Science of the Total Environment

Citizen scientists discover hotspots of meso- and microplastics – schoolchildren in Germany investigate floating litter in rivers

--Manuscript Draft--

Manuscript Number:	
Article Type:	Research Paper
Keywords:	plastic litter; floating macrolitter; Microplastics; rivers; citizen science; plastic pollution
Corresponding Author:	Tim Kiessling Leibniz Institute for Science and Mathematics Education GERMANY
First Author:	Tim Kiessling
Order of Authors:	Tim Kiessling
	Katrin Knickmeier
	Katrin Kruse
	Magdalena Gatta-Rosemary
	Alice Nauendorf
	Dennis Brennecke
	Laura Thiel
	Antje Wichels
	Ilka Parchmann
	Arne Körtzinger
	Martin Thiel
Abstract:	Rivers are an important transport route of anthropogenic litter from inland sources toward the sea. A citizen science approach was used to evaluate the litter pollution of rivers in Germany: schoolchildren within the project “Plastic Pirates” observed floating macrolitter at 282 sites and took meso-/microplastic samples (i.e. particles 1 mm - 25 mm) at over 164 sites across the entire country during the years 2016 and 2017. 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}) and floating macrolitter was sighted at 54% of sampling sites. The quantities of floating meso-/microplastics ranged from 0 to 220 particles h^{-1} (average of 6.86 ± 24.11 meso-/microplastics h^{-1}). They were present at 57% of the sampling sites. Given that only particles > 1 mm were sampled and analyzed, the pollution of rivers in Germany by microplastics is likely a ubiquitous 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. 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, adapted to the respective source, and thereby prevent the release of 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.
Suggested Reviewers:	Francois Galgani Francois.Galgani@ifremer.fr
	Aaron Lechner aaron.lechner@univie.ac.at
	Abigail Barrows abarrows@coa.edu

	Rosanna Isabel Schöneich-Argent rosanna.schoeneich-argent@uni-oldenburg.de
	Christian Schmidt christian.schmidt@ufz.de
Opposed Reviewers:	

kieler forschungs:werkstatt

Tim Kiessling
Kieler Forschungswerkstatt
Am Botanischen Garten 16i
24118 Kiel
0049 (0) 431 880 5913
kiessling@leibniz-ipn.de

Cover letter

Dear Editor,

many recent studies and models have shown that rivers are an important transport route of plastic litter to the sea. Most of these studies investigated few sampling sites. The strength of our study is the inclusion of citizen scientists (in this case schoolchildren, their teachers and other youth groups) to investigate rivers across entire Germany and cover sites that have previously been underrepresented, for example small rivers in less-densely populated areas. This way, over 250 sampling sites have been considered for the evaluation of the quantity of floating macrolitter and over 150 sites have been sampled for meso- and microplastics. The results show that few sampling sites contribute substantially to the plastic pollution of rivers in Germany, e.g. in the case of meso- and microplastics, six sampling sites account for 60% of all meso- and microplastics found in the entire study. We further evaluate the relevance of potential sources, namely plastic producing industry, wastewater treatment plants and populous areas.

We hope that you and the reviewers will find this manuscript worthy of publication in your journal. In case of any questions, please, do not hesitate to contact me any time. We are looking forward to hearing from you in due time.

Sincerely, Tim Kiessling, on behalf of all coauthors

Kiel Science Factory, Leibniz Institute for Science and Mathematics Education and Kiel University

Email: kiessling@leibniz-ipn.de

Citizen scientists discover hotspots of meso- and microplastics – schoolchildren in Germany investigate floating litter in rivers

Tim Kiessling[1,2], Katrin Knickmeier[1], Katrin Kruse[1], Magdalena Gatta-Rosemary[1], Alice Nauendorf[1], Dennis Brennecke[1], Laura Thiel[3], Antje Wichels[3], Ilka Parchmann[1], Arne Körtzinger[4,5], Martin Thiel[2,6,7]

[1]Kiel Science Factory, Leibniz Institute for Science and Mathematics Education (IPN) and Christian Albrecht University of Kiel, Kiel, Germany

[2]Facultad de Ciencias del Mar, Universidad Católica del Norte, Coquimbo, Chile

[3]OPENSEA, Alfred-Wegener-Institute Helmholtz-Centre for Polar and Marine Research, Biologische Anstalt Helgoland, Germany

[4]GEOMAR Helmholtz-Zentrum für Ozeanforschung, Kiel, Germany

[5]Christian Albrecht University of Kiel, Kiel, Germany

[6]Millennium Nucleus Ecology and Sustainable Management of Oceanic Islands (ESMOI), Coquimbo, Chile

[7]Centro de Estudios Avanzados en Zonas Áridas (CEAZA), Coquimbo, Chile

Corresponding author:

Tim Kiessling

Am Botanischen Garten 16i

24118 Kiel

Germany

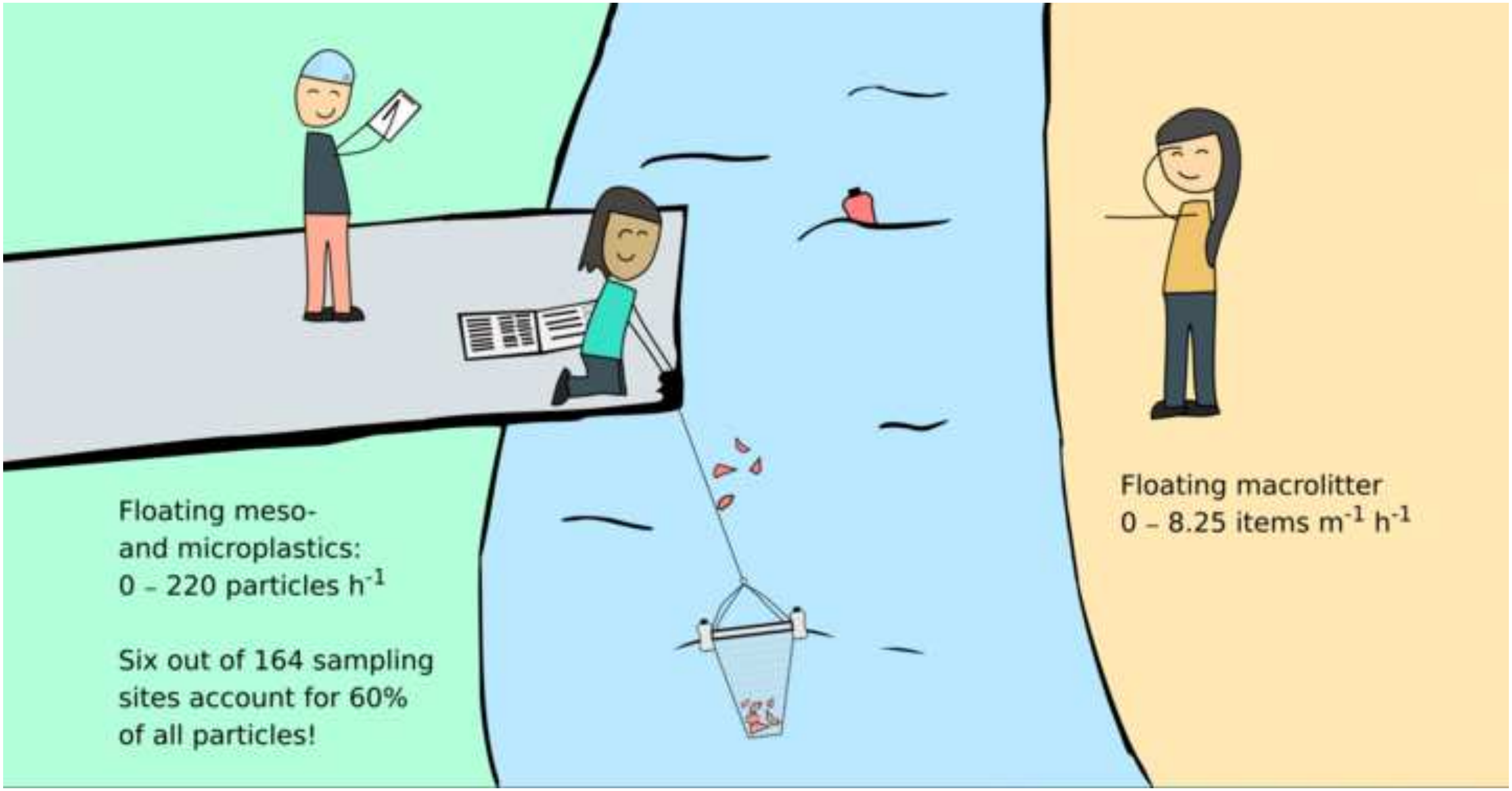
+49 (0) 431 880 5913

kiessling@leibniz-ipn.de

ORCID 0000-0003-2830-9926

Running title: Floating litter in German rivers

Graphical Abstract



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

Citizen scientists discover hotspots of meso- and microplastics – schoolchildren in Germany investigate floating litter in rivers

