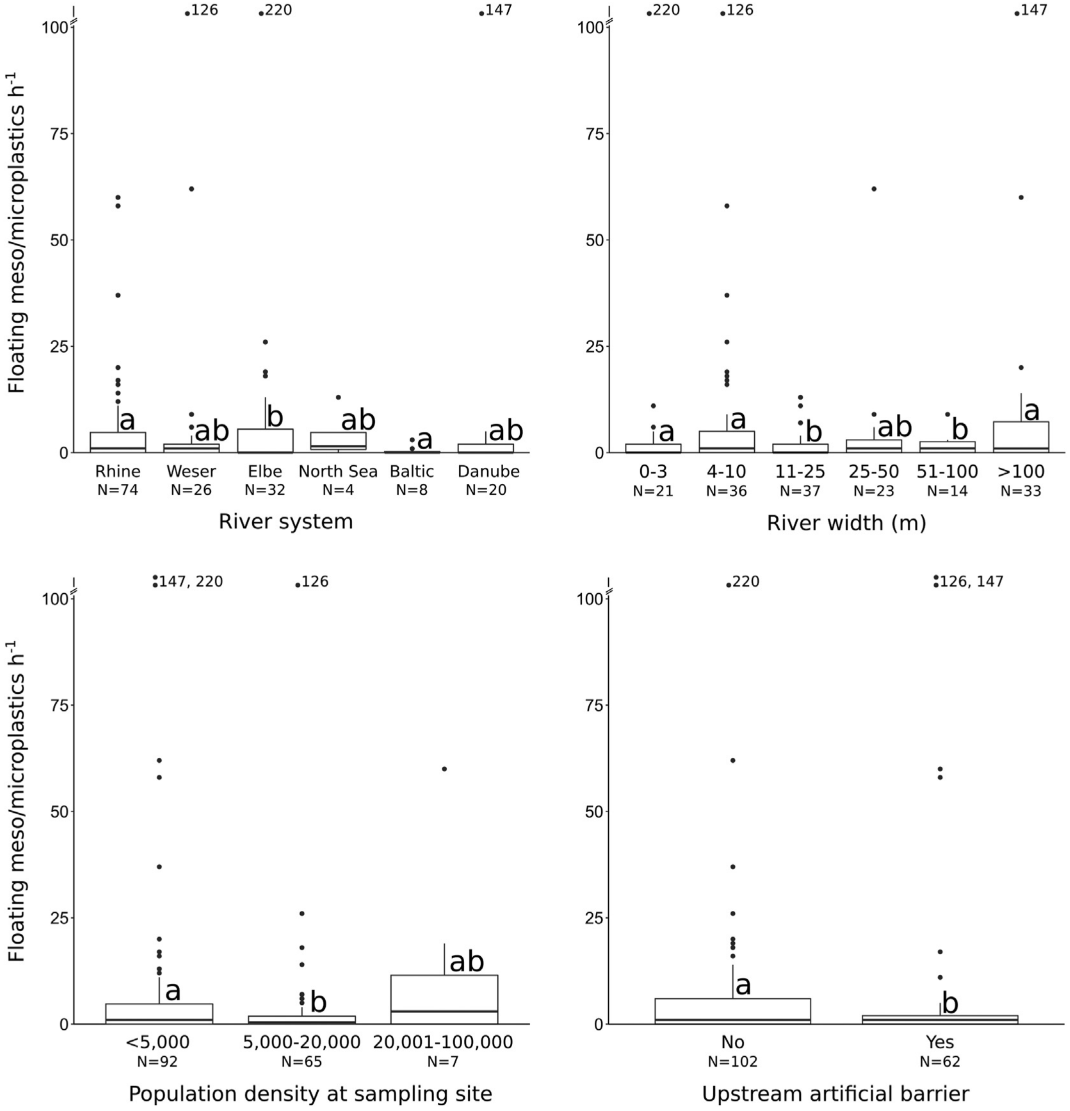

Fig. 5. Boxplots representing floating meso−/microplastic densities for the variables that were selected by the model as significant predictors of litter quantities. The horizontal lines, from bottom to top of each box represent the first quartile, the median, and the third quartile respectively. The vertical line represents the interquartile range * 1.5. Dots represent outliers, while the values of extreme outliers are marked at the top of each chart. Letters mark significant differences. N = Number of datasets in each category.

in our study this approach has led to (i) the important finding that large concentrations of meso−/microplastics can occur in small streams (which are usually not in the focus of riparian litter studies), and (ii) the identification of several pollution hotspots.