Tim Kiessling[1,2], Katrin Knickmeier[1], Katrin Kruse[1], Magdalena Gatta-Rosemary[1], Alice Nauendorf[1], Dennis Brennecke[1], Laura Thiel[3], Antje Wichels[3], Ilka Parchmann[1], Arne Körtzinger[4,5], Martin Thiel[2,6,7]

[1]Kiel Science Factory, Leibniz Institute for Science and Mathematics Education (IPN) and Christian Albrecht University of Kiel, Kiel, Germany

[2]Facultad de Ciencias del Mar, Universidad Católica del Norte, Coquimbo, Chile

[3]OPENSEA, Alfred-Wegener-Institute Helmholtz-Centre for Polar and Marine Research, Biologische Anstalt Helgoland, Germany

[4]GEOMAR Helmholtz-Zentrum für Ozeanforschung, Kiel, Germany

[5]Christian Albrecht University of Kiel, Kiel, Germany

[6]Millennium Nucleus Ecology and Sustainable Management of Oceanic Islands (ESMOI), Coquimbo, Chile

[7]Centro de Estudios Avanzados en Zonas Áridas (CEAZA), Coquimbo, Chile

Corresponding author: kiessling@leibniz-ipn.de, ORCID 0000-0003-2830-9926

Running title: Floating litter in German rivers

Abstract

Rivers are an important transport route of anthropogenic litter from inland sources toward the sea. A citizen science approach was used to evaluate the litter pollution of rivers in Germany: schoolchildren within the project “Plastic Pirates” observed floating macrolitter at 282 sites and took meso-/microplastic samples (i.e. particles 1 mm - 25 mm) at over 164 sites across the entire country during the years 2016 and 2017. 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}) and floating macrolitter was sighted at 54% of sampling sites. The quantities of floating meso-/microplastics ranged from 0 to 220 particles h^{-1} (average of 6.86 ± 24.11 meso-/microplastics h^{-1}). They were present at 57% of the sampling sites. Given that only particles > 1 mm were sampled and analyzed, the pollution of rivers in Germany by microplastics is likely a ubiquitous 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. 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, adapted to the respective source, and thereby prevent the release of 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.

Keywords: plastic litter; floating macrolitter; microplastics; rivers; citizen science

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

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, also 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 by riparian birds for nest building (Blettler et al., 2020). Further, litter at and in rivers presents a hazard to human health (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 (Franz and Freitas, 2011; Michiani and Asano, 2019), outlets of wastewater treatment plants or sewage overflow (Williams and Simmons, 1999; Di and Wang, 2018; Magni et al., 2019), plastic-producing or plastic-processing industry (Lechner et al., 2014; Lechner and Ramler, 2015; Klein et al., 2015; Tramoy et al., 2019), or illegal deposition of litter (Rech et al., 2015; McCormick and Hoellein 2016). 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., 2019; Wagner et al., 2019; Grbić et al., 2020).

In general, it can be expected that the litter load in rivers increases from the source to the mouth of rivers as it passes potential pollution sources. Some studies have found such a longitudinal gradient of increasing litter along a river course (e.g. Mani et al., 2015; Su et al., 2020), while others have not (Hoellein et al., 2017; Barrows et al., 2018). 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). 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), by a decrease in flow velocity of the river or by retention at the riverside (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.

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 from 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 5,500 schoolchildren participated in the sampling, forming 408 project groups from about 340 schools and youth organizations (Figure 1, Supplement S2). Each project group chose their sampling site according to the ease of access and interest and organized themselves into several subgroups to investigate different aspects of litter pollution (some of which have been published by Kiessling et al., 2019). 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 minutes 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 (Figure 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 minutes).

2.4 Sampling of floating meso- and microplastics

Mesoplastics (5 – 24.99 mm) and microplastics (1 – 4.99 mm) were sampled by participants with a custom-built net (HydroBios Nr. 438215; Figure 2B). The net had an opening of 35 x 11 cm, of which approximately 35 x 9 cm (0.0315 m^2) were submerged during sampling with two empty plastic bottles attached at 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. It was deployed for 60 minutes, 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 methods available to them, e.g. dissecting microscope, 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, and calculated the number of meso-/microplastics m^{-3} of river water, according to the following formula (Moore et al., 2011):

Meso-/microplastics m^{-3} = number of meso-/microplastics in net / (flow velocity of river [m s^{-1}] * net area submerged in river [m^2] * deployment time of net [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). Afterward, the entire sample, including all material that was captured in the net, was packaged and sent to the coordinating laboratory for revision.

2.5 Stepwise verification of submitted citizen science data and samples

2.5.1 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 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 (Figure 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 minutes (15 groups). Data from three groups could unfortunately not be used because the observation took place from a moving kayak and not a fixed position from the riverside. For datasets reporting 10 or more observed litter items (n = 20 groups), the coordinator was contacted to reconfirm the results. Only if they 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 (Figure 1). From the total, 123 groups were excluded because no or only partial samples were sent in for revision in the laboratory, 56 groups had not submitted information about the sampling location or sampling date, 18 groups did not sample the required time of 60 minutes, and 6 groups did not supply information about the sampling time. 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 0.1 – 1.0 m s^{-1} (a flow velocity < 0.1 m s^{-1} frequently indicated that the stick 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%) measurement of flow velocity could be associated with the sample.

2.5.2 Revision of meso- and microplastic samples and FTIR analysis

Samples sent in to the laboratory varied largely in terms of volume, dependent on the amount of organic material they contained. All samples were reviewed by visual inspection in the coordinating laboratory with a dissecting microscope (Wild Heerbrugg M3B, 10x – 40x magnification). The 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 particles considered to be plastic particles were photographed (BMS Microscopes

XCAM4K8MPA), measured, and subsequently analyzed with attenuated total reflection Fourier transform infrared (ATR-FTIR) spectrometers (for this, particles were wiped with 95% ethanol if they appeared dirty). 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). To standardize results, the output of both devices was analyzed with siMPle 1.0.1 (Primpke et al., 2020) with 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. 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. 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).

2.6 Collection of population and river infrastructure variables

In addition to the data collected by the participants further data were collected 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, 20,000 - 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.

2.7 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 Stasinopolous, 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 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 one meter of river width, 0 to 8.25 items h^{-1} were found (in the Panke in Berlin with a river width of 8 m), with an overall average of 0.34 ± 0.89 litter items m^{-1} h^{-1} (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 (the participants themselves did not submit data about the composition of floating litter). Most of those consisted of plastic (n = 30). Further, there was one documented report of swans (*Cygnus olor*) trying to rip open a plastic bag in order to get to the content of the bag (Figure 3A). At approximately 50% of the sampling sites of each river system, floating macrolitter was observed (Elbe 57%, Weser 54%, Rhine 52%, rivers flowing into the North Sea 50%, Danube 48%), except for rivers flowing into the Baltic Sea (observed at only 29% of sampling sites).

The model with the lowest AIC (Supplement S5-1) considers the river system, sampling year, river width, and population density at the sampling sites as significant predictors for observed floating macrolitter (Table 1, Figure 4). For river systems, although there is a significant difference, median values were very similar and differences were very minor. 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, differences were small. At sampling sites where the river width was narrow, more floating macrolitter was observed than at sampling sites with wider rivers. Further, more floating macrolitter was observed at more densely populated places around the sampling sites (Supplement S5-2). There was one significant interaction in the model among the variables river system and population density (Supplement S5-3). 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), with a minimum of 0 particles h^{-1}, and a maximum of 220 meso-/microplastics h^{-1} (found in the Laucha river in the municipality of Schkopau). On average 6.86 ± 24.11 meso-/microplastics h^{-1} (median of 1, IQR 3) were sampled across all sites. 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, 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 2, 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%; Figure 3B). Pellets (including hard round or lentil-shaped pellets as well as soft, more rectangular-shaped pellets, Figure 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 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. Meso-/microplastics were found in 25% to 75% of samples from different river systems (Table 1).

The model with the lowest AIC (Supplement S5-1) considers 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-/microplastics, of which the former four were included as significant predictors (the variable natural retention basins lowers the overall AIC of the model but is not a significant predictor in itself; Table 1, Figure 5). For river systems, the Elbe river system contained more meso-/microplastics than the Rhine river system and rivers flowing into the Baltic Sea; other river systems are situated in between. Sampling sites with < 5,000 inhabitants had significantly more meso-/microplastics than sites with 5,000 – 20,000 inhabitants, but not if compared to the most populous category (20,000 – 100,000 inhabitants). Further, there was a very small but significant difference between sampling sites with and without an upstream artificial barrier (Supplement S5-2). 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 S5-3). 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.

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). The average load of meso-/microplastics ranged from 0 to 0.32 particles m^{-3} of surface river water in the different river systems (Supplement S5-4).

3.3 Relationship between floating litter and litter at riversides

Regarding the relationship between different litter samplings (floating macrolitter, floating meso-/microplastics, litter at the riverside, and litter accumulations at the riverside), significant correlations could be shown 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}, although the correlation coefficients were very low for both comparisons (Kendall’s tau < 0.15). For the other comparisons no significant correlation could be shown (S5).

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 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).

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., 2015; Nelms et al., 2017; Forrest et al., 2019; Kiessling et al., 2019) and likewise, we made the experience 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 a third of groups that conducted the microplastic sampling could not be considered because of missing samples. 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 et al., 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, in our study this approach has led (i) to the important finding that small streams (usually not in the focus of riparian litter studies) can carry large amounts of meso-/microplastics, and (ii) to 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 had to be 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 overlook a maximum distance of 20 m and not the entire river width (as has 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).

Regarding the analysis of meso-/microplastics, data 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 river 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. Most citizen science projects investigating microplastics extract, analyze and identify microplastics in the laboratory, not involving the citizen scientists for these steps (e.g. Ogata et al., 2009; Zettler et al., 2017; Barrows et al., 2018; Forrest et al., 2019). Our motivation was to foster the understanding of the participants regarding microplastics and therefore had participants analyze the sample as well (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 volume of water filtered and subsequently an estimation of the total litter load of rivers, not for statistical analysis. However, 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). A reliable estimate of the volume filtered could have possibly been obtained by attaching a flow meter to the net, although the large quantity of organic material transported in some rivers would likely have obstructed the flow meter (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 some other studies investigating floating macrolitter based on visual observations in rivers in Europe (macrolitter findings of about 0.02 – 0.8 m^{-1} h^{-1}, Castro-Jiménez et al., 2019; van Emmerik et al., 2019; 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., 2019, respectively), but observed macrolitter quantities are much lower than litter quantities 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., 2019; 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 (Figure 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 macrolitter load 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 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., 2019a; 2020a) and sections surveyed by the schoolchildren might have carried less litter. We, therefore, suggest that floating macrolitter quantities for larger rivers (river width > 10 m) are underestimated. 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., 1989 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 in 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 7,860 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) had citizen scientists sample river surface water with a container and analyzed the samples in the laboratory (with no analysis conducted by the citizen scientists themselves). Both studies considered fibers (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. 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 microplastic pollution in the present study remained hidden. 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 sampling sites but allowing an overview of microplastic pollution over a large geographic area.

The above-mentioned pollution hotspots account 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 linked to populous areas but usually not located in residential areas are wastewater treatment plants and plastic-producing industry. 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 that the sample consisted of more than 100 identical primary polypropylene pellets (in addition to many weathered polystyrene particles) the production plant seems the most likely source. 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 a vast majority of 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 drainages and rivers.

4.4 Citizen science approach to determine plastic pollution in extensive river systems

Even though there were some correlations between litter samplings in the present study 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., 2014; 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, sometimes flushing microplastics to the sea (Hurley et al., 2018), either contributing microplastics from land to rivers or diluting the concentration of microplastics due to influx of rainwater (Barrows 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 (e.g. Horton and Dixon, 2018; 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.

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 supported by citizen scientists on the other hand, while requiring more simplistic sampling protocols, have been able to collect litter data over large geographic areas (Hidalgo-Ruz and Thiel, 2015). For microplastics, 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/). For macrolitter, citizen science datasets are similarly expansive, especially regarding beach litter (e.g. Nelms et al., 2017 or Zettler et al., 2017 for data collected by volunteers participating in the International Coastal Cleanup). This way the citizen science approach could be an ideal method to effectively monitor plastic pollution at hundreds of sampling sites and in continuous manner at different times of the year or discharge/weather conditions; and, as added benefits, could 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 suggest 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 temporal dynamics of riverine plastic pollution. Finally, the inclusion of one or more additional nearby sampling sites on the same river would enable to study small-scale spatial heterogeneity.

Acknowledgments

First and foremost we thank all participating schoolchildren, teachers, and volunteers – without their support and enthusiasm this project would not have been possible (see Supplement S2)! A lot of people from Kiel Science Factory helped at different stages of the project, among them Lea Wagner, Sophie Kruse, Lisa-Marie Wachramejew, Laura Stjern, Henrike Bratz, Karen Stange, Marianne Böhm-Beck, and many more! Sebastian Primpke (Alfred-Wegener-Institute) was always ready to help with the analysis of data in siMPle, his help is greatly appreciated and was crucial for microplastic analysis! We are grateful for valuable comments from Jasmin Çolakoğlu and Sebastian, substantially improving the manuscript. We thank Florian Druckenthaner, Katharina Kummer, Daniel Henkel as well as Sophie Leukel and Johannes Wolters (German Aerospace Center), and Linda Mederake, Doris Knoblauch and Karl Lehmann (Ecologic Institute), who edited the workbooks, organized the shipping of material, and took care of the project's webpage and social media channels. Further, we appreciate the work of the open source software community, developing programs and projects such as R, QGIS and OpenStreetMap. We are grateful for continuous funding of the Plastic Pirates, and the logistical support, by the German Federal Ministry of Education and Science (BMBF) since 2016. Further funding was provided by the Lighthouse Foundation (Germany) and logistical support by the Universidad Católica del Norte (UCN), the Millennium Nucleus Ecology and Sustainable Management of Oceanic Islands (ESMOI), the Cluster of Excellence "Future Ocean" of the University of Kiel (CAU), the Leibniz Institute for Science and Mathematics Education (IPN), and the Ministry of Education, Science, and Cultural Affairs of Schleswig-Holstein.

References

Andrachuk, M., Marschke, M., Hings, C., Armitage, D. (2019). Smartphone technologies supporting community-based environmental monitoring and implementation: a systematic scoping review. Biological Conservation 237, 430-442.

Barrows, A. P., Christiansen, K. S., Bode, E. T., Hoellein, T. J. (2018). A watershed-scale, citizen science approach to quantifying microplastic concentration in a mixed land-use river. Water research 147, 382-392.

Blettler, M. C., Ulla, M. A., Rabuffetti, A. P., Garello, N. (2017). Plastic pollution in freshwater ecosystems: macro-, meso-, and microplastic debris in a floodplain lake. Environmental Monitoring and Assessment 189, 1-13.