Regarding the samplings, the quantification of floating macrolitter was no problem for most participants as the self-evaluation showed. However, some groups were excluded because they had simply marked the presence or absence of macrolitter instead of counting it. One shortcoming in the present study was that at larger rivers good vantage points, i.e. bridges, were not always available to participants. Bridges have been used in most river litter observation studies (e.g. Castro-Jiménez et al., 2019; Schirinzi et al., 2020; van Emmerik et al., 2020a, b; Vriend et al., 2020), and are also recommended as observation points in the protocol presented by González-Fernández and Hanke (2017). Even though we assumed that the schoolchildren could survey a maximum distance of 20 m and not the entire river width (as had also been done by Schöneich-Argent et al., 2020 for vantage points other than bridges), results indicate that floating macrolitter quantities in larger rivers might have been underestimated (also see discussion below).

Meso−/microplastic numbers submitted by the participants rarely matched the actual quantity of particles within the sample (after FTIR-analysis, Supplement S3–2), and therefore a recount by "professional scientists" was necessary for all samples. The schoolchildren had usually spent a short amount of time analyzing the samples (often without adequate visual aids, i.e. dissecting microscopes), and teachers had to prepare the entire class for the sampling of litter (as the meso−/microplastic sampling was only part of a larger litter sampling). In the project by Hidalgo-Ruz and Thiel (2013), focusing entirely on small plastics, participants were generally able to quantify plastic particles. Many citizen science projects investigating microplastics extract, analyze and identify microplastics in professional research laboratories, not involving the citizen scientists in these steps (e.g. Ogata et al., 2009; Barrows et al., 2018; Forrest et al., 2019). Our motivation was to foster the understanding of microplastic pollution of the participants and therefore we asked them to analyze the sample (see Supplement S1).

Finally, the measurement of flow velocity by the participants proved to be so variable that we only used it for an approximation of the filtered water volume and subsequently an estimation of the total litter load of rivers, but not for statistical analysis. Furthermore, flow velocities in rivers naturally vary by a large degree over time (Poff et al., 1997) as well as over distances of a few dozen meters (Stockdale et al., 2008), and thus sampling of small particles and measurements of flow velocities should ideally be done at exactly the same place. A reliable estimate of the volume filtered could have possibly been obtained by attaching a flowmeter to the net, although the large quantity of organic material transported in some rivers would likely have obstructed the flowmeter (and equipping many nets would be prohibitively costly for citizen science projects).

4.2. Floating macrolitter in rivers in Germany

The average macrolitter quantities observed in the present study are comparable to those from other studies visually investigating floating macrolitter in European rivers (macrolitter findings of about 0.02–0.8 m^{-1} h^{-1}, Castro-Jiménez et al., 2019; van Emmerik et al., 2019a; Vriend et al., 2020). Higher values in the present study also reflect higher values found in other studies from Europe (5.7 and 7.9 macrolitter items m^{-1} h^{-1}, Crosti et al., 2018; van Emmerik et al., 2019a, respectively), but these macrolitter quantities are much lower than those observed in rivers in Malaysia and the Philippines (van Emmerik et al., 2020a, b). We saw an increase in the amounts of floating macrolitter with population density, and the two most polluted sites (with 8.25 and 8.00 macrolitter items m^{-1} h^{-1}, respectively) are both located in green spaces within urban areas, potentially indicating littering by recreational visitors (McCormick and Hoellein, 2016; Kiessling et al., 2019). Several studies investigating floating macrolitter in rivers consider populated areas with increased urban activity (e.g. commercial sites, parking lots) as important predictors of litter quantities as well (Gasperi et al., 2014; Castro-Jiménez et al., 2019; van Emmerik et al., 2019a; Tasseron et al., 2020). Another interesting aspect are macrolitter accumulation sites. In the present study, several participants mentioned litter stuck at tree branches or weirs (Fig. 3D), but this has not been quantified, as the focus was on moving litter within rivers (also see Tramoy et al., 2019 and Tasseron et al., 2020, for macrolitter accumulation sites; and Williams and Simmons, 1999, reporting macrolitter stuck in tree branches as a result of sewage overflow).