Blettler, M. C., Garello, N., Ginon, L., Abrial, E., Espinola, L. A., Wantzen, K. M. (2019). Massive plastic pollution in a mega-river of a developing country: Sediment deposition and ingestion by fish (*Prochilodus lineatus*). Environmental Pollution 255, 113348.

Blettler, M. C., Gauna, L., Andréault, A., Abrial, E., Lorenzón, R. E., Espinola, L. A., Wantzen, K. M. (2020). The use of anthropogenic debris as nesting material by the greater thornbird, an inland-wetland-associated bird of South America. Environmental Science and Pollution Research 27, 41647-41655.

Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR 2020). Stadt- und Gemeindetypen in Deutschland. https://www.bbsr.bund.de/BBSR/DE/forschung/raumbeobachtung/Raumabgrenzungen/deutschland/gemeinden/StadtGemeindetyp/StadtGemeindetyp.html (accessed 4th of February 2021).

Castro-Jiménez, J., González-Fernández, D., Fornier, M., Schmidt, N., Sempéré, R. (2019). Macro-litter in surface waters from the Rhone River: plastic pollution and loading to the NW Mediterranean Sea. Marine Pollution Bulletin 146, 60-66.

Carpenter, E., Wolverton, S. (2017). Plastic litter in streams: the behavioral archaeology of a pervasive environmental problem. Applied Geography 84, 93-101.

Crosti, R., Arcangeli, A., Campana, I., Paraboschi, M., González-Fernández, 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 29, 859-866.

Di, M., Wang, J. (2018). Microplastics in surface waters and sediments of the Three Gorges Reservoir, China. Science of the Total Environment 616, 1620-1627.

Delignette-Muller, M.L. Dutang, C. (2015). fitdistrplus: an R Package for Fitting Distributions. Journal of Statistical Software 64, 1-34.

Dris, R., Gasperi, J., Rocher, V., Saad, M., Renault, N., Tassin, B. (2015). Microplastic contamination in an urban area: a case study in Greater Paris. Environmental Chemistry 12, 592-599.

Eastman, L., Hidalgo-Ruz, V., Macaya-Caquilpán, V., Nuñez, P., Thiel, M. (2014). The potential for young citizen scientist projects: a case study of Chilean schoolchildren collecting data on marine litter. Journal of Integrated Coastal Zone Management 14, 569-579.

Franz, B., Freitas, M. A. V. (2012). Generation and impacts of floating litter on urban canals and rivers. Sustainability Today 167, 321-332.

Forrest, S. A., Holman, L., Murphy, M., Vermaire, J. C. (2019). Citizen science sampling programs as a technique for monitoring microplastic pollution: results, lessons learned and recommendations for working with volunteers for monitoring plastic pollution in freshwater ecosystems. Environmental Monitoring and Assessment 191, 1-10.

Gasperi, J., Dris, R., Bonin, T., Rocher, V., Tassin, B. (2014). Assessment of floating plastic debris in surface water along the Seine River. Environmental Pollution 195, 163-166.

González-Fernández, D., Hanke, G. (2017). Toward a harmonized approach for monitoring of riverine floating macro litter inputs to the marine environment. Frontiers in Marine Science 4, 86.

Grbić, J., Helm, P., Athey, S., Rochman, C. M. (2020). Microplastics entering northwestern Lake Ontario are diverse and linked to urban sources. Water Research 174, 115623.

Hidalgo-Ruz, V., Thiel, M. (2013). Distribution and abundance of small plastic debris on beaches in the SE Pacific (Chile): a study supported by a citizen science project. Marine Environmental Research 87, 12-18.

Hidalgo-Ruz, V., Thiel, M., (2015). The contribution of citizen scientists to the monitoring of marine litter. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer, Berlin

Hinojosa, I. A., Thiel, M. (2009). Floating marine debris in fjords, gulfs and channels of southern Chile. Marine Pollution Bulletin 58, 341-350.

Hoellein, T. J., McCormick, A. R., Hittie, J., London, M. G., Scott, J. W., Kelly, J. J. (2017). Longitudinal patterns of microplastic concentration and bacterial assemblages in surface and benthic habitats of an urban river. Freshwater Science 36, 491-507.

Hoellein, T. J., Rochman, C. M. (2021). The “plastic cycle”: a watershed- scale model of plastic pools and fluxes. Frontiers in Ecology and the Environment. https://doi.org/10.1002/fee.2294 (accessed 4th of February 2021).

Horton, A. A., Dixon, S. J. (2018). Microplastics: an introduction to environmental transport processes. Wiley Interdisciplinary Reviews: Water 5, e1268.

Hurley, R., Woodward, J., Rothwell, J. J. (2018). Microplastic contamination of river beds significantly reduced by catchment-wide flooding. Nature Geoscience 11, 251-257.

Kapp, K. J., Yeatman, E. (2018). Microplastic hotspots in the Snake and Lower Columbia rivers: a journey from the Greater Yellowstone Ecosystem to the Pacific Ocean. Environmental Pollution 241, 1082-1090.

Karlsson, T. M., Arneborg, L., Broström, G., Almroth, B. C., Gipperth, L., Hassellöv, M. (2018). The unaccountability case of plastic pellet pollution. Marine Pollution Bulletin 129, 52-60.

Kiessling, T., Knickmeier, K., Kruse, K., Brennecke, D., Nauendorf, A., Thiel, M. (2019). Plastic Pirates sample litter at rivers in Germany - Riverside litter and litter sources estimated by schoolchildren. Environmental Pollution 245, 545-557.

Klein, S., Worch, E., Knepper, T. P. (2015). Occurrence and spatial distribution of microplastics in river shore sediments of the Rhine-Main area in Germany. Environmental Science & Technology 49, 6070-6076.

Kole, P. J., Löhr, A. J., Van Belleghem, F., Ragas, A. (2017). Wear and tear of tyres: a stealthy source of microplastics in the environment. International Journal of Environmental Research and Public Health 14, 1265.

Kruse, K., Kiessling, T., Knickmeier, K., Thiel, M., Parchmann, I. (2020). Can participation in a citizen science project empower schoolchildren to believe in their ability to act on environmental problems? In: Parchmann, I., Simon, S., Apotheker, J. (Eds.), Engaging Learners with Chemistry: Projects to Stimulate Interest and Participation: The Royal Society of Chemistry.

Kühn, S., Rebolledo, E. L. B., van Franeker, J. A. (2015). Deleterious effects of litter on marine life. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter: Springer, Berlin.

Lassen, C., Warming, M., Kjøholt, J., Jakobsen, L. G., Vrubliauskiene, N., Norichkov, B., Strand, J., Feld, L., Bach, L. (2019). Survey of polystyrene foam (EPS and XPS) in the Baltic Sea. Danish Fisheries Agency/Ministry of Environment and Food of Denmark.

Lebreton, L. C., Van der Zwet, J., Damsteeg, J. W., Slat, B., Andrady, A., Reisser, J. (2017). River plastic emissions to the world’s oceans. Nature Communications 8, 15611.

Lechner, A., Keckeis, H., Lumesberger-Loisl, F., Zens, B., Krusch, R., Tritthart, M., Glas, M., Schludermann, E. (2014). The Danube so colourful: a potpourri of plastic litter outnumbers fish larvae in Europe's second largest river. Environmental Pollution 188, 177-181.

Lechner, A., Ramler, D. (2015). The discharge of certain amounts of industrial microplastic from a production plant into the River Danube is permitted by the Austrian legislation. Environmental Pollution 200, 159-160.

Lee, J., Hong, S., Song, Y. K., Hong, S. H., Jang, Y. C., Jang, M., Heo, N. W., Han, G. M., Lee, M. J., Kang, D., Shim, W. J. (2013). Relationships among the abundances of plastic debris in different size classes on beaches in South Korea. Marine Pollution Bulletin 77, 349-354.

Lenth, R. (2020). emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.5.1.0006. https://github.com/rvlenth/emmeans (accessed 4th of February 2021).

Magni, S., Binelli, A., Pittura, L., Avio, C. G., Della Torre, C., Parenti, C. C., Gorbi, S., Regoli, F. (2019). The fate of microplastics in an Italian Wastewater Treatment Plant. Science of the Total Environment 652, 602-610.

Mani, T., Hauk, A., Walter, U., Burkhardt-Holm, P. (2015). Microplastics profile along the Rhine River. Scientific reports 5, 1-7.

McCormick, A. R., Hoellein, T. J. (2016). Anthropogenic litter is abundant, diverse, and mobile in urban rivers: insights from cross- ecosystem analyses using ecosystem and community ecology tools. Limnology and Oceanography 61, 1718-1734.

McLeod, A.I., 2011. Kendall: Kendall rank correlation and Mann-Kendall trend test. R package version 2.2. https://CRAN.R-project.org/package=Kendall (accessed 4th of February 2021).

Menges, F. (2019). Spectragryph - optical spectroscopy software, Version 1.2.13, 2019, http://www.effemm2.de/spectragryph/ (accessed 4th of February 2021).

Michiani, M. V., Asano, J. (2019). Physical upgrading plan for slum riverside settlement in traditional area: a case study in Kuin Utara, Banjarmasin, Indonesia. Frontiers of Architectural Research 8, 378-395.

Moore, C. J., Lattin, G. L., Zellers, A. F. (2011). Quantity and type of plastic debris flowing from two urban rivers to coastal waters and beaches of Southern California. Journal of Integrated Coastal Zone Management 11, 65-73.

Morritt, D., Stefanoudis, P. V., Pearce, D., Crimmen, O. A., Clark, P. F. (2014). Plastic in the Thames: a river runs through it. Marine Pollution Bulletin 78, 196-200.

Nelms, S. E., Coombes, C., Foster, L. C., Galloway, T. S., Godley, B. J., Lindeque, P. K., Witt, M. J. (2017). Marine anthropogenic litter on British beaches: a 10-year nationwide assessment using citizen science data. Science of the Total Environment 579, 1399-1409.

Ogata, Y., Takada, H., Mizukawa, K., Hirai, H., Iwasa, S., Endo, S., Mato, Y., Saha, M., Okuda, K., Nakashima, A., Murakami, M., Zurcher, N., Booyatumanondo, R., Pauzi Zakaria, M., Quang Dung, L., Gordon, M., Miguez, C., Suzuki, S., ..., Thompson, R. C. (2009). International Pellet Watch: global monitoring of persistent organic pollutants (POPs) in coastal waters. 1. Initial phase data on PCBs, DDTs, and HCHs. Marine Pollution Bulletin 58, 1437-1446.

OpenStreetMap contributors (2019). https://www.openstreetmap.org/ (accessed 4th of February 2021).

Parthasarathy, A., Tyler, A. C., Hoffman, M. J., Savka, M. A., Hudson, A. O. (2019). Is plastic pollution in aquatic and terrestrial environments a driver for the transmission of pathogens and the evolution of antibiotic resistance? Environmental Science & Technology 53, 1744-1745.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E., Stromberg, J. C. (1997). The natural flow regime. BioScience 47, 769-784.

Primpke, S., Wirth, M., Lorenz, C., Gerdts, G. (2018). Reference database design for the automated analysis of microplastic samples based on Fourier transform infrared (FTIR) spectroscopy. Analytical and Bioanalytical Chemistry 410, 5131-5141.

Primpke, S., Cross, R. K., Mintenig, S. M., Simon, M., Vianello, A., Gerdts, G., Vollertsen, J. (2020). Towards the systematic identification of microplastics in the environment: evaluation of a new independent software tool (siMPle) for spectroscopic analysis. Applied Spectroscopy, https://doi.org/10.1177/0003702820917760 (accessed 4th of February 2021).

QGIS Development Team (2018). QGIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.osgeo.org (accessed 4th of February 2021).

R Development Core Team (2017). R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/ (accessed 4th of February 2021).

Rech, S., Macaya-Caquilpán, V., Pantoja, J. F., Rivadeneira, M. M., Campodónico, C. K., Thiel, M. (2015). Sampling of riverine litter with citizen scientists - findings and recommendations. Environmental Monitoring and Assessment 187, 335.

Rigby, R.A., Stasinopoulos, D.M. (2005). Generalized additive models for location, scale and shape. Applied Statistics 54, 507-554.

Roch, S., Walter, T., Ittner, L. D., Friedrich, C., Brinker, A. (2019). A systematic study of the microplastic burden in freshwater fishes of south-western Germany - are we searching at the right scale? Science of the Total Environment 689, 1001-1011.

Ross, J. B., Parker, R., Strickland, M. (1991). A survey of shoreline litter in Halifax Harbour 1989. Marine Pollution Bulletin 22, 245-248.

Sadri, S. S., Thompson, R. C. (2014). On the quantity and composition of floating plastic debris entering and leaving the Tamar Estuary, Southwest England. Marine Pollution Bulletin 81, 55-60.

Schirinzi, G. F., Köck-Schulmeyer, M., Cabrera, M., González-Fernández, D., Hanke, G., Farré, M., Barceló, D. (2020). Riverine anthropogenic litter load to the Mediterranean Sea near the metropolitan area of Barcelona, Spain. Science of the Total Environment, 714, 136807.

Schmidt, C., Krauth, T., Wagner, S. (2017). Export of plastic debris by rivers into the sea. Environmental Science & Technology 51, 12246-12253.

Schmidt, L. K., Bochow, M., Imhof, H. K., Oswald, S. E. (2018). Multi-temporal surveys for microplastic particles enabled by a novel and fast application of SWIR imaging spectroscopy - Study of an urban watercourse traversing the city of Berlin, Germany. Environmental Pollution 239, 579-589.

Schöneich-Argent, R. I., Dau, K., Freund, H. (2020). Wasting the North Sea? – a field-based assessment of anthropogenic macrolitter loads and emission rates of three German tributaries. Environmental Pollution 263, 114367.

Shim, W. J., Hong, S. H., Eo, S. E. (2017). Identification methods in microplastic analysis: a review. Analytical Methods 9, 1384-1391.

Shumilova, O., Tockner, K., Gurnell, A. M., Langhans, S. D., Righetti, M., Lucía, A., Zarfl, C. (2019). Floating matter: a neglected component of the ecological integrity of rivers. Aquatic Sciences 81, 25.

Statistische Ämter des Bundes und der Länder (2015). Einwohnerzahl je Hektar, Zensus 2011. https://www.zensus2011.de/DE/Home/Aktuelles/DemografischeGrunddaten.html (accessed 4th of February 2021).

Stockdale, R. J., McLelland, S. J., Middleton, R., Coulthard, T. J. (2008). Measuring river velocities using GPS river flow tracers (GRiFTers). Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group 33, 1315-1322.

Su, L., Sharp, S. M., Pettigrove, V. J., Craig, N. J., Nan, B., Du, F., Shi, H. (2020). Superimposed microplastic pollution in a coastal metropolis. Water Research 168, 115140.

Tasseron, P., Zinsmeister, H., Rambonnet, L., Hiemstra, A. F., Siepman, D., van Emmerik, T. (2020). Plastic hotspot mapping in urban water systems. Geosciences 10, 342.

Tramoy, R., Colasse, L., Gasperi, J., 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.

Tramoy, R., Gasperi, J., Colasse, L., Silvestre, M., Dubois, P., Noûs, C., Tassin, B. (2020). Transfer dynamics of macroplastics in estuaries - new insights from the Seine estuary: part 2. Short-term dynamics based on GPS-trackers. Marine Pollution Bulletin 160, 111566.

Trimaille, E. (2019). QuickOSM QGIS plugin. https://plugins.qgis.org/plugins/QuickOSM/ (accessed 4th of February 2021).