Surprisingly, there was no increase in the macrolitter concentration m^{-1} h^{-1} with the size of the rivers in the present study. We had anticipated that larger rivers attract more recreational visitors, which are an important source of litter (McCormick and Hoellein, 2016; Carpenter and Wolverton, 2017; Kiessling et al., 2019). Instead, more floating macrolitter was found in smaller (i.e. narrow) rivers. A possible explanation is observation bias: while small rivers can be surveyed across their entire width, larger rivers require a good vantage point, such as a bridge, and often are only studied across a part of their width. Further, macrolitter in rivers is not uniformly distributed across the river surface but dependent on weather conditions, characteristics of the river or ship traffic (van Emmerik et al., 2019b, 2020a) and sections surveyed by the schoolchildren might have carried less litter, meaning that the overall quantity of floating litter in larger rivers is more difficult to assess with the employed method. Considering the sampling year, the trend toward more observed macrolitter in the year 2017, compared to 2016, remains inconclusive as observations did not come from the same sampling sites in both years (similarly, for litter at riversides we found significant but very small differences between the same years, Kiessling et al., 2019).

Regarding interactions between variables, for the macrolitter model more litter was found at the Elbe in combination with higher population densities. This is likely the result of high population densities in Hamburg, possibly in combination with harbor infrastructure and urban beaches located right within the city limits (also see Ross et al., 1991 who found recreational litter in Halifax Harbour).

4.3. Floating meso- and microplastics in rivers in Germany

The average quantity of meso−/microplastics found in the present study (0.18 particles m^{-3}) is of the same order of magnitude as the quantity found in some studies investigating rivers in Europe (Lechner et al., 2014; Sadri and Thompson, 2014) with 0.32 and 0.03 particles m^{-3}, respectively, but much lower compared to other studies. For example, Schmidt et al. (2018) found an exceptionally high median load of 7860 particles m^{-3} in the Teltow Canal (Berlin, Germany), and Wagner et al. (2019) found averages of 66 to 77 particles m^{-3} in the Parthe river (Leipzig, Germany). Even at sites considered as pollution hotspots in the present study, maximum particle loads only reached 5.46 particles m^{-3}. In general, studies investigating microplastics are difficult to compare given that they use different sampling methods, investigate different compartments of the river, and consider different particle sizes. Even other citizen science studies addressing microplastics differ from the approach employed in the present study: Barrows et al. (2018) and Forrest et al. (2019) asked citizen scientists to sample river surface water with a container and then analyzed the samples in the laboratory (with no analysis conducted by the citizen scientists themselves). Both studies considered microfibers (representing the majority of microplastics) and size ranges as small as 100 μm in the case of Barrows et al. (2018). Importantly, the present study considered only particles larger than 1 mm in size and excluded microfibers. As the vast majority of microplastics in German rivers are smaller than 1 mm (Mani et al., 2015; Schmidt et al., 2018; Wagner et al., 2019), it can be expected that much of the actual microplastic pollution remained hidden in the present study. Therefore pollution with small plastic particles could well be a widespread problem in rivers in Germany affecting large and small rivers alike. This also illustrates the value of citizen science studies, not necessarily investigating very small microplastics at specific sampling sites but allowing an overview of microplastic pollution over a large geographic area.