Tyers, M. (2017). Package ‘riverdist’, river network distance computation and applications. https://cran.r-project.org/web/packages/riverdist/index.html (accessed 4th of February 2021).

van Emmerik, T., Tramoy, R., van Calcar, C., Alligant, S., Treilles, R., Tassin, B., Gasperi, J. (2019). Seine plastic debris transport tenfolded during increased river discharge. Frontiers in Marine Science 6, 642.

van Emmerik, T., Seibert, J., Strobl, B., Etter, S., den Oudendammer, T., Rutten, M., bin Ab Razak, M. S., van Meerveld, I. (2020a). Crowd-based observations of riverine macroplastic pollution. Frontiers in Earth Science 8, 298.

van Emmerik, T., Van Klaveren, J., Meijer, L. J., Krooshof, J. W., Palmos, D. A. A., & Tanchuling, M. A. (2020b). Manila river mouths act as temporary sinks for macroplastic pollution. Frontiers in Marine Science 7, 770.

Vriend, P., Van Calcar, C., Kooi, M., Landman, H., Pikaar, R., van Emmerik, T. (2020). Rapid assessment of floating macroplastic transport in the Rhine. Frontiers in Marine Science 7, 10.

Wagner, S., Klöckner, P., Stier, B., Römer, M., Seiwert, B., Reemtsma, T., Schmidt, C. (2019). Relationship between discharge and river plastic concentrations in a rural and an urban catchment. Environmental Science & Technology 53, 10082-10091.

Wang, W., Ndungu, A. W., Li, Z., Wang, J. (2017). Microplastics pollution in inland freshwaters of China: a case study in urban surface waters of Wuhan, China. Science of the Total Environment 575, 1369-1374.

Watkins, L., McGrattan, S., Sullivan, P. J., Walter, M. T. (2019). The effect of dams on river transport of microplastic pollution. Science of the Total Environment 664, 834-840.

Wickham, H. (2016). ggplot2: elegant graphics for data analysis. Springer, New York.

Williams, A. T., Simmons, S. L. (1999). Sources of riverine litter: the river Taff, South Wales, UK. Water, Air, and Soil Pollution 112, 197-216.

Zhang, K., Gong, W., Lv, J., Xiong, X., Wu, C. (2015). Accumulation of floating microplastics behind the Three Gorges Dam. Environmental Pollution 204, 117-123.

Zhang, K., Chen, X., Xiong, X., Ruan, Y., Zhou, H., Wu, C., Lam, P. K. (2019). The hydro fluctuation belt of the Three Gorges Reservoir: source or sink of microplastics in the water? Environmental Pollution 248, 279-285.

Zettler, E. R., Takada, H., Monteleone, B., Mallos, N., Eriksen, M., Amaral-Zettler, L. A. (2017). Incorporating citizen science to study plastics in the environment. Analytical Methods 9, 1392-1403.

Figures

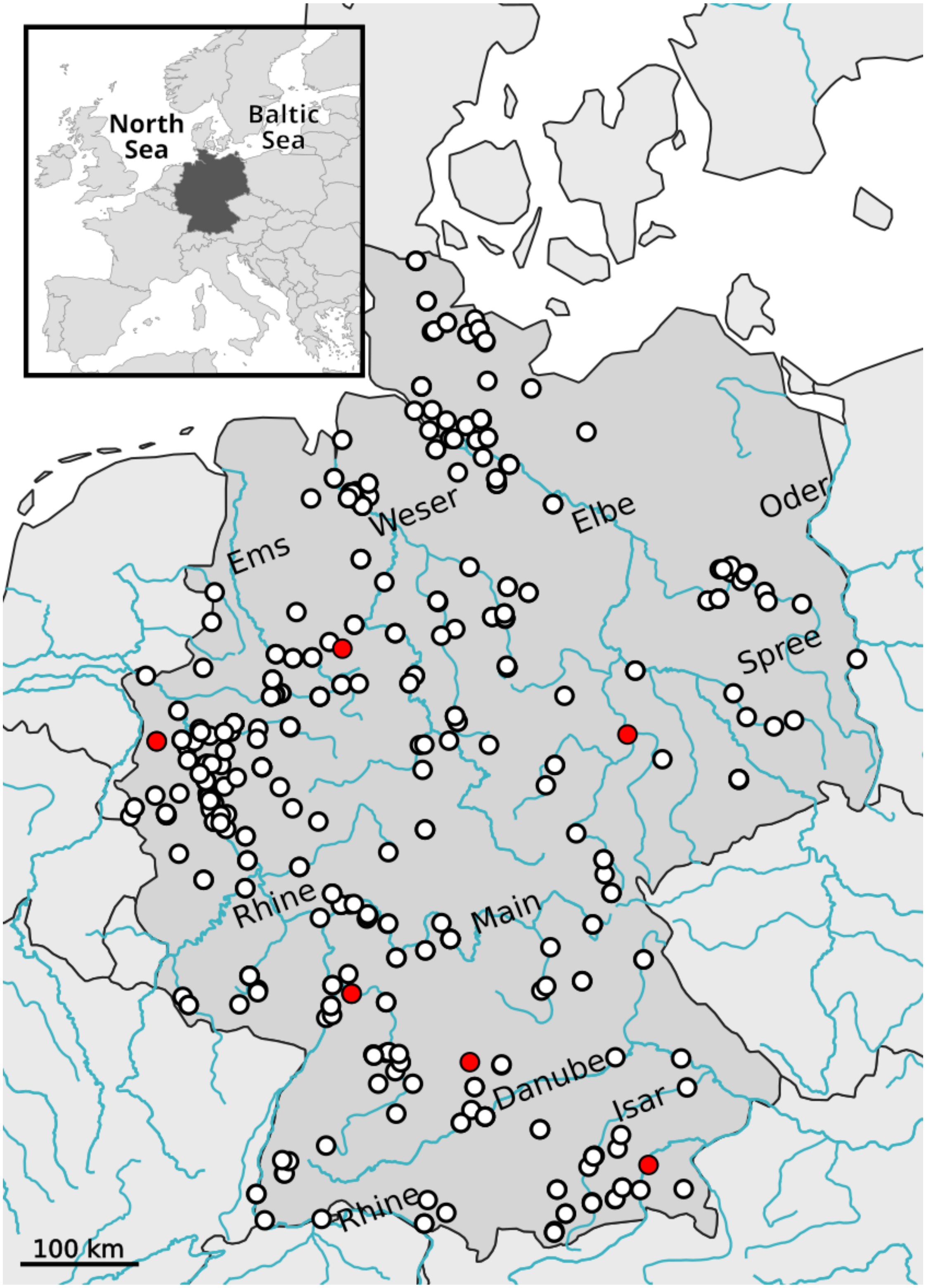


Figure 1. Map of Germany with major rivers and sampling sites of the Plastic Pirates in 2016 and 2017. Red circles represent sites with many meso-/microplastics (more than 50 particles h^{-1}).

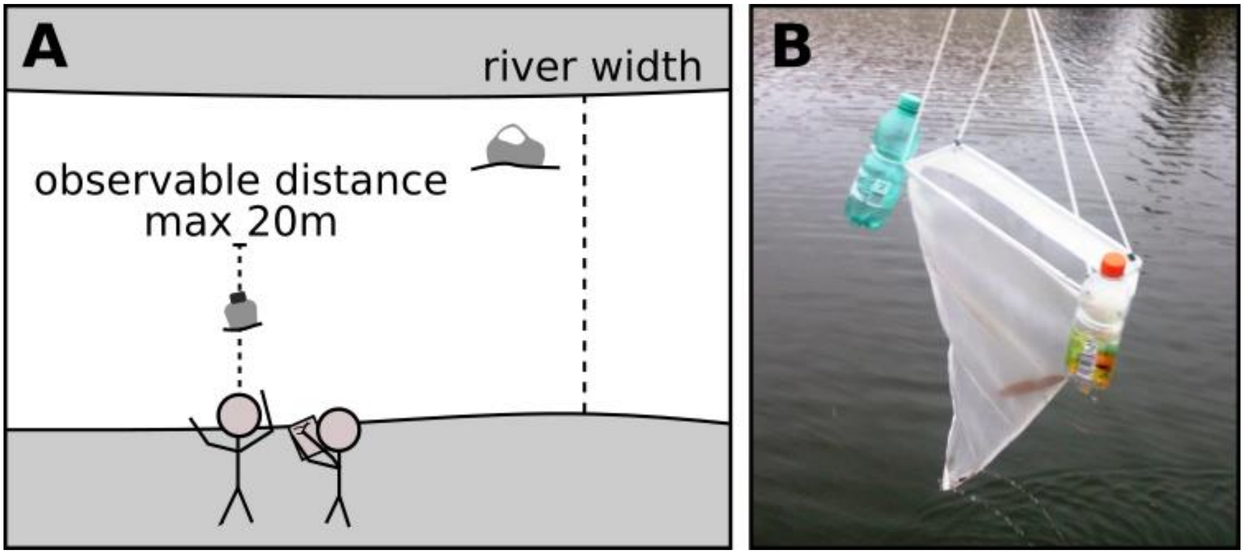


Figure 2. (A) Survey method for floating macrolitter: litter passing by the observers was counted. For wide rivers a maximum observable distance of 20 m was assumed (see text for details). (B) Sampling net for small plastic particles, equipped with two 0.5 L plastic bottles for buoyancy. © Europaschule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

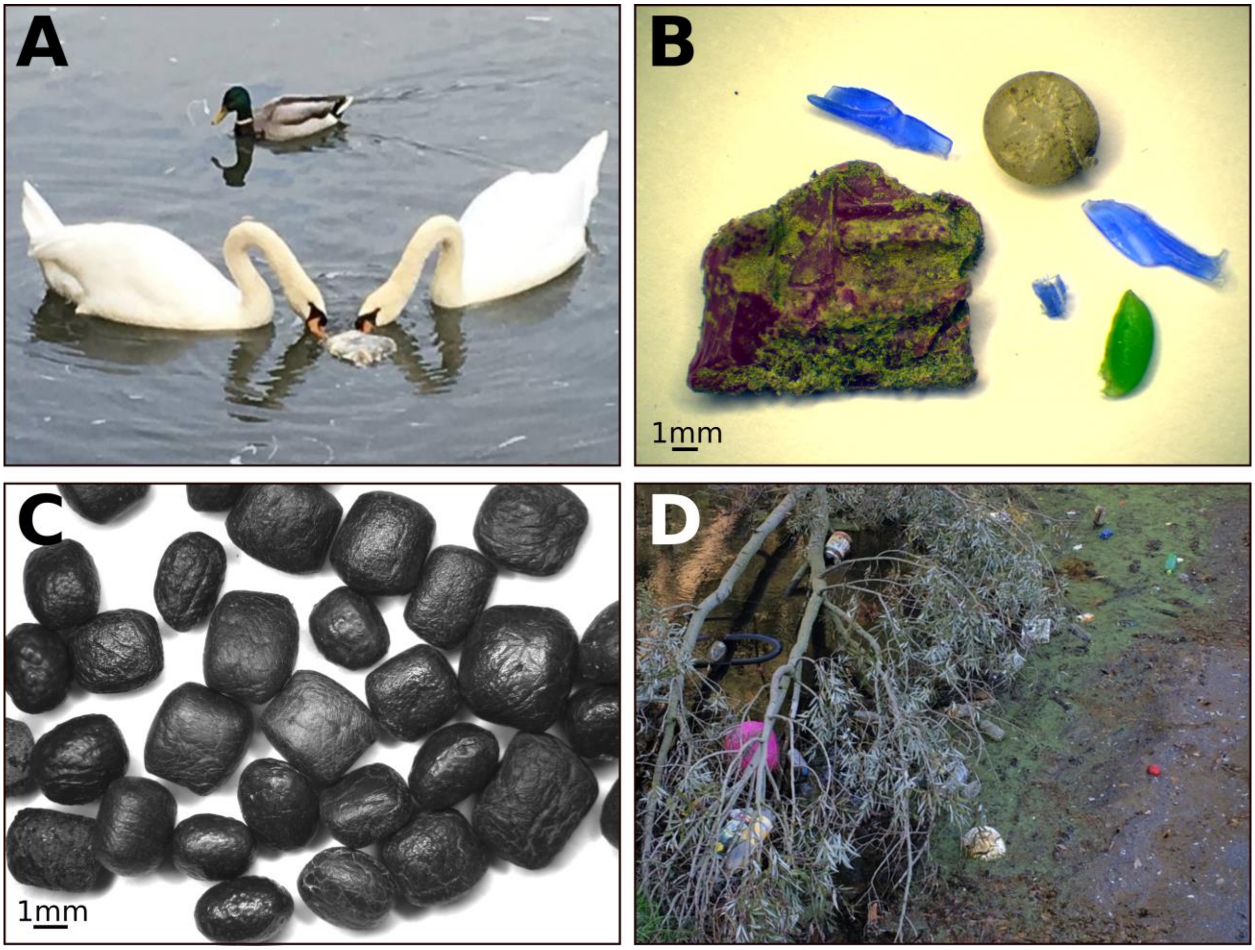


Figure 3. (A) Swans trying to open a floating plastic bag containing old bread in the Main. © Ernst-Reuter-Schule Frankfurt am Main. (B) Meso-/microplastics found by Realschule Bissingen investigating the Enz (Rhine river system). (C) Some of the polypropylene pellets sampled by Sekundarschule Schkopau 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.