The above-mentioned pollution hotspots accounted for most differences and interactions in the model. For example, higher average meso—/microplastic quantities have, in addition to populous areas, also been found at less populated sites, suggesting that smaller plastic particles accumulate at different sites than floating macrolitter (which was more abundant at high population densities – see above). Potential sources of these meso—/microplastics are wastewater treatment plants and plastic-producing industry, but while these are linked to populous areas they are usually not located in residential areas. Regarding the latter, the most contaminated sample was retrieved in Schkopau, just downstream of a major plastic production site belonging to a multinational chemical corporation. Given the proximity and the large number of more than 100 identical primary polypropylene pellets in the sample (in addition to many weathered polystyrene particles), the production plant seems the most likely source. The pellets could originate from spills during transport and/or storage, as had been observed by Karlsson et al. (2018) for an industry site in Sweden. The plastic industry has been frequently discussed as a potential major source of plastic pollution (e.g. for rivers in Europe by Lechner et al., 2014; Klein et al., 2015; Mani et al., 2015; Tramoy et al., 2019). Tracing plastic particles back to the point of leakage is challenging, but Lechner and Ramler (2015) and Karlsson et al. (2018) identified plastic producers as direct sources of pellets in Austria and Sweden, respectively.

The large amount of meso—/microplastics at two further hotspots could be influenced by the presence of weirs: the sample retrieved in Wasserburg was taken just downstream of a dam, and the sample from Aalen was taken directly at a small weir, i.e. at a choke point within the river flow. Dams act as barriers for macrolitter and can also accumulate microplastics either by directly retaining floating items as well as by reducing flow velocity (Zhang et al., 2015; Watkins et al., 2019; Zhang et al., 2019). This is also emphasized by the composition of the samples: both consist of mainly secondary, weathered microplastics, accumulating at choke points. Watkins et al. (2019) also found an increase in microplastic concentration at some downstream sampling sites compared to the dam reservoir sampling site; a similar effect could have occurred at the weirs in the present study. Another hotspot with mostly secondary microplastics was located close to a wastewater treatment plant but it is uncertain whether many particles could have originated from it. Wastewater treatment plants are known to emit large quantities of plastic particles to rivers but usually retain most particles >1 mm (e.g. Dris et al., 2015; Magni et al., 2019). For the other two hotspots, no potential source could be identified in the vicinity: they are located in mostly residential areas.

The large number of mostly weathered, expanded polystyrene particles found in the present study could result from the packaging and construction sector. Especially the latter, using expanded polystyrene for thermal insulation of buildings, could be a relevant source: the construction sector produced ~43,000 tons of expanded polystyrene waste in 2016/2017 in Germany, of which only 10% were recycled (see review by Lassen et al., 2019). The loss of expanded polystyrene due to cutting insulation sheets as well as the deconstruction of insulated buildings would amount to substantial pollution of the environment around construction sites and subsequently of drainage and river systems.

4.4. Using a large-scale collaborative approach to investigate plastic pollution in rivers

Even though there was a relationship between the quantities of floating macrolitter and floating meso—/microplastics as well as between floating macrolitter and the litter located at riversides the effect was very small. This suggests that litter in the riparian environment is influenced by a wide range of spatiotemporal factors and their interactions. This is supported by other studies investigating litter quantities in different environmental compartments (e.g. Hoellein et al., 2017; McCormick and Hoellein, 2016; Blettler et al., 2017; Blettler et al., 2019; Schöneich-Argent et al., 2020). One example of a complex interaction is that rain, floods and storms affect the quantities, distribution and composition of microplastics in rivers: on the one hand microplastics are flushed from land to the river, on the other hand the concentration of microplastics in the river is diluted due to water influx (Barrows et al., 2018; Hurley et al., 2018). The distribution, transport, and fate of plastic litter in rivers is therefore very dynamic and complex, and litter does not only move linearly, i.e. directly from the source to sea (see for example the “plastic cycle” conceptual model by Horton and Dixon, 2018, and also Tramoy et al., 2020; Hoellein and Rochman, 2021). This is also emphasized in the present study by the absence of an increased particle load with the distance from the stream source of rivers. Similarly, the vertical and horizontal distribution of litter within rivers varies substantially, as has been shown, for example, by van Emmerik et al. (2019a, 2020a) for the distribution of macrolitter within a river section and Lenaker et al. (2019) and Scherer et al. (2020) for the distribution of microplastics in the water column and sediments in rivers.

Due to this complexity, it is imperative to investigate a variety of environments at different times and conditions to effectively monitor environmental pollution by plastic litter. So far, most river litter studies addressing microplastics have investigated few sampling sites – also studies addressing larger river sections or river systems have collected at best a couple of dozen samples (understandably so, given logistical constraints; e.g. Mani et al., 2015; Su et al., 2020). Even models aiming at estimating the input of river litter across large geographical areas, sometimes the entire globe, are based on relatively few data points (Lebreton et al., 2017; Schmidt et al., 2017).

Studies conducted in collaboration with members of the general public (citizen scientists) on the other hand, while requiring more simplistic sampling protocols, have been able to collect many microplastic samples over large geographic areas: Barrows et al. (2018) and Forrest et al. (2019) studied dozens of samples from large sections of a watershed and the project International Pellet Watch received hundreds of plastic pellet samples from over 50 countries (http://www.pelletwatch.org/; Ogata et al., 2009). For macrolitter, citizen science datasets are similarly expansive, especially regarding beach litter (e.g. Nelms et al., 2017; Zettler et al., 2017; Thiel et al., 2018). This way the citizen science approach could be an ideal method to effectively diagnose plastic pollution at hundreds of sampling sites at different times of the year or discharge/weather conditions, and could furthermore help increase the scientific literacy and environmental awareness of participants (Zettler et al., 2017; Kruse et al., 2020).

5. Conclusions and outlook

The present study showed that a considerable amount of floating plastics, large and small, contaminate rivers in Germany. Especially small plastics seem to be ubiquitous, given that approximately half of the samples contained microplastics and that only the larger fraction of microplastics (> 1 mm) was investigated. The majority of microplastics found in the present study derive from a small number of samples, indicating microplastic hotspots. The distribution and composition of meso—/microplastics suggested the plastic-producing and the plastic-processing industry as an important source. Mitigation measures should, as a first step, focus on these microplastic hotspots to significantly reduce the number of particles in rivers and be adapted to each hotspot. Requiring plastic producers to hermetically transport and store plastic and demanding from the construction sector to abstain from the use of easily-fragmented polystyrene insulation could substantially reduce the pollution with small plastics.

The citizen science approach employed in the present study proved especially valuable, as it allowed to collect data on river litter pollution nationwide and identify pollution hotspots. A potential extension of the citizen science approach to include taking samples of particles <1 mm (that would exclusively be analyzed in the laboratory) would close a current observation gap in a particle range that has been shown to be relevant in other studies. Another interesting variation would be to permit a continuous monitoring (e.g. by consecutive cohorts of schoolchildren, sampling at different seasons or discharge/weather conditions) in order to gain insight into the temporal dynamics of riverine plastic pollution. Finally, the inclusion of one or more additional nearby sampling sites at the same river would enable to study small-scale spatial heterogeneity.

CRediT authorship contribution statement

Tim Kiessling: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Katrin Knickmeier:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Katrin Kruse:** Conceptualization, Project administration. **Magdalena Gatta-Rosemary:** Data curation, Investigation, Methodology, Validation, Writing – review & editing. **Alice Nauendorf:** Data curation, Investigation, Methodology, Validation. **Dennis Brennecke:** Conceptualization, Project administration, Writing – review & editing. **Laura Thiel:** Methodology. **Antje Wichels:** Methodology, Resources, Writing – review & editing. **Ilka Parchmann:** Supervision, Writing – review & editing. **Arne Körtzinger:** Supervision, Writing – review & editing. **Martin Thiel:** Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

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

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