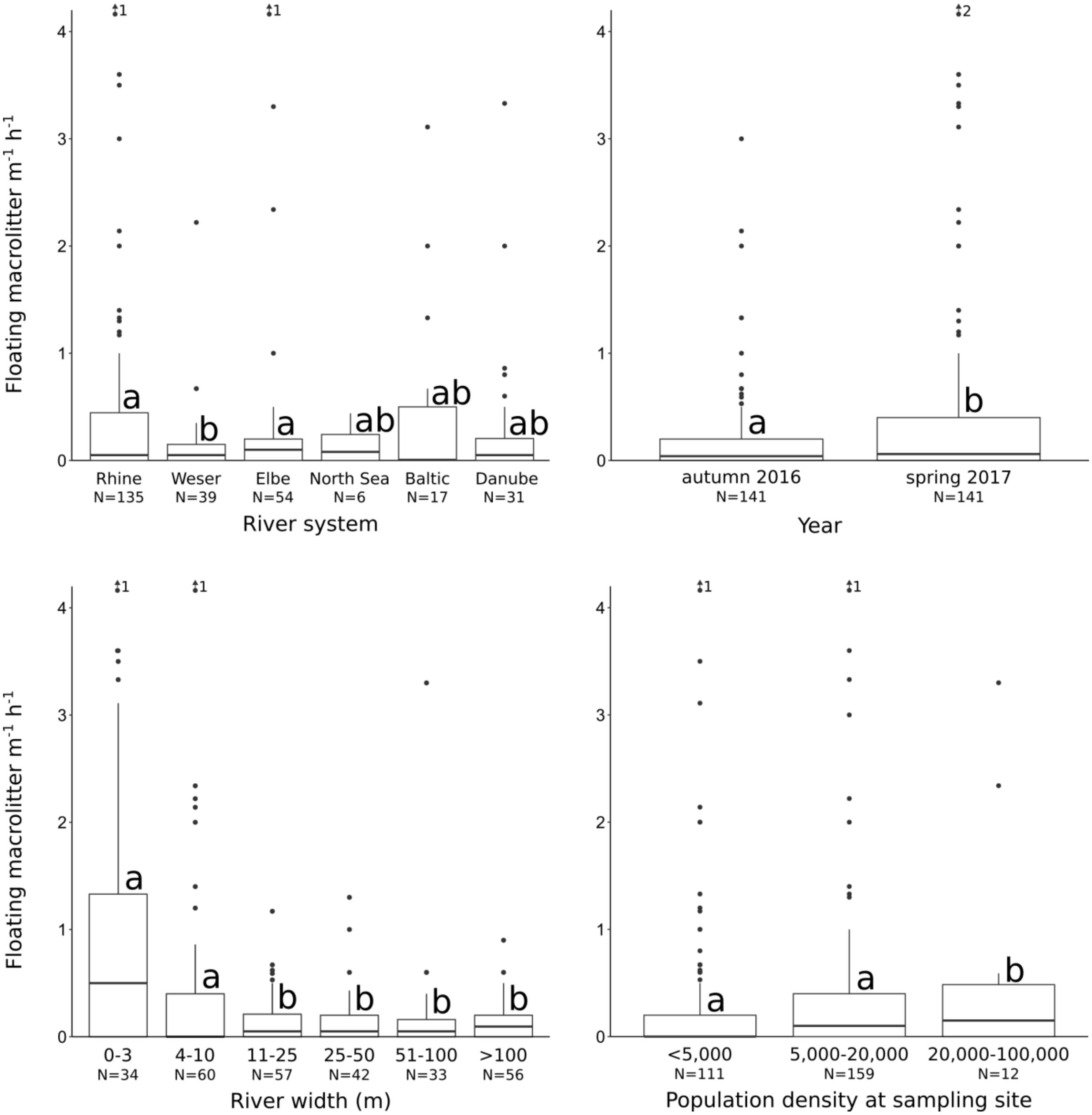


Figure 4. Floating macrolitter densities for the variables that were selected by the model as significant predictors of litter quantities. N = Number of datasets in each category. Dots with arrows and numbers at the top of charts indicate the number of outliers in each category. Letters mark significant differences.

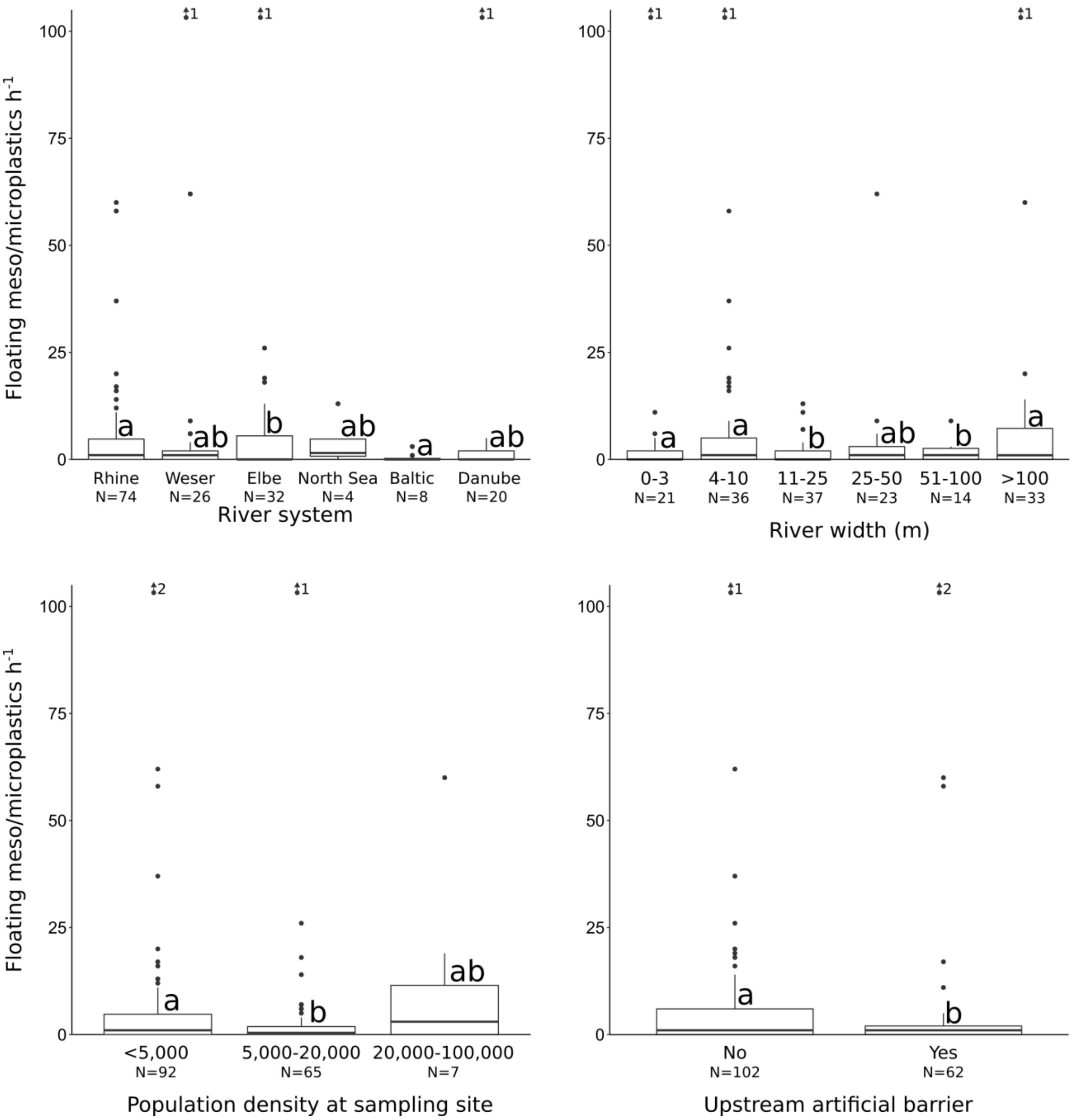


Figure 5. Floating meso-/microplastic densities for the variables that were selected by the model as significant predictors of litter quantities. N = Number of datasets in each category of each variable. Dots with arrows and numbers at the top of charts indicate the number of outliers in each category. Letters mark significant differences.

Tables

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 – 3m	47% (34)	1.10 ± 1.69	0.59 (1.33)
	4 – 10m	57% (60)	0.47 ± 1.18	0 (0.43)
	11 – 25m	44% (57)	0.16 ± 0.23	0.05 (0.21)
	26 – 50m	45% (42)	0.15 ± 0.27	0.05 (0.20)
	51 – 100m	45% (33)	0.20 ± 0.58	0.05 (0.16)
	> 100m	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)
	20,000 – 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 – 3m	48% (21)	12.00 ± 47.74	0 (2.00)
	4 – 10m	69% (36)	9.94 ± 23.38	1.00 (6.75)
	11 – 25m	49% (37)	1.97 ± 3.59	0 (2.00)
	26 – 50m	57% (23)	4.48 ± 12.78	1.00 (3.00)
	51 – 100m	57% (14)	1.70 ± 2.42	1.00 (2.58)
	> 100m	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)
	20,000 – 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 (2.00)

Table 2. 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; Figure 3C); mainly spherical, often weathered polystyrene particles (95)	Small river (~ 3 m wide) within 500 m downstream of a chemical industry production site (size of industrial area ~ 4 km²).
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 colours (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 colours (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 PE (42); other particles	Small river (~ 10 m wide), sampled right at small weir. Open farm and woodland nearby, few houses.

Table 3. 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)

Supplementary Material

S1. Excerpts from the Plastic Pirates project booklet

S2. List of participating schools and organizations in the citizen science project Plastic Pirates

S3. Citizen science data verification

  S3-1. Problems during litter sampling reported by citizen scientists

  S3-2. Evaluation of meso-/microplastic data submitted by citizen scientists

S4. Results of floating macrolitter and floating meso-/microplastic pollution for each sampling site

S5. Results of statistical tests and models

  S5-1. Final gamlss models for floating macrolitter and floating meso-/microplastics

  S5-2. Results of posthoc tests of the gamlss models for floating macrolitter and floating meso-/microplastics

  S5-3. Interactions between variables of gamlss models

  S5-4. Results of Kendall rank correlation tests between floating macrolitter, floating meso-/microplastics, litter at riversides, and accumulations at riversides

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 Interest Statement

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: