

Plastic pollution of rivers - citizen scientists investigate litter quantities, composition, and sources

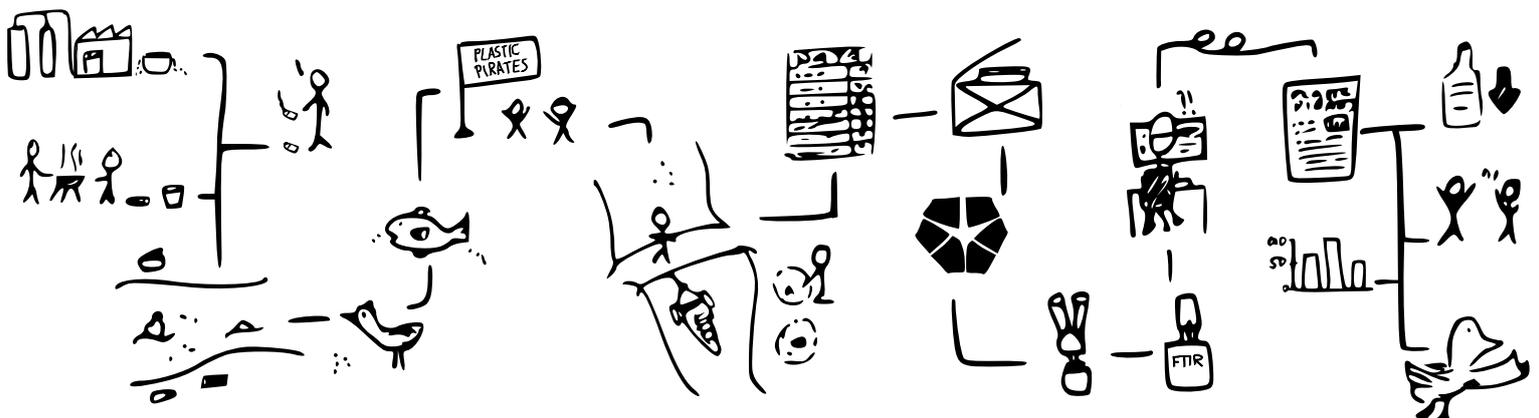
DISSERTATION

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Abstract

The pollution of the environment with anthropogenic litter, especially plastics, has become a major global problem. Large quantities of litter pose a hazard to hundreds of species, infrastructure, and human health. While the ocean pollution of plastics has been the research focus of most studies to date, the majority of litter derives from land and rivers play a key role in the transport of litter from inland sources to the sea. As litter sources are very diverse, it is imperative to investigate a variety of environments to gain an overview of the extent of pollution and derive mitigation measures. Citizen science (involving the general public in research) is a promising approach to collect such data over large geographic areas.

This thesis presents the results of the citizen science campaign Plastic Pirates, involving schoolchildren in the research of anthropogenic litter pollution of rivers. The project was conducted in Germany and Chile, involving (since 2016) over 15,000 schoolchildren and their teachers. The studies presented here analysed data from the campaigns of 2016 and 2017 of the Plastic Pirates. The results show that litter pollution of the riparian environment is ubiquitous in both countries: larger litter at the sampling sites occurred at almost all sampling sites (91% in Germany, 100% in Chile), including litter hazardous to humans (found at 89% of sampling sites in Germany, in Chile this analysis was not conducted). Litter quantities at the riverside averaged 0.5 items and 1.8 items per m² in Germany and Chile, respectively. In both countries, plastics and cigarette butts were among the most frequently found litter items. The most important source of much of this litter are recreational visitors (i.e. people passing spare time at the riverside, consuming food). In addition, in Chile, residents and people illegally dumping litter have also been identified as important sources. Small plastic particles (meso- and microplastics, i.e. particles in the size range of 24.99 to 1 mm) have also frequently been found in the nets used to sample the river water (in 57% of samples in Germany, and 43% of samples in Chile). Considering that only particles larger than 1 mm were sampled, it can be assumed that the pollution by even smaller particles is common in the two countries. In Germany, some hotspots of pollution with small plastic particles were discovered, meaning sites where many particles were found (over 50 particles per hour). Potential sources of these particles were the plastic producing industry and wastewater treatment plants.

The employed citizen science approach, involving schoolchildren and their teachers, proved valuable to collect many data in entire Germany and large sections of

Chile. A wide variety of rivers were investigated, including smaller rivers, usually not in the focus of riparian litter studies. In addition to the scientific data collected by the schoolchildren, citizen science is a promising approach to raise the environmental awareness and scientific literacy of participants, and, in this process, plays an important role towards the opening of research processes to the general public.

Zusammenfassung

Die menschengemachte Müllverschmutzung der Umwelt, insbesondere durch Plastikmüll, ist ein globales Problem, das hunderte Arten, die menschliche Gesundheit als auch die Infrastruktur gefährdet. Obwohl das Plastikmüllproblem im Ozean bisher am besten untersucht wurde, stammt der meiste Müll vom Land. Flüsse sind hier ein wichtiger Faktor für den Transport von Müllteilen aus dem Landesinnern an die Küste. Da Müllquellen sehr divers sind, ist es essentiell Daten zur Müllverschmutzung an einer Vielzahl von Standorten zu sammeln, um daraus Lösungsvorschläge abzuleiten. Citizen Science („Bürgerwissenschaften“, d.h. die Einbeziehung der Öffentlichkeit in wissenschaftliche Prozesse) ist hierbei eine vielversprechende Möglichkeit diese Daten über großflächige Gebiete zu sammeln.

Diese Dissertation basiert auf den Ergebnissen des Citizen Science-Projekts „Plastic Pirates“ („Plastikpiraten“), das Schüler*innen in die wissenschaftliche Untersuchung der Müllverschmutzung von Flüssen einbezieht. Das Projekt wurde in Deutschland und Chile durchgeführt. Seit 2016 nahmen mehr als 15.000 Schüler*innen und Lehrkräfte teil. Die Ergebnisse in dieser Dissertation basieren auf den Daten der Plastic Pirates aus den Jahren 2016 und 2017. Die Ergebnisse zeigen, dass die Müllverschmutzung von Flüssen in beiden Ländern allgegenwärtig ist: Müll am Flussufer fand sich an beinahe allen beprobten Standorten (91% in Deutschland, 100% in Chile). Dazu zählte auch Müll, der potentiell gefährlich für die menschliche Gesundheit ist (an 89% der Standorte in Deutschland gefunden; in Chile wurde diese Analyse nicht durchgeführt). In Deutschland fanden sich im Durchschnitt 0,5 Müllteile pro m², in Chile waren es 1,8 Müllteile pro m². In beiden Ländern gehörten dabei Plastikobjekte und Zigarettenkippen zu den häufigsten Funden. Als wichtigste Müllquelle wurden Flussbesucher*innen identifiziert, also Personen, die ihre Freizeit am Flussufer verbringen und dabei Lebensmittel konsumieren. In Chile waren außerdem Anwohner*innen und Personen, die illegal Müll abladen, wichtige Quellen des vorgefundenen Mülls. Auch kleine Plastikpartikel (Meso- und Mikroplastik, d.h. Partikel mit einer Größe von 24,99 bis 1 mm) wurden häufig in den Netzen, mit denen die Flussoberfläche beprobt wurde, gefunden (in 57% der Proben in Deutschland und 43% der Proben in Chile). Da ausschließlich Partikel größer als 1 mm berücksichtigt wurden, lässt sich darauf schließen, dass die Verschmutzung mit kleinen Plastikpartikeln ebenfalls allgegenwärtig in beiden Ländern ist. In Deutschland wurden *hotspots* mit kleinen Plastikpartikeln gefunden, d.h.

Standorte, an denen mehr als 50 Partikel pro Stunde gefunden wurden. Mögliche Quellen dieser Partikel sind die Kunststoffindustrie und Kläranlagen.

Mit dem Citizen Science-Ansatz, also dem essentiellen Beitrag der Schüler*innen und Lehrkräfte zur Untersuchung, konnten großflächig viele Daten in ganz Deutschland und in vielen Regionen Chiles gesammelt werden. Dadurch konnte eine Vielzahl von Standorten abgedeckt werden, darunter auch kleine Flüsse, die normalerweise weniger Beachtung in wissenschaftlichen Untersuchungen finden. Citizen Science ist außerdem ein vielversprechender Ansatz um das Umweltbewusstsein und -handeln sowie das Wissenschaftsverständnis der Teilnehmer*innen zu stärken, womit diese Art der Beteiligung eine wichtige Rolle hinsichtlich der gesellschaftlichen Öffnung der Wissenschaften spielt.

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Chapter I: Introduction

I.1. Plastic litter in the environment

Plastics are an integral part of our lives. They are lightweight, cheap to manufacture, durable, and can be processed into nearly any shape and form. They are used in a myriad of applications; amongst others, plastics serve as food packaging, casings for electronic and household products, building insulation, or the basis for textiles (PlasticsEurope 2020). Added as small particles to cosmetic products, detergents, fertilisers and food complements they function as fillers, spacers, or as envelopes and barriers, protecting their content (ECHA 2019). According to PlasticsEurope (2020), in 2019 a total of 368 million tons of plastics have been produced worldwide. The packaging sector and the construction industry had the highest demand for plastics (PlasticsEurope 2020).

Contrary to one of the main properties of plastic, its longevity, a large share of manufactured plastics have a very short use time. Subsequently, a large share of plastic products become litter after a short time of use. Geyer et al. (2017) estimated the fate of all plastics that have ever been produced and concluded that globally only 9% of plastics were recycled, while 79% were deposited into landfills or ended up in the environment (while the rest was incinerated). Naturally, this varies from country to country but in the past decades it has become apparent that mismanaged plastic litter (i.e. litter that is not properly disposed of) has become a huge burden to the environment.

As a consequence, plastic litter, large and small, has been documented wherever researchers have turned their eye to: plastic bags have been found in the Mariana Trench (Chiba et al. 2018), vast quantities of plastics wash up on remote islands without human inhabitants (Convey et al. 2002, Lavers and Bond 2017), microplastics, including polymer textile microfibres, have been found frozen in sea ice (Obbard et al. 2014), in the atmosphere (Dris et al. 2015), in the snow of Mount Everest (Napper et al. 2020), and in agricultural soil (Piehl et al. 2018). Further, microplastics have been found within the bodies of a variety of marine species fished for human consumption (Smith et al. 2018), as well as in table sea salt (Karami et al. 2017), and in tap water and bottled water (Koelmans et al. 2019). Even in the placenta of humans, microplastics have been detected (Ragusa et al. 2021) and bisphenol A, a precursor of major plastics, could be measured in blood, urine, and sweat from the majority of the participants of a study (Genuis et al. 2012).

I.2. Impacts of plastic litter on the environment and people

Early reports of plastic pollution mainly came from the marine environment (e.g. Merrell 1980, Morris 1980) where plastic litter seems especially displaced, thousands of kilometres from land, and the marine environment remains the best-studied ecosystem regarding the impacts of the plastic pollution problem (see Ryan 2015 for a history on the research of marine plastic pollution). In their review, Kühn et al. (2015) list 557 marine species that are directly affected by plastics, either by being entangled in it (entanglement occurs for example in discarded or lost fishing gear or other plastic items that can easily loop around marine wildlife; Figure I.1A) or by ingesting plastic pieces (Figure I.1B). Ingestion of plastics can lead to a blockage or perforation of the gastrointestinal tract of organisms and the release of additives or other chemicals associated with plastic particles (see review by Puskic et al. 2020). Floating plastic litter can also serve as a habitat for a variety of species, potentially facilitating the spread of invasive species (Kiessling et al. 2015; Figure I.1C). Further, sessile organisms such as corals and vegetation can be smothered by plastic sheets (Kühn et al. 2015). The presence of plastic litter in the ocean may also alter the population dynamics of some oceanic ecosystems: e.g. *Halobates* deposits eggs on floating substrata, which has become much more commonplace because of the presence of plastic particles in the ocean's gyres. As a result the predation of this marine insect on its food source, zooplankton and fish eggs, could increase (Goldstein et al. 2012). The impacts are not limited to the marine environment. Many freshwater fishes ingest plastic (e.g. de Souza e Silva Pegado 2018, Roch et al. 2019, Wang et al. 2020), as do birds living in riverine and freshwater environments (Reynolds and Ryan 2018, D'Souza et al. 2020). Plastics are also used as a material for building nests by bird species living in wetlands (Jagiello et al. 2018, Blettler et al. 2020). Ingestion of microplastics has been documented for a variety of terrestrial species, ranging from earthworms to chickens and camels (Lwanga et al. 2017, Eriksen et al. 2021).

In addition to these environmental impacts, polluted beaches are less attractive to visitors, resulting in a loss of revenue for the tourism sector and incurring costs for cleaning services, while floating litter also presents a hazard to shipping and harbour infrastructure (Newman et al. 2015). Most of these costs are not paid for by the producers of products or the polluters, so the "polluter pays principle" does not apply to the plastic litter problem, as Newman et al. (2015) point out. Plastic litter can also pose a hazard to human health (Figure I.1D), for example by causing lacerations when stepped upon

(Campbell et al. 2016). Another concern are microbial communities living on small plastic particles (described as the “plastisphere”, Zettler et al. 2013), some of which develop antibiotic resistance when coming into contact with wastewater contaminated with antibiotics (Parthasarathy et al. 2019). The effect of microplastics and associated additives or persistent organic pollutants within the human body remains inconclusive (Rist et al. 2018), but dozens of additives used for plastic packaging of food products are of concern to human health and are classified as persistent, bioaccumulative, and toxic, or endocrine-disrupting chemicals (Groh et al. 2019).



Figure I.1. Impacts of plastic litter in the environment. (A) A sea lion entangled in netting. Photograph by Lauren Packard, Creative Commons license 2.0 CC-BY. <https://www.flickr.com/photos/110485367@N08/11180067935> (B) A Laysan albatross on Midway Atoll, its stomach filled with plastic litter, including plastic bottle lids and a lighter. Photo copyright: Chris Jordan, <http://www.chrisjordan.com/gallery/midway/#CF000313%2018x24>. (C) A diver next to a derelict fishing net with bamboos as floats in the midst of the South Pacific. Several organisms rafted on and close to this net, among them many barnacles, illustrating how large litter objects create “islands” for species at the high sea. Photo taken on the Algalita South Pacific research cruise by Tim Kiessling, Creative Commons license 4.0 CC-BY. (D) People camping and preparing food next to a pile of plastic litter and other trash at a beach in the Antofagasta

region (Chile), exposing themselves to potentially hazardous waste. Photo by Tim Kiessling, Creative Commons license 4.0 CC-BY.

I.3. Sources of plastic litter and rivers as a transport pathway

Sources of plastic litter are diverse. It is estimated that approximately 20% of anthropogenic litter present in the marine environment derives from sea-based activities (mostly fisheries) while approximately 80% of litter derives from land (Andrady 2011). About 13 million tons of plastic litter are input into the ocean from coastal areas (population living within 50 km of the coast) each year, according to a global model by Jambeck et al. (2015). Two further global models estimated the input of plastic litter from sources further inland via rivers at 2.4 and 2.8 million tons annually (Lebreton et al. 2017, Schmidt et al. 2017, respectively). Therefore litter at and in rivers is an important contributor to marine pollution – in addition to the impacts caused in the riparian environment (see chapter above).

All of the above-mentioned models consider the population density as a major predictor for the amount of plastic litter that reaches the ocean. Likewise, at riversides, the population density is also an important predictor: many studies found an overall higher litter density downstream of populous areas (e.g. van Emmerik et al. 2019a, Wagner et al. 2019, Grbić et al., 2020). On a more local level, such areas with a high population density and commercial activity (e.g. shopping districts, parking lots) also commonly feature a large quantity of plastic waste (e.g. Armitage 2007, Gasperi et al. 2014, McCormick and Hoellein 2016, Tasserou et al. 2020). For less densely populated sites, people dumping litter illegally (e.g. Williams and Simmons 1996, 1999, Rech et al. 2015, McCormick and Hoellein 2016), as well as recreational visitors, have been identified as main litter sources for larger litter items (e.g. McCormick and Hoellein 2016, Carpenter and Wolverson 2017). Sources of microplastics include the plastic-producing and plastic-processing industry, losing plastic pellets during transport and storage (Lechner and Ramler 2015, Karlsson et al. 2018), and effluents of wastewater treatment plants (Magni et al. 2019, Schmidt et al. 2020). The latter is a pathway for domestic plastic particles, for example fibres from washing machines (Napper and Thompson 2016, De Falco et al. 2019), or microplastics present in cosmetic products (Lei et al. 2017, Praveena et al. 2018).

Identifying the sources of litter is not trivial. While for larger litter items at times the origin can be inferred based on labelling on the product together with information of potential sources in the vicinity of the sampling site (Tudor and Williams 2004, Prevenios

et al. 2018), tracing of the origin of microplastics has only been possible so far when sampling directly within or at the effluents of wastewater treatment plants (Magni et al. 2019, Schmidt et al. 2020) or runoff waters of plastic industry sites (Lechner and Ramer 2015, Karlsson et al. 2018).

One reason why this inference of litter sources is complicated is that the distribution of litter at and in rivers is influenced by a variety of factors: wind, floods, and rain can mobilize litter located in the vicinity of rivers or at the riverside and flush it towards the river, or can deposit litter items located within the river or at the riverside (e.g. Williams and Simmons 1997, Hurley et al. 2018, van Emmerik et al. 2019b, c, Lima et al. 2020, Vriend et al. 2020). The morphology of the river itself influences for example the flow velocity of river water, in turn affecting the distribution and settlement of particles at the riverside or within river sediments (Crosti et al. 2018, Schmidt et al. 2018). Further characteristics of the particles themselves, e.g. buoyancy and size, influence the distribution of litter within the water column (Lenaker et al. 2019).

To account for these factors and investigate the plastic pollution of rivers during different seasons and weather conditions at different rivers it would be imperative to investigate a large range of sampling sites. However, taking and analysing litter, especially microplastic samples, is a large logistical effort, and further complicated by a lack of standardization of sampling techniques (see e.g. González-Fernández and Hanke 2017, and Hartmann et al. 2019 for different aspects of this issue). Few studies have investigated more than a couple of dozen sampling sites (e.g. Mani et al. 2015, Su et al. 2020), therefore the conclusions of many studies regarding litter sources, litter quantities, and litter composition are limited to a narrow spatial and/or temporal coverage. This limits the potential for successful litter mitigation measures or the usefulness of data as the basis for policies. One opportunity to overcome some of these limitations is to involve the general public in the research of the environmental plastic pollution problem.

I.4. Citizen science to investigate plastic litter pollution

Citizen science projects involve people without a formal scientific education in research processes, for example in the development of research questions, in taking samples or making observations, or in the analysis of data. Throughout this document, the terms “citizen scientists” or “participants” are used to denominate people taking part in citizen science projects while the term “professional researcher” is used to denominate

individuals with a formal scientific education who usually have a coordinating role in citizen science projects (for an extended discussion of the terminology of citizen science, citizen scientists, and potential caveats see Eitzel et al. 2017 and Liebenberg et al. 2021). Data originating from citizen scientists are used in a variety of ways, e.g. to advance the goals of communities the citizen scientists belong to, to strengthen the collaboration between involved parties, and to further scientific knowledge (Robinson et al. 2018). Besides collecting data, participation in citizen science projects can increase the scientific literacy and environmental awareness of participants and can transmit expert knowledge to the citizen scientists (Dickinson et al. 2012, Toomey and Domroese 2013, Bela et al. 2016, Bonney et al. 2016; Figure I.2).

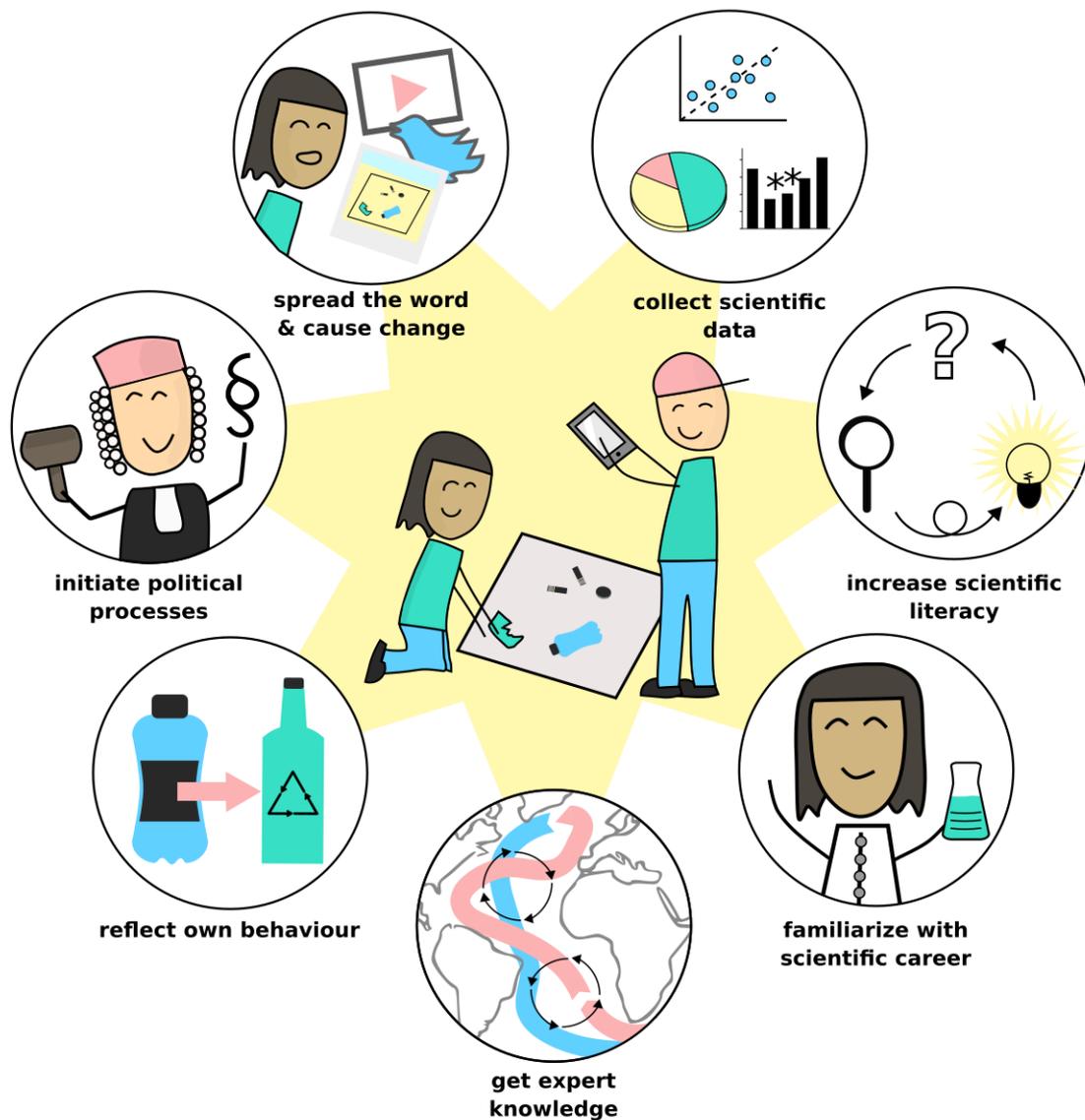


Figure I.2. Some of the benefits that can originate from citizen science projects for participants, society and science. Adapted from Kruse et al. (2020), under Creative Commons license BY 4.0.

Citizen science studies often enable the investigation of research questions on a scale unattainable to other studies not involving the general public. Therefore, it is not surprising that dozens of studies investigating environmental litter pollution have used data originating from citizen scientists (see e.g. Hidalgo-Ruz et al. 2015, Thiel et al. 2018 for an overview). The most extensive litter pollution dataset contributed by volunteers is arguably the data from the International Coastal Cleanup, a cleanup event and citizen science activity organized annually by the Ocean Conservancy and local coordinators (<https://oceanconservancy.org/trash-free-seas/international-coastal-cleanup/>). Data from the International Coastal Cleanup have been collected for over 30 years and are used in numerous scientific publications (Zettler et al. 2017). There are further extensive citizen science projects covering beach pollution (e.g. Nelms et al. 2020) as well as pollution by microplastics (e.g. International Pellet Watch, <http://pelletwatch.org>; Ogata et al. 2009). Fewer citizen science studies have focused on the plastic pollution of other environments, but see for example Rech et al. 2015, Barrows et al. 2018 and Forrest et al. 2019 for studies involving the general public for the investigation of plastics at and in rivers.

One challenge for citizen science projects is to ensure data quality, i.e. ensuring that data from participants without a formal scientific background are comparable to that of “professional researchers” (Kosmala et al. 2016). For this, straightforward sampling protocols, training of participants previous to the samplings and data quality mechanisms to subsequently verify citizen science data (e.g. in the form of photos) are recommended (e.g. Wiggins et al. 2011, Kosmala et al. 2016). Given the above-mentioned data control mechanisms, data quality from citizen science studies investigating environmental litter pollution can match data quality from “professional scientists” (Zettler et al. 2017). This research approach therefore seems especially suited to investigate the litter pollution of rivers at a large scale, and, additionally, to raise the environmental awareness of the plastic pollution problem among the general public.

I.5. The citizen science project Plastic Pirates and research questions

The Plastic Pirates are a citizen science project in which schoolchildren and other youth groups investigate the litter pollution of their local rivers with different methods. The project was developed by the *Kieler Forschungswerkstatt* (“Kiel Science Factory” - <https://www.forschungs-werkstatt.de/english/>) and the *Científicos de la Basura* (“Litter Scientists”, a citizen science program located at the Universidad Católica del Norte,

Coquimbo, Chile, <http://www.cientificosdelabasura.cl/en/>), and is coordinated at Kiel Science Factory. Kiel Science Factory is the school laboratory, teaching laboratory for future teachers and student research centre of Kiel University and the Leibniz Institute for Science and Mathematics Education, located in Kiel, Germany. Kiel Science Factory, amongst other things, offers science-based thematic visits for schoolchildren as well as guided excursions to the coast and coordinates citizen science projects. One such project, the precursor of the Plastic Pirates, was “Following the Pathways of Plastic Litter”, a binational citizen science project that investigated beach litter in Chile and Germany (Honorato-Zimmer et al. 2019, Kruse et al. 2020).

The Plastic Pirates are funded by the Federal Ministry of Education and Research of Germany, first as part of the ministry’s *Wissenschaftsjahr 2016*17 Meere und Ozeane* (“Year of Science 2016*17 Seas and Oceans”), then as part of the ministry’s research project *Plastik in der Umwelt – Quellen, Senken, Lösungsansätze* (“Plastics in the Environment – Sources, Sinks, Solutions”). Since the inauguration in 2016 more than 15,000 participants from over 700 schools and organisations have participated in the project, uploading more than 900 datasets to the project’s webpage (<https://www.plastic-pirates.eu/en>; Figure I.3) and investigating litter across entire Germany. Groups investigated different aspects of litter pollution: the occurrence of larger litter items (macrolitter), dangerous material and accumulations of litter at the riverside, the occurrence of floating macrolitter as well as small plastic particles, and potential sources of these litter items. The method of the Plastic Pirates was developed for older schoolchildren, however, several younger children have participated in the campaigns. Teachers or leaders of youth groups can order sampling booklets for their group, sampling nets as well as educational material at no cost (Figure I.3). Additional aims of the Plastic Pirates, besides collecting data on the litter pollution of the riparian environment, are to raise the environmental awareness of participants and the general public and to increase the scientific literacy of the schoolchildren and youth groups.

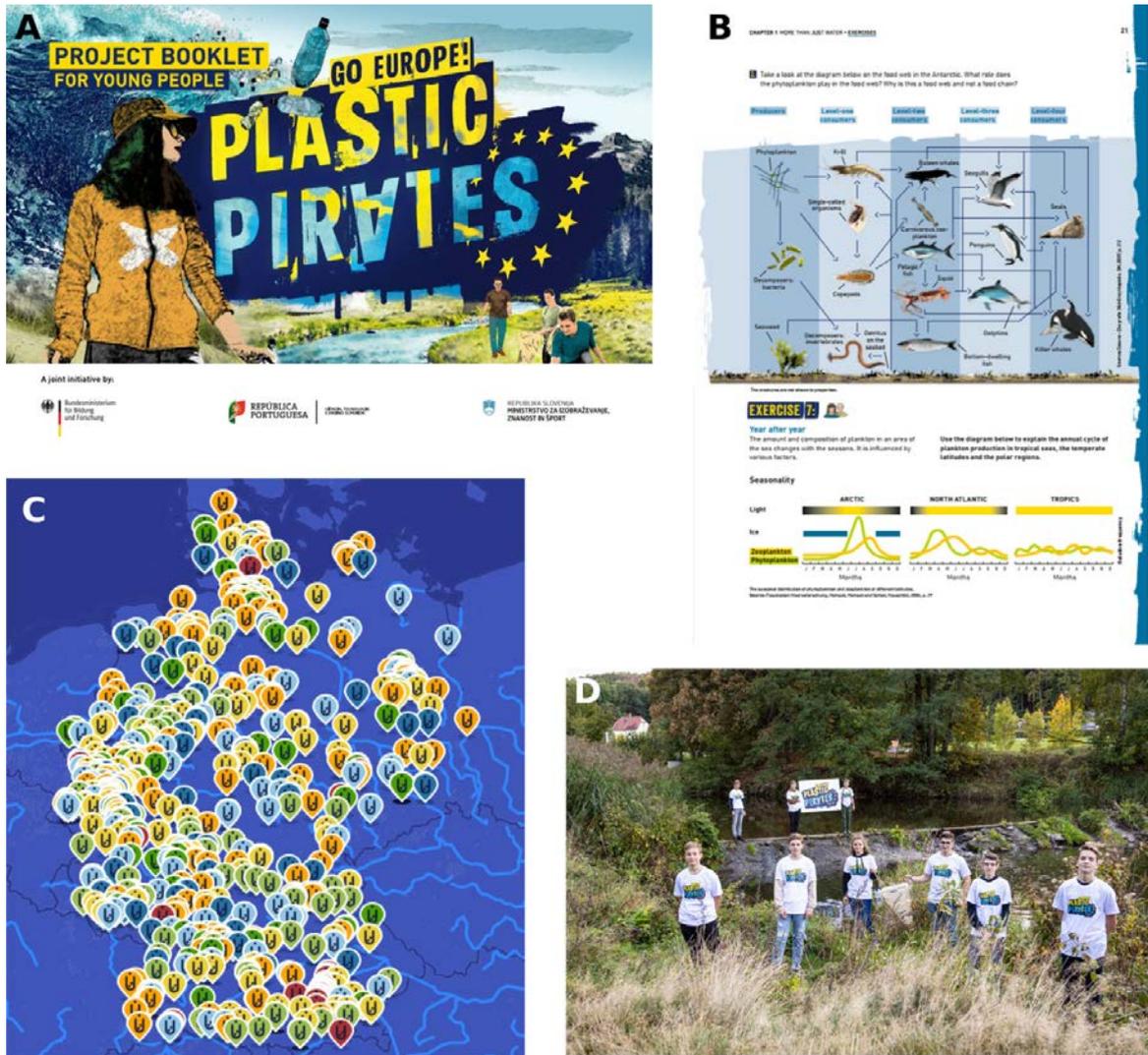


Figure I.3. Plastic Pirates material and participants. (A) The title page of the project booklet of the citizen science project (version 2020) containing a brief introduction to the plastic pollution problem, detailed sampling instructions, and a result protocol. (B) Excerpt from the teaching material of the Plastic Pirates, containing detailed information and exercises about the ocean ecosystems, the anthropogenic use of the ocean, the plastic pollution problem and how participants could engage to solve the litter problem. (C) Map of Germany from the website of the Plastic Pirates detailing where samplings took place (different colours represent different sampling campaigns, <https://www.plastic-pirates.eu/en/results/map>). (D) Schoolchildren of the school Geschwister-Scholl-Gymnasium Nossen conducting the sampling at the river Freiburger Mulde in the spring of 2020 (during the COVID-19 pandemic). Photo copyright BMBF/Gesine Born. The booklets are available at <https://www.plastic-pirates.eu/en/material/download>

I.6. Research questions and thesis outline

In addition to the educational and environmental-awareness raising goals of the project the research aims of the studies addressed in this thesis specifically are:

- (i) To identify the composition, quantities, and sources of larger litter located at riversides in Germany as well as to obtain information on the presence of items hazardous to human health
- (ii) To identify the composition and quantities as well as potential sources of larger litter objects and small plastic particles (mesoplastics and microplastics) afloat in rivers in Germany
- (iii) To investigate the quantities, composition, and sources of litter located at the riverside and within rivers in Chile and compare them to a previous sampling, having taken place in 2013
- (iv) To give insights into the citizen science campaign (with an emphasis on the aspect of data verification), and illustrate how teachers can use the materials developed for the citizen science project, also to continue work in the classroom past the sampling campaign

The following four chapters present the results of these litter pollution samplings and insights from the citizen science project. Chapter II details results of the litter pollution at the riverside based on the data from two sampling campaigns in Germany (2016 and 2017), including an evaluation of litter sources. The article has been published in *Environmental Pollution* (Kiessling et al. 2019). Chapter III presents results of the pollution of river waters by floating macrolitter and meso- and microplastics and is based on the same sampling campaigns as the previous chapter. The article has been published in *Science of the Total Environment* (Kiessling et al. 2021). Chapter IV shows results of a citizen science campaign in 2017 conducted in Chile, within the program of the Científicos de la Basura, with the findings being compared to a citizen science campaign conducted in 2013 with a similar method. This article has been submitted to *Environmental Pollution*. Chapter V is an article published in German in *Unterricht Chemie* (Kiessling et al. 2020), a journal directed towards school teachers and illustrates how the citizen science project Plastic Pirates can be implemented in schools and offers additional educational input to discuss the plastic pollution problem in the classroom. Chapter VI is a synthesis and outlook of the presented manuscripts.

I.7. References

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Chapter II: Plastic Pirates sample litter at rivers in Germany – Riverside litter and litter sources estimated by schoolchildren

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II.1. Abstract

Rivers are an important source of marine anthropogenic litter, but the particular origins of riverine litter itself have not been well established. Here we used a citizen science approach where schoolchildren examined litter at riversides and identified possible sources at over 250 sampling spots along large and small rivers in Germany, during autumn 2016 and spring 2017. Litter densities have an overall median of 0.14, interquartile range 0 – 0.57 items m⁻² and an overall average (\pm standard deviation) of 0.54 ± 1.20 litter items m⁻². Litter quantities differed only little by sampling year. The principal litter types found were plastics and cigarette butts (31% and 20%, respectively), followed by glass, paper, and metal items, indicating recreational visitors as the principal litter source. At many sites (85%), accumulations of litter, consisting principally of cigarettes and food packaging, have been found. At almost all sampling sites (89%), litter potentially hazardous to human health has been observed, including broken glass, sharp metal objects, used personal hygiene articles and items containing chemicals. In the search for litter sources, the schoolchildren identified mainly people who use the rivers as recreational areas (in contrast to residents living in the vicinity, illegal dumping, or the river itself depositing litter from upstream sources). These results indicate the urgent need for better education and policy measures in order to protect riparian environments and reduce input of riverine litter to the marine environment.

II.2. Introduction

Marine pollution by anthropogenic litter (especially plastics) has received much scientific and public attention and its impacts are well-documented (Thompson et al. 2009, Kühn et al. 2015, Newman et al. 2015). Although much litter originates from sea-based sources, like fishing and aquaculture, most marine litter has land-based sources (GESAMP 2010, Andrady et al. 2011). It was estimated that up to 12.7 million tons of plastic waste entered the marine environment in 2010 from coastal sources alone, and that this number is growing (Jambeck et al. 2015). Additionally, rivers have been suggested as important transport routes for litter to the marine environment from populations living farther inland (e.g. Willoughby 1986, Tudor and Williams 2004, Shimizu et al. 2008, Laglbauer et al. 2014, Rangel-Buitrago et al. 2017). Two recent global studies estimate that up to 2.8 million tons of plastic waste enter the ocean annually from rivers (Lebreton et al. 2017, Schmidt et al. 2017). According to those models, the most polluting rivers are located in

Asia and Africa, accounting for about 70% of global litter input to the coastal and marine environment. However, how the litter gets into the rivers in the first place is not well known.

Potential sources of litter pollution in rivers are manifold: sewage outlets from wastewater treatment plants are known to contain microplastics (for example microbeads used in cosmetic products or clothing fibres; Browne et al. 2011, McCormick et al. 2014, Dris et al. 2015) but sewage waters can also liberate larger sanitary items (Williams and Simmons 1999, Morritt et al. 2014). Litter floating in the river or present at a riverside can also originate from recreational activity in the vicinity (Gasperi et al. 2014, McCormick and Hoellein 2016, Carpenter and Wolverton 2017) or from areas of high urban activity (e.g. commercial districts; Armitage 2007, Carson et al. 2013). Larger litter accumulations or household items are often the result of people intentionally depositing litter at riversides (Williams and Simmons 1997a, 1999, Rech et al. 2015, McCormick and Hoellein 2016). Littering of household items by residents without access to waste collection infrastructure along with domestic sewage release is another source of riverine litter (Franz and Freitas 2011, Di and Wang 2017).

Most studies on river litter pollution focus on the river as a pathway for buoyant (and therefore mainly plastic) debris, and ultimately quantify the amount of items that are already on the move within a river (e.g. Moore et al. 2011, Gasperi et al. 2014, Lechner et al. 2014, Morritt et al. 2014, Mani et al. 2015). Anthropogenic litter on the shores or in the vicinity of rivers has been studied less frequently (but see Williams and Simmons 1997b, 1999, Rech et al. 2014, 2015, McCormick and Hoellein 2016), although it might be one of the principal sources of litter flowing towards the sea. For example, heavy rainfall, subsequent flooding and strong wind (Moore et al. 2011, Carson et al. 2013, Veerasingam et al. 2016) can liberate litter deposited on the riverside.

These events are often seasonal and the occurrence of litter appears to fluctuate throughout the year, for example coinciding with the monsoon season in regions where many of the most polluting rivers are located (Lebreton et al. 2017). The season is also likely to influence the number of visitors to the river environment as hypothesized by McCormick and Hoellein (2016) to explain higher litter quantities during summer. Visitors can also (deliberately or unintentionally) displace litter items from riversides into the river. It is therefore important to identify primary sources of riverine litter pollution and to investigate the effect of seasonal change on litter densities.

In recent years, the investigation of coastal and freshwater litter pollution has been supported by data originating from citizen science project, which allows data collection over large areas and time spans (e.g. Hoellein et al. 2015, Rech et al. 2015, Nelms et al. 2017, Hidalgo-Ruz et al. 2018), given appropriate data quality mechanisms (Zettler et al. 2017).

The present study used a citizen science approach to examine riverside litter pollution (i.e. litter items that are not yet or not anymore located within a river) in Germany. Large rivers as well as many small streams extend throughout Germany, often converging to large river systems (Figure II.1). With over 7,000 km of navigable waterways (WSV 2017), and almost all major cities (including the populous Rhine-Main industrial complex) being located at or close to streams, rivers and the riparian environment in Germany play also an important ecological, economic, and recreational role. The present study with its citizen science approach allowed us to (i) estimate the quantity of litter at rivers of various sizes and identify the material composition of litter, (ii) evaluate whether larger accumulations of litter or objects potentially hazardous to human health are present at riversides, and (iii) determine the sources of litter.

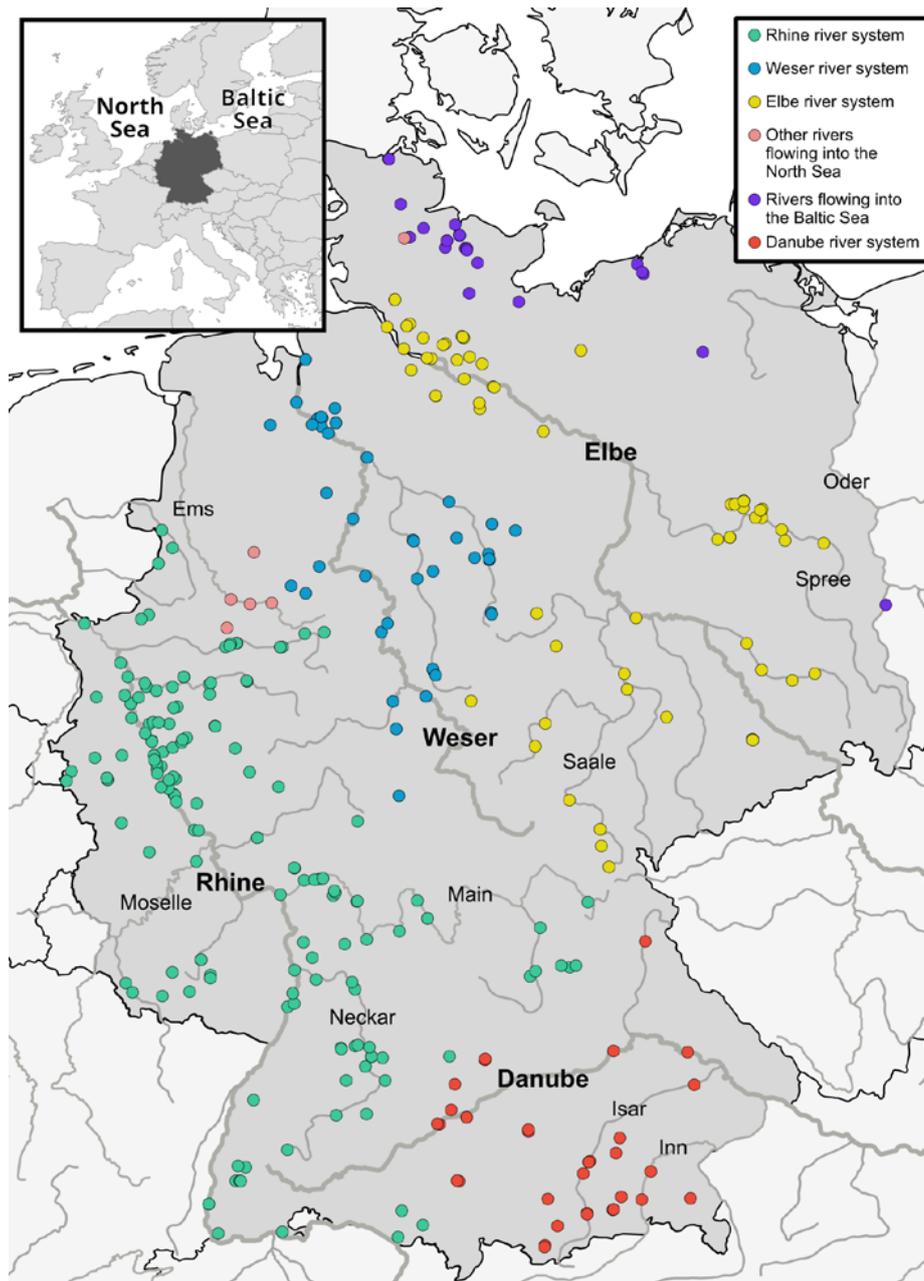


Figure II.1. Map of major rivers and sampling spots of the Plastic Pirates in 2016 and 2017 in Germany. The colour of the dots represent the different river systems (or seas the smaller rivers flow into).

II.3. Materials and Methods

II.3.1. Citizen science approach

This study is part of an extensive citizen science project (“Plastikpiraten”, Plastic Pirates) that examined different aspects of litter pollution at rivers in Germany. The sampling methodology was adapted from Rech et al. (2015) and developed by the *Kieler Forschungswerkstatt* in Germany (<http://www.forschungs-werkstatt.de/>) and the *Científicos de la Basura* in Chile (<http://www.cientificosdelabasura.cl/>). Schools and other

youth organizations from Germany were invited to investigate litter contamination at a riverside of their choice. A project booklet with sampling instructions for each participant (Supplement A1), and a workbook with information about litter and the riverine and marine environment for each supervisor were available at no cost. One designated supervisor, the teacher or leader of youth organization, served as our contact to organize shipping of material, obtaining data, and answering questions in case of ambiguity. The intended age of participants was 10 to 16 years, although younger and older students participated.

II.3.2. Sampling dates, number of participants and study area

The sampling was conducted during boreal autumn 2016 (16th of September to 18th of November) and spring 2017 (4th of May to 17th of July). In total more than 5,500 students from over 340 different schools and organizations from all 16 German administrative regions participated. Sometimes multiple classes from one school participated, leading to a total of 408 project groups that conducted the sampling or parts thereof. Participants were free to choose any river, regardless of size or location. Smaller groups were formed to investigate different aspects of litter pollution in the riverine environment. There was no obligation to investigate all aspects; each school and organization chose the activities according to their capacity and motivation (i.e. number of participants, available time, and interests of participants).

All sampling sites were grouped according to river system, i.e. a main river and all tributary streams and rivers, or (if the river system was small or investigated by few groups) according to the sea they finally flow into. In total nearly all major river systems and many smaller rivers in Germany have been investigated (Figure II.1): the Rhine, Weser and Elbe river systems draining into the North Sea, smaller rivers flowing into the Baltic Sea, and the Danube river system draining into the Black Sea. Other rivers flowing into the North Sea, which do not belong to any of the above-mentioned systems, have also been grouped for analysis. The Rhine river system was sampled most frequently, followed by the Elbe, Weser and Danube system. About half of the groups went to rivers less than 20 m wide (an estimation of river width was submitted by the participants, and if necessary corrected based on measurements with the ruler tool in Google Earth 7.31.4507).

II.3.3. Sampling of riverside litter

Up to three transects were established perpendicular to the river course. Each transect consisted of three sampling stations, one in each predefined zone: the river edge (0 – 5 m distance to river, assumed to have regular contact with it), the river bank (5 – 15 m distance to river, irregular contact with water of river during flood events), and the river crest (15 m or more distance to river, not in contact with the river; Figure II.2A). At each station a circle with a radius of 1.5 m (~7.1 m²) was established with a stick, string and pebbles. This method was based on the study by Rech et al. (2015) that used circles instead of quadrats because circles were easier to establish on complex substrata and/or sites with abundant vegetation cover. Participants sampled all litter within the circles and classified it according to type: paper, cigarettes, plastic, metal, glass, food leftovers, and other items. This classification followed categories previously used in litter studies with schoolchildren (e.g. Rech et al. 2015, Hidalgo-Ruz et al. 2018). More detailed lists with more specific categories of litter items were not used to not increase the complexity of this activity. A photo of the litter from each station was taken on a white background (Figure II.3A) and sent, together with the collected data, to the coordinating laboratory (*Kieler Forschungswerkstatt*). Afterwards the litter was disposed into litter bins.

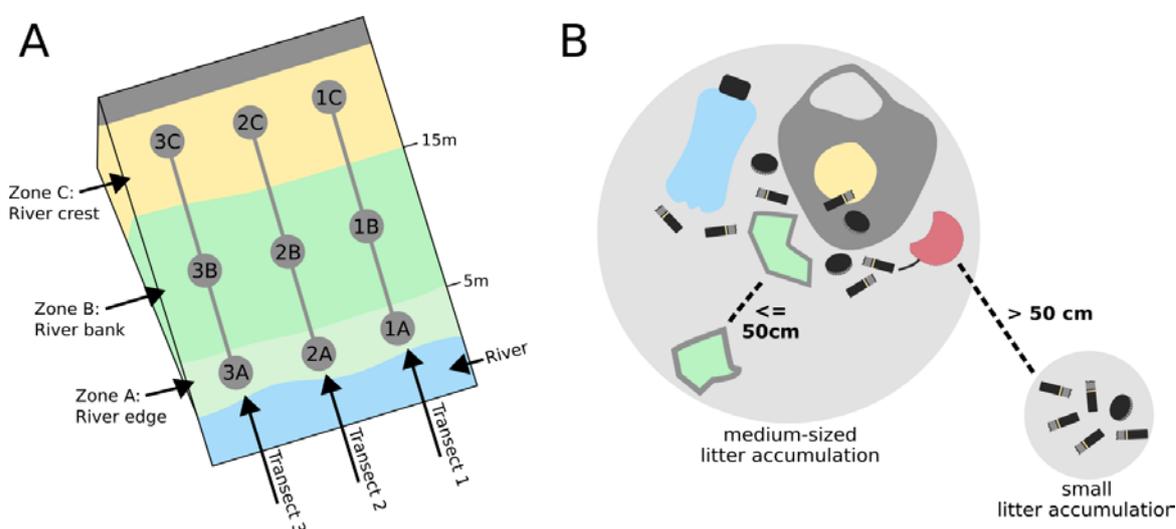


Figure II.2. (A) Sampling method for riverside litter: three transects were established in three different zones, according to the distance to the river. (B) Identification of litter accumulations according to the numbers of litter items encountered at one spot: at least three items had to be located close to each other to count as a litter accumulation. All items less than 50 cm apart were part of the same accumulation. If items were more than 50 cm apart they counted as a new accumulation (or as no accumulation, if less than three items were present). Images can be reused under Creative Commons license Attribution 4.0 International (CC-BY 4.0).

II.3.4. Sampling of litter accumulations and identification of dangerous materials

A roughly rectangle-shaped area was established with a measuring tape at the riverside and coordinates of the corner points were recorded with a GPS device or smartphone. The longer side was established parallel, the shorter side perpendicular to the river course. The size of the rectangle varied according to the available space, but covered at least 1000 m², in which litter accumulations were surveyed. An “accumulation” was counted as such if three or more litter items were located not more than 50 cm apart from each other (Figure II.2B). The participants had to count and take pictures of small (3 to 10 litter items, Figure II.3B), medium-sized (11 to 25 items, Figure II.3C), and large litter accumulations (more than 25 items, Figure II.3D). The surface area a litter accumulation occupied was not measured by participants as this had led to complications in a previous study (Rech et al. 2015). In 2016 we had asked participants to identify the main material the litter accumulations consisted of, additionally to the size. This frequently led to confusion and many groups counted single litter objects as accumulations. For the sampling in 2017, only the size of a litter accumulation was registered.

Participants also identified any of the following items potentially dangerous to human health in the same area used to survey litter accumulations: broken glass, sharp metal objects, used personal hygiene articles, decomposing food leftovers (which could attract disease-carrying animals or harm small children upon accidental ingestion), and litter items containing chemicals (e.g. aerosol cans, batteries, paint containers). Potentially dangerous litter items were not quantified but only absence or presence was noted. If litter was collected during this part of the investigation (this decision was left to the supervisor) it was disposed into litter bins.



Figure II.3. (A) Some of the riverside litter found by students from the school Reichswald-Gymnasium, having identified a total of 383 litter items at their sampling site at the Mohrbach (part of the Rhine river system). The majority of litter encountered by this group were broken pieces of glass. (B) A small litter accumulation consisting of cigarette butts, found by students from the Realschule Maria Stern at the Eger-Wörnitz river, belonging to the Danube river system. (C) A medium-sized litter accumulation encountered by students from the Gymnasium Fabritianum at the Rhine, consisting of plastic cutlery and wet wipes. (D) A large litter accumulation representing leftovers from a barbecue (fireplace, plastic bottles, plates and bags, amongst other litter). Also found by students from the Gymnasium Fabritianum at the Rhine. Photos can be reused under Creative Commons license Attribution 4.0 International (CC-BY 4.0).

II.3.5. Inference of litter sources

Participants explored the surroundings of their sampling site, and, using several criteria (the use-type of encountered items, the size of litter objects or accumulations, and the location of litter at the riverside), they inferred which of the following sources are likely contributing to local litter pollution: residents, visitors (people using the river environment as a recreational area), people dumping litter illegally, industry, ship/boat traffic (including small leisure crafts as well as large river barges), and the river itself (washing up litter from upstream sources). Each of the sources had to be ranked on a five-point-scale: possible responses to the research question “Is the respective source contributing to local litter pollution?” were “Yes”, “Likely”, “Possibly”, “Unlikely”, and

“No”. For analysis the first two responses were merged to represent a positive response to the question and the latter two responses were merged to represent a negative response (the answer “Possibly” was not taken into account).

II.3.6. Stepwise verification of submitted citizen science data

To verify data it was first checked whether vital information about the sampling was available (e.g. date and place). Then, data for each individual group were assessed in multiple steps and accepted if criteria were passed (Figure II.4, Supplement A2-1). For riverside litter and litter accumulations, the photos of the respective litter findings were compared to the data submitted by participants. Only data from groups that provided at least one photograph were accepted (unless no litter was found). If no photo was provided, or if the litter was misidentified or misclassified, the dataset was rejected (see Supplement A2-2 and A2-3 for a detailed description of the stepwise verification process and example photos used to evaluate data). To verify the size of the sampling area established by participants surveying litter accumulations, we used the submitted GPS coordinates and (with the polygon tool in Google Earth Pro 7.31.4507) compared the value to the area measured by the groups with the measuring tape.

Data for the identification of dangerous materials and the inference of litter sources were accepted if submitted data sheets were legible, complete, and unambiguous (Supplement A2-4, A2-5). To support the evaluation of litter sources by the participants, we reviewed photos of litter accumulations and assigned likely sources to each accumulation based mainly on the use-type of items within an accumulation (Supplement A2-5).

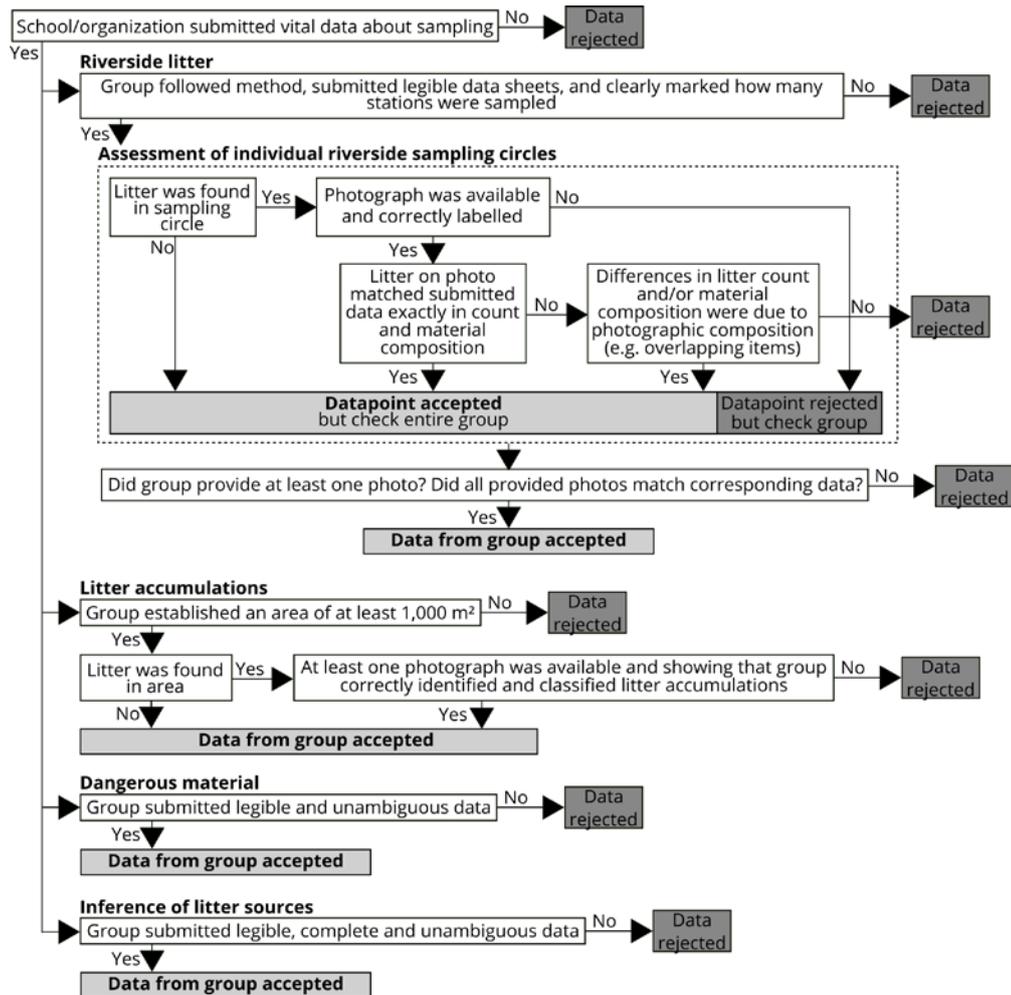


Figure II.4. Data verification flowchart for riverside litter, litter accumulations, the identification of dangerous materials, and inference of litter sources. For riverside litter each data point (originating from one sampling circle) was analyzed individually (located within dotted box) and subsequently considered in the context of all data from the respective group. See also Supplement A2 for further information.

II.3.7. Statistical analyses

For the analysis of riverside litter each sampling circle was treated as one data point (each circle had the same area), so that one group could contribute up to nine data points. A zero-altered negative binomial (hurdle) model was developed (Zeileis et al. 2008, Zuur et al. 2009), testing which variables (river system, sampling year, riverside zone, or any interaction thereof) would explain the differences in litter quantities encountered at the sampling sites. This is a two-step model comparing the amount of zeroes independently from the positive values, because it is assumed that zero values can have two different causes: there may be no litter because a litter source is absent (e.g. riverside is not accessible or unattractive for recreational visitors or the river is too small for ship/boat

traffic). On the other hand, no litter may be found because a particular source that was present did not cause any litter at the sampling site.

Only integer values are considered by the model, therefore the total litter count per circle was used for this analysis. Datasets from rivers flowing into the North Sea were excluded ($n = 3$), as only data from 2016 were available, leading to missing interactions which made the model incomputable. Different models were created with combinations (and interactions) of the variables “river system” (Rhine, Weser, Elbe, Baltic Sea, Danube), “sampling year” (2016, 2017), and “sampling zone” (river edge, river bank, river crest). The model with the lowest AIC value was accepted. Subsequently, pairwise post-hoc tests (with Tukey-HSD p-value adjustment) were conducted for each variable and significant interaction.

Litter densities at rivers of different sizes (i.e. widths of rivers) were compared using a Kruskal-Wallis rank sum test, as variances between the size categories were not homogeneous (Levene's test, $df = 5$, $F\text{-value} = 2.94$, $p\text{-value} = 0.01$). Dunn's post-hoc test (with Holm-Šidák p-value adjustment) was conducted for pairwise comparisons when significant differences were found.

For litter accumulations a one-way ANOVA was conducted for each size class (small, medium, and large) and for the total number of accumulations (variances were homogeneous across river systems, Supplement A3-1).

For the analysis of dangerous materials, and the inference of litter sources, Fisher's exact test of independence (two tailed, 10,000 repetitions) was used to compare whether the response (presence or absence for dangerous materials, and likely or unlikely litter source) was distributed differently across dangerous litter types, and litter sources, respectively (McDonald 2014). If a significant difference was discovered it was followed up with a Bonferroni-corrected pairwise comparison.

The p-value of all tests was set at 0.05. The following packages from R (version 3.4.1; R Development Core Team 2017) were used for analyses: `pscl` 1.5.2 (Zeileis et al. 2008, Jackman 2017), `lmtest` 0.9-35 (Zeileis and Hothorn 2002), `lsmeans` 2.27-61 (Lenth 2016), `car` 2.1-6 (Fox and Weisberg 2011), and `dunn.test` 1.3.5 (Dinno 2017).

II.4. Results

II.4.1. Data verification

After stepwise verification of the submitted data, 62 out of 408 project groups (15%) had to be excluded because vital information about the sampling was missing. 360 groups conducted the sampling of riverside litter and data from 179 groups (50%) were accepted and used for analysis (for example 80 groups did not submit any photograph and their data were therefore rejected, see Supplement A2-2 for details). Litter accumulations were surveyed by a total of 355 groups and data from 66 groups (20%) were accepted. 158 groups conducted the sampling in 2016 for which data were rejected (see Materials and Methods) and many other groups did not corroborate their findings with photographs (Supplement A2-3). For the 46 groups that submitted appropriate GPS measurements of their sampled area an average deviation of 6,100 m² to their measured area was found. Nevertheless, we chose to consider all 66 datasets, as errors are more likely related to faulty measurement with GPS devices or smartphone applications (instruction on how to record coordinates were not explicit in the workbook) than to actual errors using measuring tape during sampling.

For the identification of dangerous materials datasets from 387 groups (83%) were received and data from 320 groups accepted (Supplement A2-4). 314 groups submitted data for the inference of litter sources and data from 261 groups (83%) were accepted (see Supplement A2-5 for details).

II.4.2. Riverside litter

A total of 5,955 litter items were quantified at riversides for an overall median of 0.14, interquartile range (IQR) 0 – 0.57 items m⁻² and an overall average (\pm standard deviation) of 0.54 ± 1.20 litter items m⁻². Litter densities ranged from 0 items per circle to a maximum of 174 items found in a circle at the river Mohrbach. The majority of groups (91%) identified at least one litter item at their sampling site, and almost two thirds of all sampling circles contained litter (Table II.1). The best-fitting model considered the river system and sampling year (but not the shore zone) as significant to predict encountered litter densities (Table II.2). The percentage of sampling circles with litter (Figure II.5A) as well as the count of litter items differed significantly between river system and sampling year (Figure II.5B, see Supplement A3-2 for posthoc tests) but this pattern was inconsistent: in some river systems the density was higher in 2016 (e.g. the Rhine), while

in others higher densities were observed in 2017 (e.g. the Elbe and Danube). Rivers flowing into the Baltic Sea consistently had low densities. Litter quantities and percentage of sampling circles containing litter at other river systems were in between (Figure II.5, Table II.1).

Table II.1. Overview of riverside litter, litter accumulations and dangerous materials for each river system and sampling year. Only accepted datasets are represented.

	Percentage of sampling sites with litter findings (number of surveyed sites)	Percentage of sampling circles containing litter (number of surveyed circles)	Median litter density, with interquartile range per m ² in sampling circles (surveyed area in m ²)	Percentage of sampling sites with litter accumulations (number of surveyed sites)	Average number of litter accumulations of any size per 1,000 m ² ± standard deviation (surveyed area in m ²)	Percentage of sampling sites with findings of dangerous materials (number of surveyed sites)
All river systems, both years	91% (179)	61% (1,564)	0.14, 0 – 0.57 (11,056)	na	na	89% (320)
All river systems 2016	90% (95)	60% (832)	0.14, 0 – 0.57 (5,881)	na	na	87% (160)
All river systems 2017	93% (84)	63% (732)	0.14, 0 – 0.57 (5,175)	85% (66)	1.52 ± 2.03 (418,875)	91% (160)
Rhine 2016	98% (48)	69% (426)	0.28, 0 – 0.85 (3,011)	na	na	87% (75)
Rhine 2017	93% (43)	60% (376)	0.14, 0 – 0.57 (2,658)	90% (30)	1.69 ± 2.42 (185,420)	91% (75)
Weser 2016	91% (11)	51% (87)	0.14, 0 – 0.42 (615)	na	na	88% (24)
Weser 2017	92% (12)	58% (98)	0.14, 0 – 0.57 (693)	60% (5)	1.53 ± 1.88 (22,200)	89% (19)
Elbe 2016	77% (17)	50% (150)	0.07, 0 – 0.42 (1,060)	na	na	83% (30)
Elbe 2017	92% (13)	62% (117)	0.14, 0 – 0.71 (827)	77% (13)	1.05 ± 0.92 (112,890)	94% (31)
North Sea, other 2016	100% (3)	74% (27)	0.28, 0.7 – 0.85 (191)	na	na	75% (4)
North Sea, other 2017	na	na	na	na	na	100% (2)
Baltic Sea 2016	67% (9)	41% (81)	0.00, 0 – 0.28 (573)	na	na	87% (15)
Baltic Sea 2017	100% (5)	71% (42)	0.14, 0 – 0.42 (297)	80% (5)	0.75 ± 1.43 (33,375)	89% (9)
Danube 2016	86% (7)	59% (61)	0.14, 0 – 0.28 (431)	na	na	100% (12)
Danube 2017	91% (11)	73% (99)	0.28, 0 – 0.92 (700)	92% (13)	2.28 ± 1.95 (64,990)	88% (24)

The model also showed a significant difference in litter quantities per sampling year (Tukey-adjusted posthoc test, $df = 1516$, $t\text{-ratio} = -3.10$, $p\text{-value} < 0.01$), yet the difference is very small: the median for both years was the same at 0.14, IQR 0 – 0.57 items m^{-2} . Litter densities at the riverside further differed according to the size of the river (Kruskal-Wallis rank sum test, $df = 5$, $\chi^2 = 67.90$, $p < 0.01$): smaller rivers (up to 10 m wide) had significantly less litter than wider rivers (median small rivers: 0.07, IQR: 0 – 0.39 items m^{-2} ; median wide rivers: 0.28, IQR: 0 – 0.71 items m^{-2} ; see Supplement A3-3 for all size classes).

Table II.2. Results of the zero-altered negative binomial (hurdle) model selection process. A * marks interactions between variables. The results of the likelihood ratio test refer to comparison with the previous model in the table. The selected model with the lowest AIC value is marked in bold.

Model	df	AIC	Likelihood ratio test
River system * Year * Zone	61	7,069	
River system * Year + Zone	25	7,045	$\chi^2 = 48.11$ ($df = -36$, $p = 0.085$)
River system * Year	21	7,040	$\chi^2 = 2.68$ ($df = -4$, $p = 0.613$)
River system + Year	13	7,061	$\chi^2 = 36.68$ ($df = -8$, $p < 0.001$)
River system	11	7,061	$\chi^2 = 4.43$ ($df = -2$, $p = 0.109$)

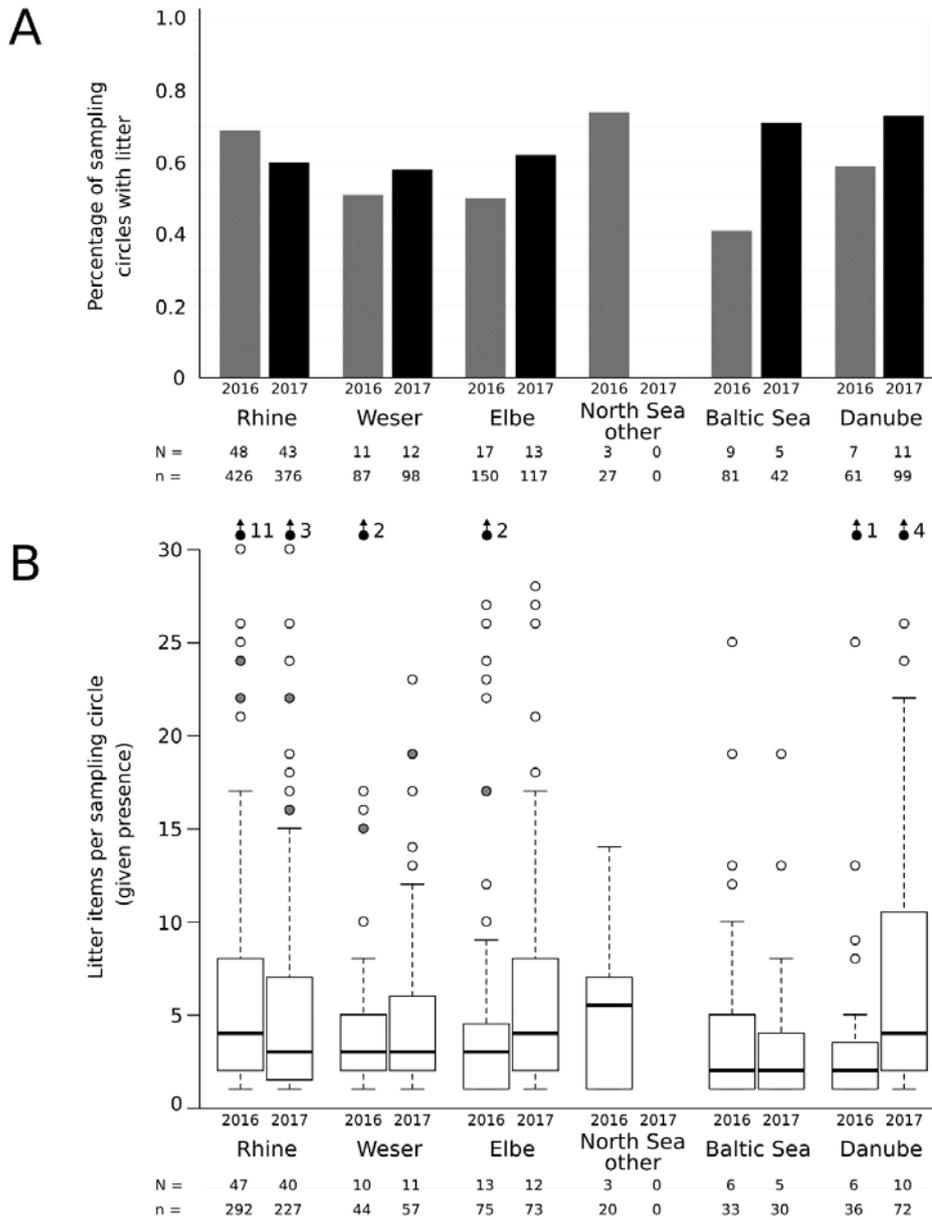


Figure II.5. Representation of data considered by the two-step hurdle model to analyse riverside litter in sampling circles for different river systems and sampling years: (A) first the probability to encounter litter in a sampling circle is analysed (zero versus non-zero values), and subsequently, (B) if litter is found, the total amount of litter per sampling circle is compared across variables. Whiskers of the boxplot represent the 1.5 interquartile range. Outliers are represented by dots (filled if multiple outliers have the same value). The number of outliers exceeding the scale are indicated by the number next to arrows at the top of the boxplot. N = Number of datasets considered, n = number of sampling circles considered for respective part of the model.

Riverside litter consisted mainly of plastics (30.5% of all litter found), followed by cigarette butts (20%), glass (16%), paper (13%), and metal (11.5%). Food leftovers (2%) and other items (7%) accounted for a fraction of the litter found (Figure II.6). Litter

composition differed between river systems, years, and rivers of different sizes (e.g. more plastics were found at the Rhine, compared to the Elbe and Danube river system, Kruskal-Wallis rank sum test, $df = 5$, $\chi^2 = 36.53$, $p < 0.01$), but differences were often relatively small and not consistent.

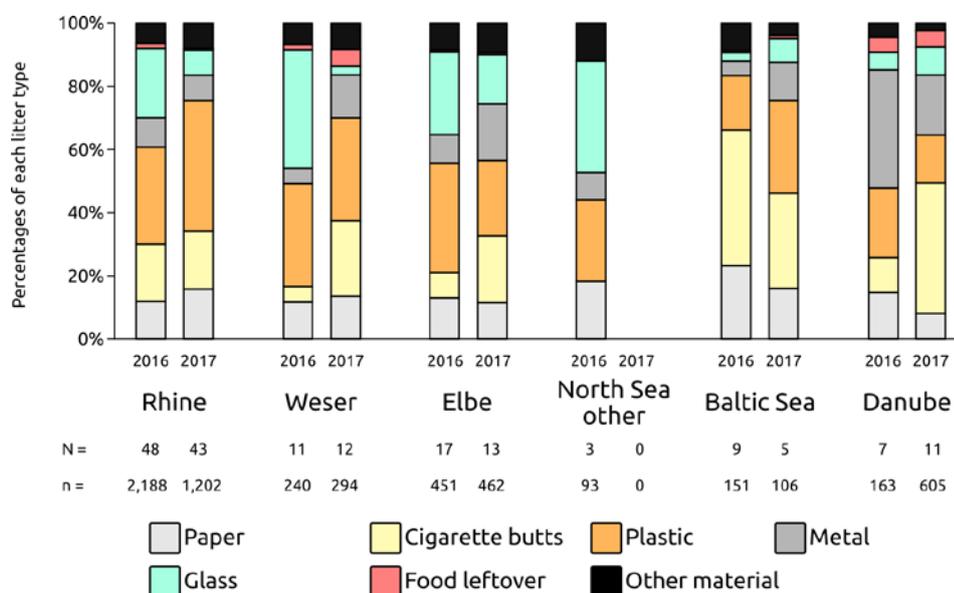


Figure II.6. Composition of riverside litter according to sampling year and river system. N = number of datasets considered, n = number of litter items found.

II.4.3. Litter accumulations

Most datasets considered for analysis of litter accumulations mention the occurrence of small accumulations (83%). Medium-sized or even large litter accumulations had been seen less frequently (by 43% and 34% of the groups, respectively). In total 638 litter accumulations were identified in an area of 418,875 m², averaging 1.5 ± 2.0 accumulations * 1000 m⁻². More litter accumulations were spotted at riversides of the Danube river system (2.3 ± 2.0 accumulations * 1000 m⁻²), followed by the Rhine, Weser, and Elbe system (Table II.1). Least accumulations were found at rivers flowing into the Baltic Sea (0.8 ± 1.4 accumulations * 1000 m⁻²). No datasets were available for litter accumulations at other rivers flowing into the North Sea. There were no significant differences between river systems considering the total amount of litter accumulations or size classes of litter accumulations (see Supplement A3-1 for ANOVA results).

For 277 photographs of litter accumulations the material composition could be inferred by the coordinating laboratory. Plastic and cigarettes were the principal components in most of them (43% and 23%, respectively). Regarding the use-type of

items, many of these accumulations contained items related to food packaging (44%), smoking (26%), preparing and consuming food (18%, indicated by e.g. plastic cutlery or barbecue grills), and consumption of alcohol (11%).

II.4.4. Observation of dangerous materials

Nearly all groups (87% in 2016 and 91% in 2017, overall 89%) observed at least one dangerous litter item of any category at their sampling site (Figure II.7A, Table II.1). The type of dangerous materials found differed significantly (Fisher's test, 10,000 replicates, p-value < 0.01): broken glass was found significantly more often (at 70% of the sites) than sharp metal objects and used personal hygiene articles (at ~50% of all sites). Those latter items were also significantly more frequent than decomposing food leftovers (found at 34% of sampling sites), which in turn was found significantly more often than items classified as chemicals (present at 21% of sampling sites; Table II.3). There was little and non-significant variation between river systems and sampling years in the percentage of sampling sites where dangerous materials is present (Fisher's test, 10,000 replicates, p-value = 0.97, and Fisher's test, 10,000 replicates, p-value = 0.38, respectively).

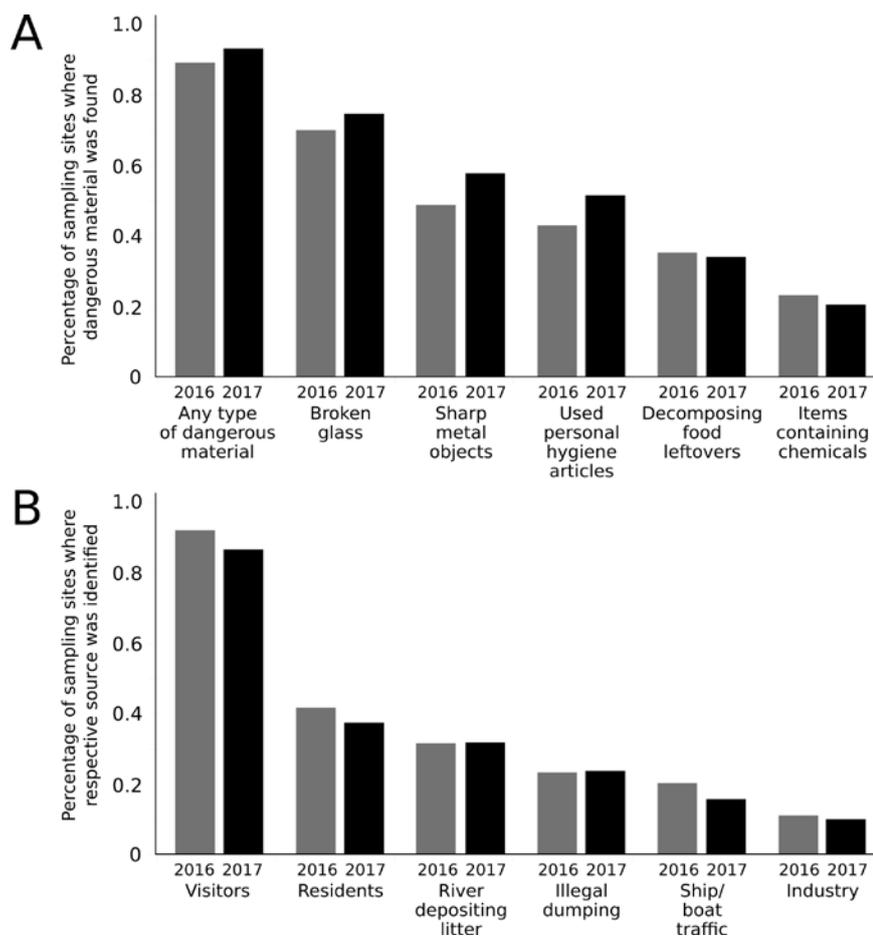


Figure II.7. (A) Percentage of sampling sites with findings of respective dangerous materials in 2016 and 2017 at sampling sites across Germany (number of datasets for 2016 = 160, 2017 = 160). (B) Percentage of sampling sites across all Germany in 2016 and 2017 where respective source has been identified as a likely origin of encountered litter (number of datasets for 2016 = 134, 2017 = 127).

II.4.5. Inference of litter sources

Groups at almost all sampling sites (90% in 2016 and 84% in 2017, overall 87%) considered visitors who use the river as a leisure area as a likely source for local litter pollution (Figure II.7B). This was significantly more often than the consideration of residents and the river itself (depositing litter from upstream sources) as litter sources (Fisher's test, 10,000 replicates, p -value < 0.01, Table II.3), which have been identified by about a third of the groups (38% and 31%, respectively). People dumping litter illegally, ship/boat traffic and industry have been identified less frequently as likely sources. These evaluations were consistent between years and with few exceptions also for river systems: visitors have been identified in all river systems and both years as the most likely source of litter, but the order of other sources varied slightly (Supplement A3-4). Size of the river did not affect the frequency of mentioned sources, with the exception of ship/boat traffic

being mentioned more frequently as a likely source of litter for rivers wider than 100 m (Supplement A3-4).

The revision of 277 photos of litter accumulations suggested that the majority of accumulations could be attributed to visitors (88%). Fewer photos contained indication that litter accumulations originated from residents (13%), were illegally deposited (11%), or came from an industrial activity (4%), with other sources (ship/boat traffic, river itself) being of minor importance (Supplement A2-5).

Table II.3. Results of Bonferroni-corrected pairwise comparisons for Fisher’s exact test of independence for dangerous materials and litter sources. The p-value of 0.05 has to be divided by the numbers of comparisons conducted by the Bonferroni posthoc-test (McDonald 2014), i.e. p-value of 0.005 for dangerous materials (p-value 0.05 / 10 comparisons), and 0.003 for litter sources (p-value 0.05 / 15 comparisons). Significant comparisons are marked in bold.

Comparison	p-value
Dangerous materials	
Broken glass – Sharp metal objects	<0.005
Broken glass – Used personal hygienic articles	<0.005
Broken glass – Decomposing food leftovers	<0.005
Broken glass – Chemicals	<0.005
Sharp metal objects – Used personal hygienic articles	0.155
Sharp metal objects – Decomposing food leftovers	<0.005
Sharp metal objects – Chemicals	<0.005
Used personal hygienic articles – Decomposing food leftovers	<0.005
Used personal hygienic articles – Chemicals	<0.005
Decomposing food leftovers – Chemicals	<0.005
Litter sources	
Visitors – Residents	< 0.003
Visitors – River depositing litter from upstream sources	< 0.003
Visitors – Illegal dumping	< 0.003
Visitors – Ship/boat traffic	< 0.003
Visitors – Industry	< 0.003
Residents – River depositing litter from upstream sources	1
Residents – Illegal dumping	< 0.003
Residents – Ship/boat traffic	< 0.003
Residents – Industry	< 0.003
River depositing litter from upstream sources – Illegal dumping	0.073
River depositing litter from upstream sources – Ship/boat traffic	< 0.003
River depositing litter from upstream sources – Industry	< 0.003
Illegal dumping – Ship/boat traffic	0.662
Illegal dumping – Industry	< 0.003
Ship/boat traffic – Industry	0.427

II.5. Discussion

II.5.1. Citizen science approach and data collection

Many studies addressing litter pollution and its impacts in the coastal environment have made use of data contributed by volunteers (e.g. Gregory 1991, Moore et al. 2009, van Franeker et al. 2011, Nelms et al. 2017, Hidalgo-Ruz et al. 2018). The citizen science approach may have limitations (e.g. Dickinson et al. 2010), but when these are taken into account and adequate strategies applied (e.g. training of volunteers, simple instructions, and data verification mechanisms, Hidalgo-Ruz and Thiel 2015), the quality of data contributed by volunteers are able to match that of professional scientists (Zettler et al. 2017). Citizen science is used in a variety of fields, e.g. biodiversity, conservation, astronomy, meteorology, and so on (Dickinson et al. 2010), and does not only contribute scientific data but can also increase the scientific literacy of participants and allow them to participate in decision-making processes by informing policy makers (e.g. Thiel et al. 2014).

The present study incorporated a stepwise verification process of citizen science data. If requirements were not met, respective datasets were excluded from analyses to guarantee reliable and replicable data. Here we applied the most stringent criteria, rejecting entire datasets when minor discrepancies between submitted data and photos were detected (Supplement A2-2). Further, all datasets without photographic evidence were rejected, even though the data verification process (for datasets with photographs) illustrated that relatively few data points were erroneous (about 6%). Therefore, most groups and participants were able to correctly identify, quantify and classify the litter encountered at riversides. A large problem were missing photographs or information, which led to rejection of datasets from over 100 groups. Reasons for this were mainly logistical, including problems with uploading photos to the project website, and the time that passed between the reception of data and asking for missing information by the coordinating laboratory due to the large number of participating groups.

The identification of dangerous litter items in the present study relied on commonly known and well-identifiable objects. Similar litter items are also classified by volunteers in widely employed beach litter samplings (OSPAR 2010, Ocean Conservancy 2018). For the inference of litter sources, the photos of litter accumulations were helpful to verify that most litter originated from visitors. To further support the source identification it would be helpful to investigate each litter item more closely, and assign possible sources

via multivariate techniques or the identification of indicator items (Tudor et al. 2004, Silva et al. 2008, Prevenios et al. 2018). A specific guide for participants on taking pictures of litter would help implement these steps in citizen science studies, where the collected litter items are not available to the coordinating laboratory for posterior verification.

Litter accumulations in 2016 were frequently misquantified, most likely because participants were instructed to additionally record the composition of litter accumulations. In 2017, after simplifying instructions, we rarely found this mistake repeated. Participants in a study by Rech et al. (2015) often misjudged the area surveyed for litter accumulations. To avoid this we asked participants to actually measure the surveyed area with a measuring tape. The additional use of GPS coordinates resulted in many mismeasurements as participants were not properly instructed on how to track coordinates with a GPS device or smartphone.

II.5.2. Litter quantities at rivers in Germany

Quantities of riverside litter differed between river systems: the more polluted riversides were located along the Rhine and Danube system, flowing through Germany's most, and second-most populous region, respectively. For the coastal environment, Jambeck et al. (2015) showed a link between population density and the amount of mismanaged plastic waste entering the sea. This, combined with a high per capita waste production of over 2.1 kg per inhabitant per day in Germany (Hoornweg and Bhada-Tata 2012), may lead to high litter burden at densely-populated sites in the present study. However, there are exceptions: several study sites of the less polluted Elbe and Weser system were located in populous cities, and therefore other factors should be considered as a predictor of local litter pollution as well. Larger rivers (wider than 10 m) also showed higher litter densities than smaller streams. This may be due to better accessibility of larger rivers, larger areas that are open for recreational use, or less possibilities to cross large rivers, which therefore may lead to aggregation of visitors at one well accessible riverside. Larger rivers are also likely to attract more recreational visitors.

Even though there is a significant difference in litter densities between sampling years, this difference is very small and tendencies are opposing in the different river systems, so it cannot be determined conclusively whether litter quantities are higher during spring or autumn. A future study to investigate this would ideally have participants sample the same site during different seasons. In the present study the sampling effort was

not balanced between seasons and sites due to logistical reasons (time-frame in which schools and organizations could participate and their ability to access sampling sites).

The present study also showed no significant difference in litter densities across shore zones. A higher density of litter in the upper zones of beaches has been observed in many coastal litter studies (see Hidalgo-Ruz et al. 2018 and references therein), and this has been hypothesized to coincide with preferred spots used by beach visitors. A possible explanation for the lack of a clear zonation pattern in the present study is a more heterogeneous terrain of river environments when compared to coastal beaches. For example, little space is available at riversides in cities (meaning that litter would be deposited within the first meters of the water's edge), while at other sites large areas are available for public use that may stretch beyond our designated sampling zone.

Considering the occurrence of litter accumulations and dangerous materials, overall there is no difference between river systems and sampling year. The high probability of finding potentially dangerous materials in the present study illustrates that litter not only endangers wildlife but also people (for a discussion of hazardous litter at beaches see Williams et al. 2013). A study on Tasmanian beaches found that a fifth of visitors were affected by litter at some point, mainly by lacerations caused by sharp items (Campbell et al. 2016). Sharp objects were also the most frequently hazardous item in the present study but other items could also present a risk upon accidental ingestion by small children (e.g. food leftovers or even cigarette butts, which have been mentioned as a concern by do Sul and Costa 2007). A quantification of these litter items, and an evaluation of their presence in frequented areas would facilitate a risk assessment of riverside litter to human health.

On average, about two thirds of the litter encountered at the riverside has buoyant properties: paper and cigarette butts can float for a short time, and the latter can quickly contaminate large amounts of water (Green et al. 2014). Most plastics are “persistent buoyant” (Rech et al. 2014) and have a long floating lifetime. It is not given that they reach the sea, though, as river infrastructure (e.g. dams or pillars of bridges), designated litter collection devices (such as litter booms or litter traps; Armitage 2007, Carson et al. 2013, Gasperi et al. 2014), or vegetation at the riverside (Williams and Simmons 1996, 1999) can trap floating litter. However, smaller litter items or microplastics can more readily overcome these obstacles.

II.5.3. Sources of riverine litter pollution and litter mitigation strategies

In the present study visitors to the river environment have been identified as the main source of litter. This is in contrast to Williams and Simmons (1996, 1999) and Rech et al. (2015) who investigated riversides in Wales and Chile, respectively, and identified illegal dumping as a main source of litter. In Germany illegal dumping is probably less likely to occur, because of a better waste infrastructure, also taking care of bulky household waste (when compared to present-day Chile and to Wales two decades ago, judging from solid waste recycling rates; Comisión Nacional del Medio Ambiente 2010, OECD 2018), and possibly more effective law enforcement and prosecution. A higher chance of finding large patches of litter was also associated with riversides that are accessible by car, and aesthetically less appealing (Williams and Simmons 1999), aspects that would merit future investigations in Germany at sites where litter accumulations have been found.

Other sources of river litter that have been suggested in other studies; for example, household litter by residents (Franz and Freitas 2011, Di and Wang 2017), or industry-related litter have been identified in few cases, but the latter source contributes significantly to pollution by microplastics (Lechner et al. 2014, 2015, Klein et al. 2015), which were not sampled in the present study. Ship/boat traffic was not frequently identified as a likely litter source, though naturally more often so at larger rivers. Litter from ships/boat traffic is also not available for survey at riversides (unless washed up), and therefore this potential source is likely underestimated.

Visitors as a principal litter source have been identified in several river litter studies (e.g. Gasperi et al. 2014, Rech et al. 2015, McCormick and Hoellein 2016, Carpenter and Wolverson 2017), and some of those studies have further analysed characteristics of individual litter objects (e.g. their weight and expected motility or purpose of use) to identify which group of visitors cause most litter. In the present study the analysis of photos of litter accumulations indicated that consuming or preparing food and smoking are the principal activities causing litter from visitors to the river environment. McCormick and Hoellein (2016) found highest litter densities related to alcohol consumption at accessible but hidden spaces, where vandalism was also common. Carpenter and Wolverson (2017) identified visitors who consume food or discard litter from vehicles at a well accessible riverside with parking lot, in addition to passing-by visitors and recreational fishers at a hiking path (inferred from beverage bottles and fishing gear that have been left behind).

Litter mitigation strategies should be designed accordingly. Based on the results from the present study we recommend to focus litter mitigation efforts on smokers and people consuming or preparing food at riversides in Germany, although site-specific characteristics (access or proximity to populous areas) should also be considered. In the coastal environment, community education but also prosecution and fees are accepted by many beach visitors to discourage littering (Santos et al. 2005, Eastman et al. 2013). In the riverine environment, picking up litter in the presence of visitors has also been shown to reduce litter quantities (Wagstaff and Wilson 1998, Cingolani et al. 2016). Involving schoolchildren in practical, short-lived activities (such as the present project) seems also important to create awareness and engage them in litter-reducing activities (Hartley et al. 2015). Finally, a governmental strategy to reduce the production of single-use plastic products (as is currently proposed in the European Union for certain items; European Commission 2018) would ensure that fewer products typically consumed by riverside visitors would be packaged in persistent and environmentally harmful material (Rochman and Browne 2013).

II.6. Conclusions and Outlook

Most studies addressing environmental litter pollution treat rivers primarily as a source or litter pathway, contributing to marine pollution. Impacts of litter in the riverine environment, quantities of litter at the riverside (with the potential of becoming marine debris), and sources of riverine litter have been rarely investigated. The present study found that certain litter at many riversides (e.g. sharp and toxic items) present a danger to human health, and that most litter on German riversides is produced by recreational visitors. Future studies should consider which characteristics of sampling sites influence litter densities and distribution (e.g. distance to populous areas or accessibility of riverside), how litter quantities at river sides relate to litter located within a river, and how riverine litter impacts wildlife and people, similar to investigations conducted at beaches and the coastline.

II.7. References

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II.8. Acknowledgements

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

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III.1. 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 $\text{m}^{-1} \text{h}^{-1}$ (average of 0.34 ± 0.89 litter items $\text{m}^{-1} \text{h}^{-1}$). 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 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.

III.2. 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, 2011; 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.

III.3. Materials and Methods

III.3.1. 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.

III.3.2. 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 A1) 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 III.1, Supplement B2). 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). Data for the present study were collected in boreal autumn (16th September to 30th November 2016) and spring (8th May to 17th July 2017).

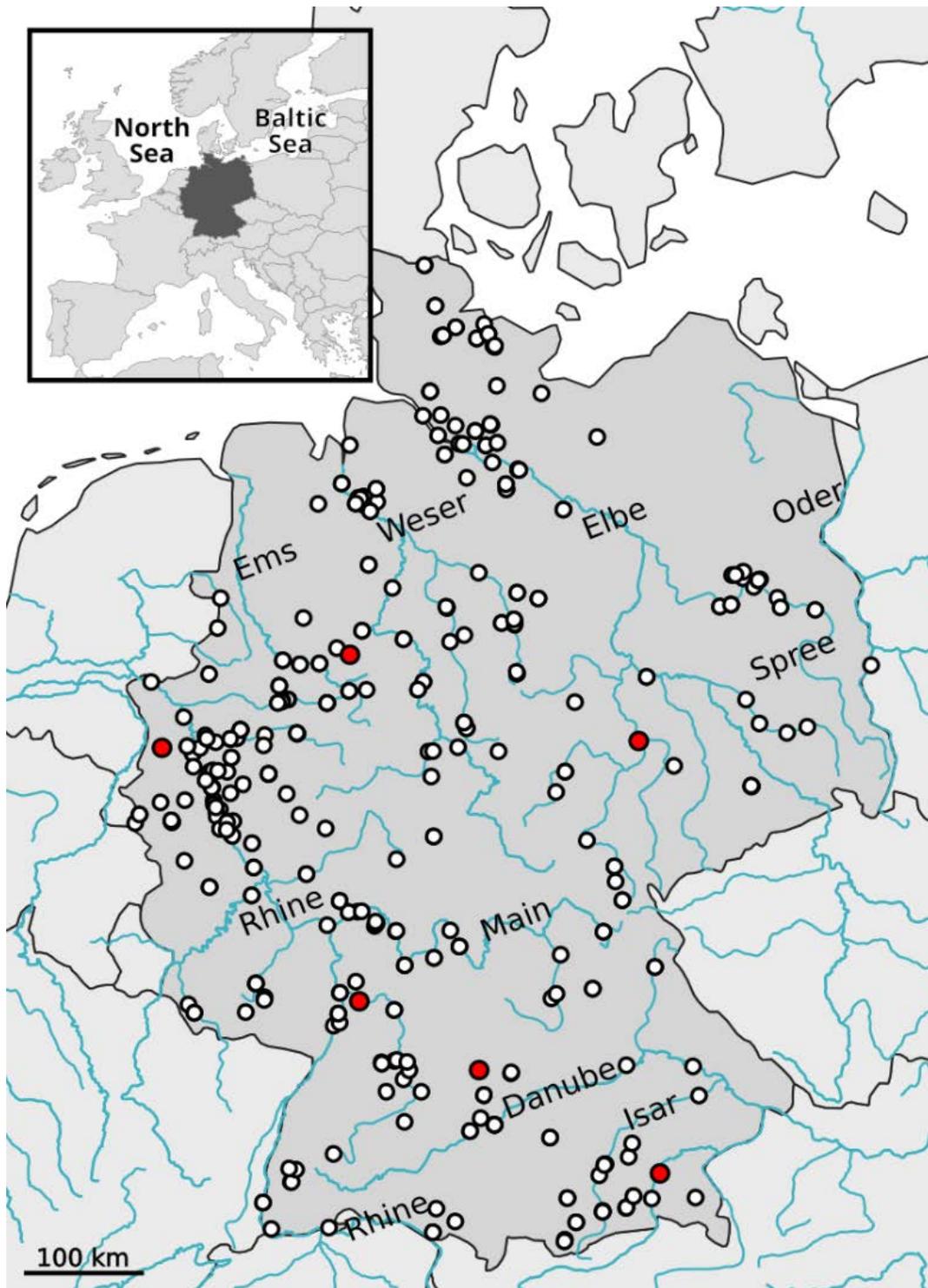


Figure III.1. Map of Germany with major rivers and sampling sites of the Plastic Pirates in 2016 and 2017. Red circles represent sites with many meso-/microplastics (more than 50 particles h⁻¹).

III.3.3. 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 III.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).

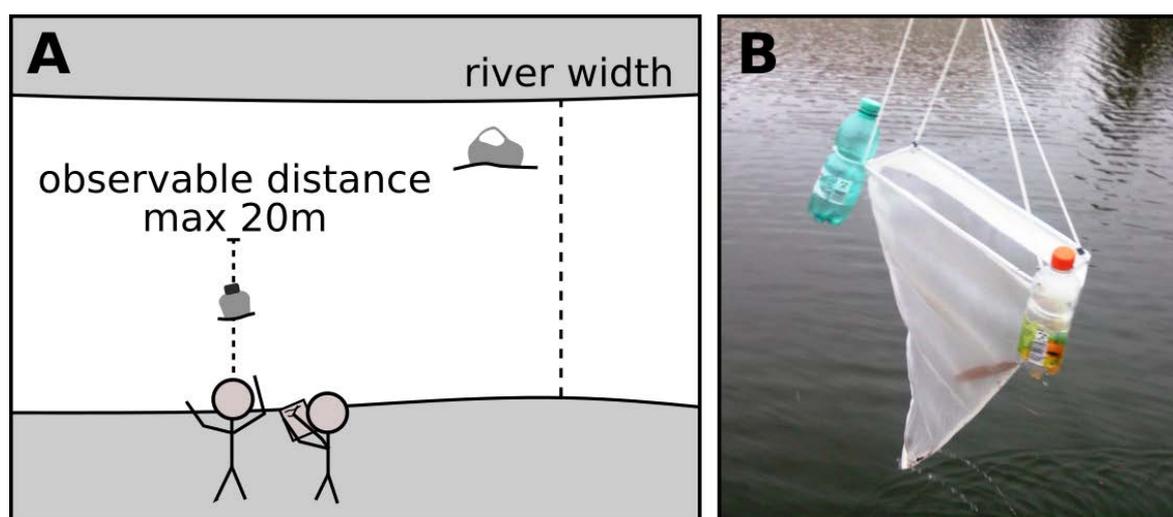


Figure III.2. (A) Survey method for floating macrolitter: litter passing by the observers was counted. For wide rivers a maximum observable distance of 20 m was assumed (see text for details). (B) Sampling net for small plastic particles, equipped with two 0.5 L plastic bottles for buoyancy. © Europaschule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

III.3.4. 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; Figure III.2B). The net had an opening of 35 x 11 cm, of which approximately 35 x 9 cm (0.0315 m²) 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 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 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 tools 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 (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):

$$\text{Meso-/microplastics } \text{m}^{-3} = \text{number of meso-/microplastics in net} / (\text{flow velocity of river} [\text{m s}^{-1}] * \text{net area submerged in river} [\text{m}^2] * \text{deployment time of net} [\text{s}])$$

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).

III.3.5. 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 1,000 m² on the riverside (see Kiessling et al., 2019 for details).

III.3.6. Stepwise verification of submitted citizen science data and samples

III.3.6.1. 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 B3-1). 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 III.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 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 where 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 (Figure III.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 minutes (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 $0.1 - 1.0 \text{ m s}^{-1}$ (a flow velocity $< 0.1 \text{ m s}^{-1}$ frequently indicated that the stick floated in circles or got stuck repeatedly, while a flow velocity $> 1.0 \text{ m s}^{-1}$ 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.

III.3.6.2. 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, 10x – 40x 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. K appler 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 B3-2).

III.3.7. 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 m² 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 km²) 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 m² 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.

III.3.8. 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 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 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.

III.4. Results

III.4.1. 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 $\text{m}^{-1} \text{h}^{-1}$ were found (the maximum number of items $\text{m}^{-1} \text{h}^{-1}$ 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 $\text{m}^{-1} \text{h}^{-1}$ 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 B4 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 (Figure III.3A). At approximately 50% of the sampling sites of each river system floating macrolitter was observed (Table III.1, Supplement B5).

Table III.1. Overview of floating macrolitter and floating meso-/microplastics for each river system as well as for significant variables.

		Percentage of sam- pling sites with litter findings (number of sam- pling sites)	Mean \pm SD	Median (IQR)
Floating macrolitter $\text{m}^{-1} \text{h}^{-1}$				
All sampling sites		54% (282)	0.34 \pm 0.89	0.05 (0.30)
River system	Rhine	45% (135)	0.38 \pm 0.90	0.05 (0.46)
	Weser	46% (39)	0.15 \pm 0.38	0.05 (0.15)
	Elbe	44% (54)	0.38 \pm 1.22	0.10 (0.20)
	North Sea, other	50% (6)	0.15 \pm 0.18	0.08 (0.24)
	Baltic Sea	59% (17)	0.48 \pm 0.88	0 (0.50)
	Danube	48% (31)	0.31 \pm 0.69	0.05 (0.21)
Sampling year	Autumn 2016	50% (141)	0.20 \pm 0.41	0.04 (0.20)
	Spring 2017	43% (141)	0.48 \pm 1.17	0.09 (0.40)
River width at sam- pling site	0 – 3m	47% (34)	1.10 \pm 1.69	0.59 (1.33)
	4 – 10m	57% (60)	0.47 \pm 1.18	0 (0.43)
	11 – 25m	44% (57)	0.16 \pm 0.23	0.05 (0.21)
	26 – 50m	45% (42)	0.15 \pm 0.27	0.05 (0.20)
	51 – 100m	45% (33)	0.20 \pm 0.58	0.05 (0.16)
	> 100m	39% (56)	0.15 \pm 0.20	0.10 (0.20)
Population density around sampling site	< 5,000	51% (159)	0.28 \pm 0.80	0 (0.23)
	5,000 – 20,000	41% (111)	0.40 \pm 0.99	0.10 (0.40)
	20,001 – 100,000	33% (12)	0.61 \pm 1.07	0.15 (0.49)
Floating meso-/microplastics h^{-1}				
All sampling sites		57% (164)	6.86 \pm 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)
	20,001 – 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)

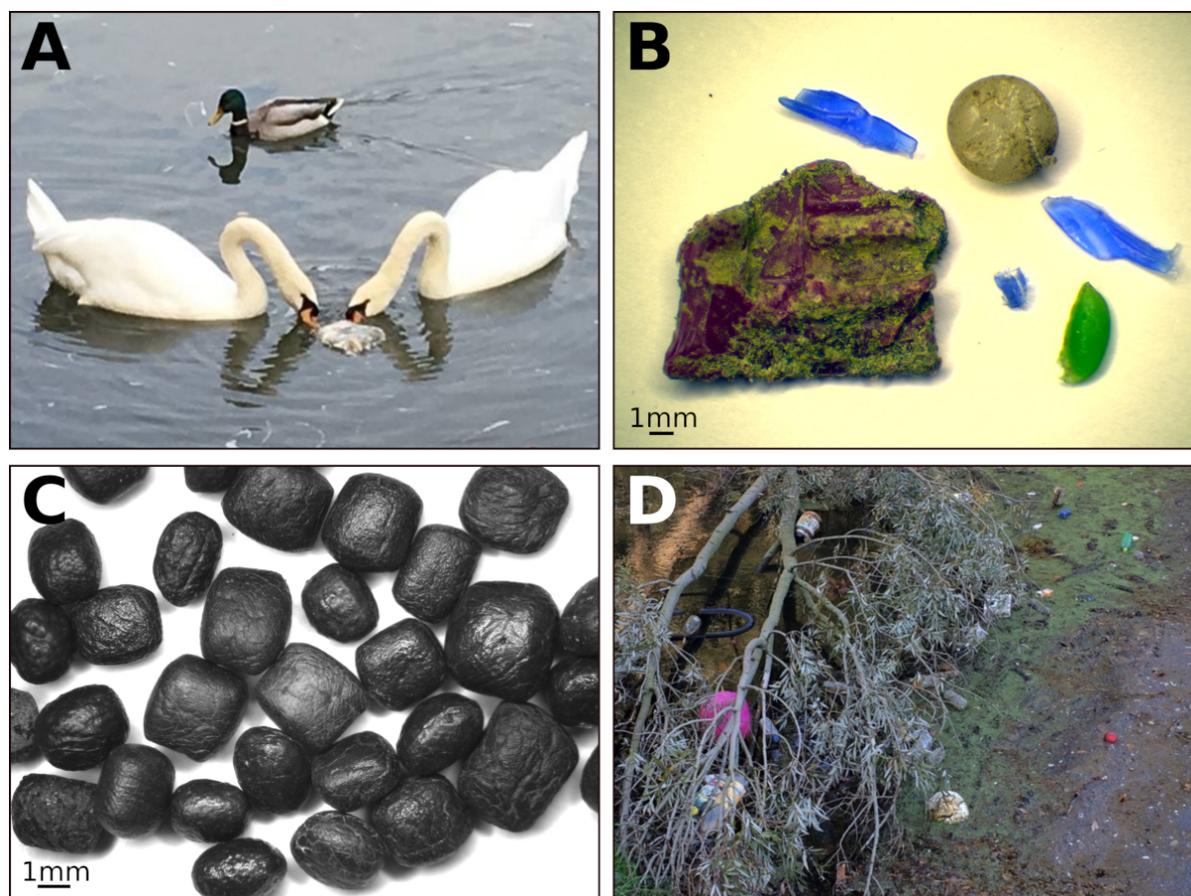


Figure III.3. (A) Swans trying to open a floating plastic bag containing old bread in the Main. © Ernst-Reuter-Schule Frankfurt am Main. (B) Meso-/microplastics found by Realschule Bissingen investigating the Enz (Rhine river system). (C) Some of the polypropylene pellets sampled by Sekundarschule Schkopau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

The model with the lowest AIC (Supplement B6-1) considered the river system, sampling year, river width, and population density at the sampling sites as significant predictors for observed floating macrolitter quantities (Table III.1, Figure III.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 B6-2). There was one significant interaction in the model among the variables river system and population density (Supplement B6-3). 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.

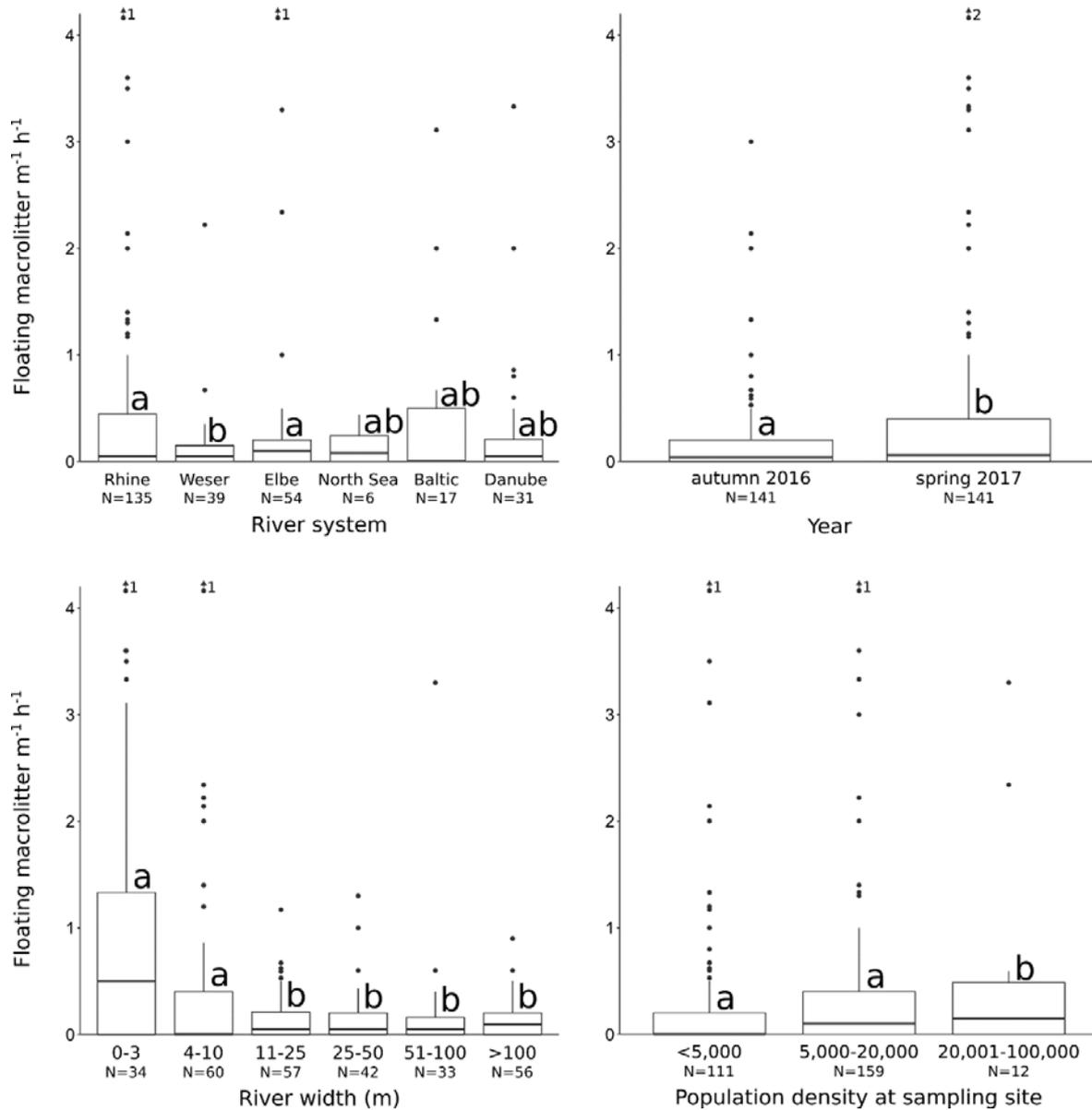


Figure III.4. Boxplot representing floating macrolitter densities for the variables that were selected by the model as significant predictors of litter quantities. The horizontal lines, from bottom to top of each box represent the first quartile, the median, and the third quartile respectively. The vertical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

III.4.2. 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 m³ 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 B4). 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 III.2).

Table III.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 \pm 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)

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 III.3, see Supplement B4 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).

Table III.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; Figure III.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 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 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.

Most meso-/microplastics were soft (42%) and hard fragments (28%; Figure III.3B). Pellets (including hard round or lentil-shaped pellets as well as soft, more rectangular-shaped pellets, Figure III.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 (Supplement B7). 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 III.1, Supplement B5).

The model with the lowest AIC (Supplement B6-1) 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 III.1, Figure III.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 B6-2). 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 B6-3). 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.

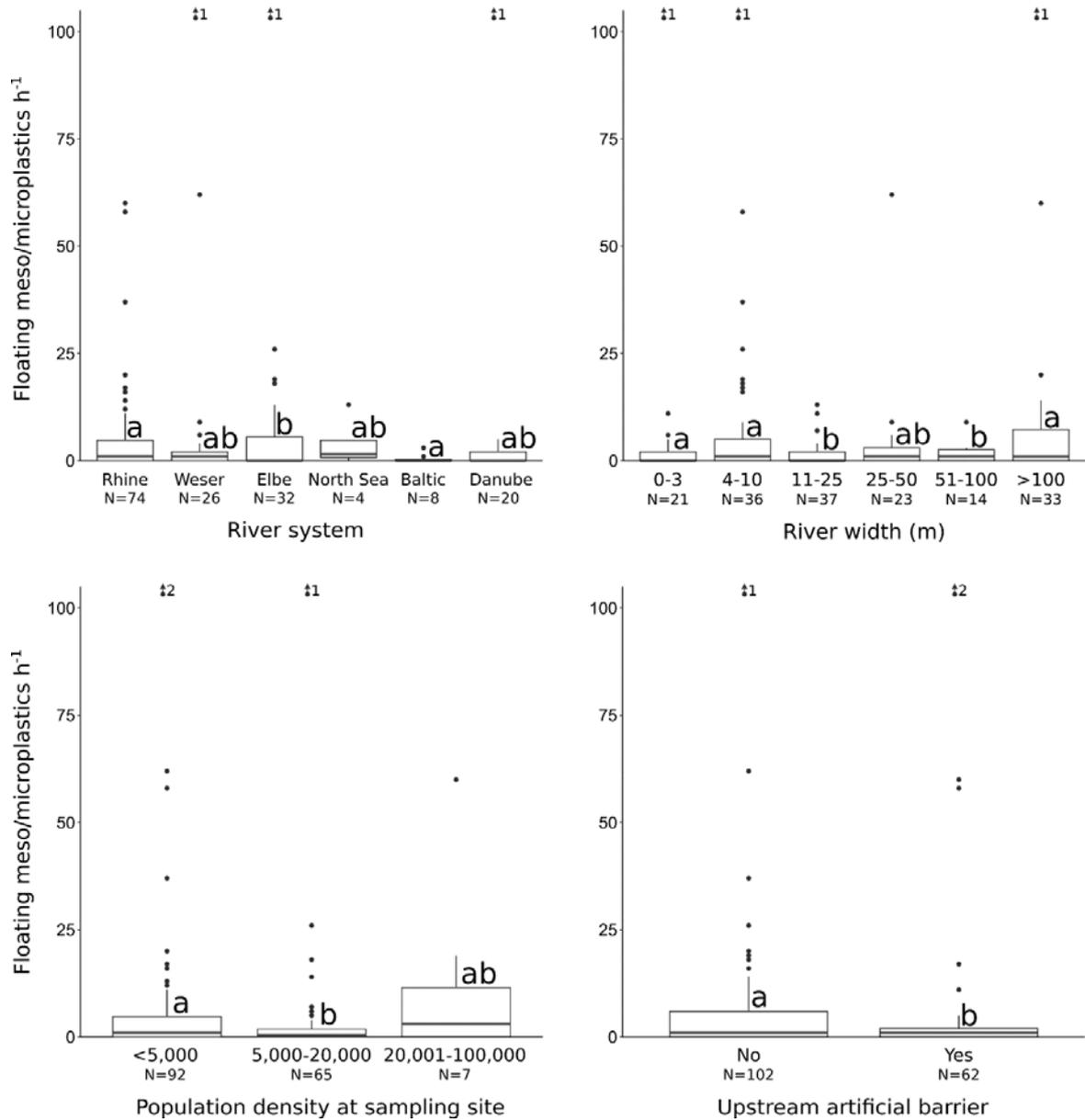


Figure III.5. Boxplots representing floating meso-/microplastic densities for the variables that were selected by the model as significant predictors of litter quantities. The horizontal lines, from bottom to top of each box represent the first quartile, the median, and the third quartile respectively. The vertical line represents the interquartile range * 1.5. Dots represent outliers, while dots with arrows and numbers at the top of charts indicate the number of extreme outliers in each category. Letters mark significant differences. N = Number of datasets in each category.

III.4.3. 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 $\text{m}^{-1} \text{h}^{-1}$ and floating meso-/microplastics h^{-1} , and between floating macrolitter $\text{m}^{-1} \text{h}^{-1}$ and litter quantities at the riverside m^{-2} . For the other comparisons no significant correlation was found (Supplement B6-4).

III.5. Discussion

III.5.1. 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, 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 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 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-/microplastics numbers submitted by the participants rarely matched the actual quantity of particles within the sample (after FTIR-analysis, Supplement B3-2), 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. 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 B1).

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 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).

III.5.2. 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 $0.02 - 0.8 \text{ m}^{-1} \text{ h}^{-1}$, 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 $\text{m}^{-1} \text{ h}^{-1}$, 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 $\text{m}^{-1} \text{ h}^{-1}$, 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 (Figure III.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 $\text{m}^{-1} \text{ h}^{-1}$ 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 Wolverson, 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., 1989 who found recreational litter in Halifax Harbour).

III.5.3. 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 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) 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 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 $\sim 43,000$ 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.

III.5.4. 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., 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: 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).

III.6. 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 on the same river would enable to study small-scale spatial heterogeneity.

III.7. References

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Chapter IV: Mountain streams flushing litter to the sea

– Andean rivers as conduits for plastic pollution

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IV.1. Abstract

Rivers polluted by anthropogenic litter are major transport routes of litter from inland to the coastal zone and the ocean. However, litter studies have primarily focused on marine environments, and the litter dynamics in rivers are still poorly understood. Herein, we explored the abundances, composition and sources of litter at the riversides and in surface waters of mountain rivers from continental Chile in two different years. Additionally, we evaluated whether different temporal, geographic, topographic, hydrologic or anthropogenic factors influence the abundances of litter. Anthropogenic litter was prevalent in Chilean rivers, both at the riversides and in surface waters. Average abundances of riverside litter, floating macrolitter, and small floating plastics were 1.8 items m⁻², 10.1 items h⁻¹ and 5.8 items h⁻¹, respectively, and abundances were generally higher in northern Chile. Plastics dominated in all compartments, comprising 29% of riverside litter and more than 70% of small floating litter, but other litter categories were also present at riversides. Sources of litter in Chilean rivers were mostly local, such as recreational visitors, residents, and illegal dumping, and there were no clear effects of the different tested factors on the abundances of litter. Litter densities in surface waters were low compared to those in lowland slow-flowing rivers in other countries, suggesting that retention of litter is limited in the highly dynamic and rapidly flushing mountain rivers, and thus most litter (primarily plastics) is transported directly to the sea. The results suggest that to adequately address this problem in Chile, prevention measures should be aimed at the identified local sources, by means of education, public policies, legislation, and enforcement.

IV.2. Introduction

It is generally recognized that most marine plastic litter comes from land-based sources (Andrady, 2011), among which riverine input is considered a major contributor, given that rivers transport litter that is produced inland (Lebreton et al., 2017; Schmidt et al., 2017). Consequently, identifying the primary sources of anthropogenic litter in rivers is essential to prevent and adequately manage the problem in riparian environments, and also to reduce coastal and marine litter. Nevertheless, research about litter in freshwater systems is still considerably scarcer than in marine environments (Blettler et al., 2018).

Even though it is widely accepted that rivers do transport litter to the coastal zone, the fraction of riverine litter that effectively reaches the sea through waterways remains

unclear. For instance, while concentrations of floating litter may increase downstream (Kapp and Yeatman, 2018), possibly due to its transport and to the summation of upstream sources, other studies have not found the same increasing trend (Barrows et al., 2018; Weideman et al., 2020). Moreover, floating litter can be frequently retained by getting stranded on the riverside (Williams and Simmons, 1999), by getting trapped behind dams (Zhang et al., 2015), by floating debris-retention booms (Gasperi et al., 2014), or it may be deposited in bottom sediments due to low-flow conditions (Watkins et al., 2019) or to biofilm growth on its surface (Rummel et al., 2017).

Such findings suggest that several factors and conditions may influence the transport of litter downstream, and also that studying and integrating the river shores and the adjacent waters may be relevant to more comprehensively understand litter dynamics in riparian ecosystems. However, the few existing studies about riverine litter are very fragmented, most of them focusing on only one type of environment (i.e., shore or stream) and/or only one type of litter (i.e., macrolitter or microplastics; e.g., Sadri and Thompson, 2014; Mani et al., 2016; Cowger et al., 2019; Kiessling et al., 2019). In turn, markedly fewer investigations have evaluated litter at both the riverside and in the stream (for exceptions see Hoellein et al., 2014; Schöneich-Argent et al., 2020; Kiessling et al., 2021).

A number of studies have suggested population density, mismanaged waste, land use, and/or other anthropogenic variables as the most relevant factors influencing the quantities of litter, its transport in rivers, and its input into the ocean (see e.g., Lebreton et al., 2017; Schmidt et al., 2017; Barrows et al., 2018; Cowger et al., 2019). However, not all rivers are alike and features intrinsic to the rivers, such as hydrology and topography, have seldom been considered. For instance, it could be expected that the abundances and transport of litter show different dynamics in lowland and mountainous rivers.

In lowland rivers with extensive floodplains, flood events may contribute to the transport and deposition of litter onto the adjacent lands, as floodplains are areas of sedimentation and flood retention (Weber and Opp, 2020). In contrast, mountain rivers have relatively narrow valleys with steep slopes, high flow velocity, turbulence, frequent rapids and waterfalls, but without extensive floodplains or long-term depositional areas (Wohl, 2000). These characteristics, along with being the main input of sediments to both lowland river basins (Viviroli et al., 2003) and the sea (Milliman and Syvitski, 1992), suggest that mountain rivers have a high erosional potential and therefore may, during heavy rainfall, storms or floods, transport litter directly into the coastal zone. For example,

Gündoğdu et al. (2018) reported a significant increase in microplastic transport to the sea via a mountain river after a flood period.

In Chile, a very long country with about 4,000 km of coastline, most river basins that drain into the Pacific Ocean originate at high altitudes in the Andean and pre-Andean regions (Ferrando, 1992). Moreover, given the narrow width between the Andes and the Pacific Ocean (90–450 km along the country), these rivers present characteristics of mountain rivers along most of their length. These special features turn Chile into an ideal system to investigate the dynamics of anthropogenic litter in rivers from mountainous regions.

Since citizen science has proven helpful and adequate to study riverine litter (e.g., Rech et al., 2015; Barrows et al., 2018; Cowger et al., 2019; Kiessling et al., 2019), herein we evaluated, with the contribution of schoolchildren as citizen scientists, the litter situation in rivers along and across Chile in 2013 and 2017. During this time period, a consistently rising environmental awareness among the Chilean population led to the implementation of many local policies to regulate litter generation (Amenábar Cristi et al., 2020), and thus a positive change in riverine litter could have been expected. Nonetheless, the opposite (or no change) is also possible, as no temporal changes were found for anthropogenic litter on Chilean beaches from 2008 to 2016 (Hidalgo-Ruz et al., 2018).

Based on the above considerations, the aims of this study were to (i) investigate litter in different compartments of Chilean rivers (i.e., at the riversides and at the water surface), (ii) identify the main litter sources, by means of surveying litter composition, litter accumulations, and exploring different features (e.g., use-type, size, location) of litter, and (iii) evaluate the possible dynamics of litter in these systems, testing whether the abundances of litter in the studied rivers are influenced by different temporal, geographic, topographic, hydrologic or anthropogenic factors, which may serve as a proxy to understand the behavior of litter in mountain rivers.

IV.3. Materials and Methods

IV.3.1. Volunteer participation and citizen science approach

The present study was carried out as part of the activities conducted by the Chilean citizen science program *Científicos de la Basura* (“Litter Scientists”; www.cientificosdelabasura.cl), which focuses on collaborative investigations of environmental litter pollution together with teachers and schoolchildren. Two nationwide samplings of litter in

rivers were conducted, in 2013 and 2017. During each year, teachers and schools located near rivers throughout the country were invited to participate in the project. Some schools participated only one year (either 2013 or 2017), while others did in both years; in total, around 30 schools, 700 schoolchildren and 35 teachers participated each year. In each school, the riverine litter sampling was part of a year-long project and the participating schoolchildren generally belonged to one or more grades (e.g., from extracurricular science workshops). Overall, the ages ranged from 10 to 18 years.

During the project, the schoolchildren first acquired insights into the scientific method, the marine and the riparian environments, the marine litter problem and its relationship with rivers. This served as preparation and motivation for their active participation in a scientific study. The schools then conducted the litter sampling in a nearby river. Throughout the entire project, the schoolchildren were directly guided by their teachers, who, in turn, were constantly accompanied and supported by the coordination team of *Científicos de la Basura*. Following the litter sampling, the data collected by all participating schools were gathered and analyzed by the coordination team. The results (both local and national) were shared with the schools as feedback, and to encourage reflection and discussion about their findings and implications.

IV.3.2. Study area and period

Chile is a very long (>4000 km) and narrow (90–450 km) South American country with an extensive and complex hydrographic network. Rivers are distributed all along the country and most of them flow from the Andes Mountains to the Pacific Ocean. They are generally short and fast-flowing, but present variable regime and discharge characteristics from north to south (Ferrando, 1992) given the wide climatic and geographic variations within Chile, as well as large inter-annual streamflow variation due to the influence of El Niño Southern Oscillation (ENSO, Masiokas et al., 2019). To account for Chile's climatic, geographic, and socio-economic latitudinal variability, herein the country was subdivided into different zones from north to south (zones 1 to 5, following the classification by Bravo et al., 2009; Figure IV.1; see also Supplementary Information C for more background about the study area).

A total of 51 different sites along 27 rivers were surveyed by 60 participating groups: 30 sites along 16 rivers in 2013, and 30 sites along 21 rivers in 2017 (Figure IV.1; for details about sampling sites and rivers see Supplement Tables C1 and C2). Several of the sites and rivers surveyed in 2013 were also studied in 2017, which is why the numbers

indicated for each year do not add up to the total. In some cases, the sampling sites in 2013 and 2017 were not exactly the same but they were in the general vicinity of each other (< 15 km distance along the river).

In general, sampling sites were selected based on their ease of access and safety for the schoolchildren. The samplings were conducted in 2013 and again in 2017 to determine possible general spatial and temporal tendencies at the national level (see Supplementary Information C for details). They were conducted between April and September, but were mostly concentrated in May-June (late austral fall and early winter); the precise sampling dates (Supplement Table C1) depended on the schedules of the schools and the weather conditions at each locality.

Schools conducted various sampling approaches to investigate the different aspects of litter pollution, namely litter at riversides, litter accumulations, floating macro- and small litter, and they also inferred the sources of litter (Supplement Table C1). At each sampling site, the respective school decided which protocol(s) to conduct according to their capacity (i.e., number of schoolchildren and available time). Some of the protocols underwent minor variations from 2013 to 2017, as the first experience facilitated some improvements to the methodologies (details provided in the following sections).

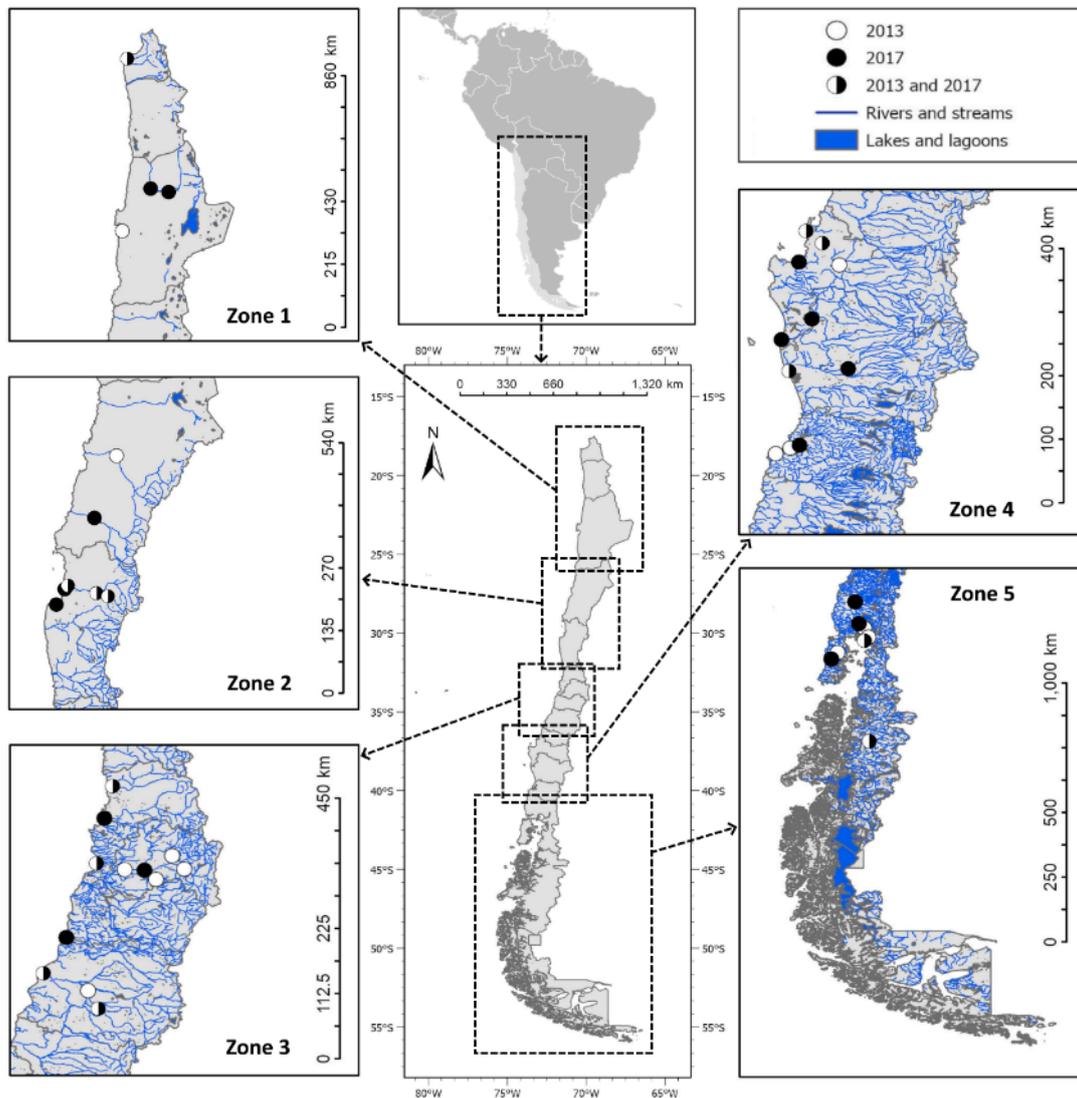


Figure IV.1. Map of Chile showing the five zones in which the country was subdivided for this study and the different sites sampled within each one, per year of sampling. All maps of Chile were generated with ArcGIS Pro 2.4.1.

IV.3.3. Sampling protocols

IV.3.3.1. Sampling of riverside litter

To determine the abundance and composition of litter at riversides, the methodology developed by Rech et al. (2015) and adapted by Kiessling et al. (2019) was used. One to three transects were established at the riverside perpendicular to the river course, each consisting of three sampling stations. Each station was positioned within a particular zone (river edge, river bank, and river crest) to representatively sample the riverside (for details, see Kiessling et al., 2019). At each station a circle with a radius of 2 m (in 2013) or 1.5 m (in 2017) was established, within which all surface macrolitter (i.e., all litter equal to or

larger than a cigarette butt or 25 mm) was collected, quantified and classified into the following categories: papers, cigarette butts, plastics, metals, glass, and other items. In 2017, food leftovers were counted as a separate category.

Since the data were standardized to items m^{-2} , the outcomes of the analyses should not be severely affected by the difference in the radius of the sampling circles. Likewise, Rech et al. (2015), who also sampled circles of different radii, demonstrated that these variations did not affect data analyses as they found a non-significant correlation between the abundance of litter (items m^{-2}) and total area sampled.

IV.3.3.2. Sampling of litter accumulations at riversides

Since illegal dumping had already been identified as a major problem in four main Chilean rivers (Rech et al., 2015), herein we also surveyed litter accumulations at the riversides to evaluate whether it actually constitutes an important source of riverine litter nationwide. The schoolchildren registered the presence/absence of small, medium and large litter accumulations, defined by the area they covered (in 2013) or by the number of litter items that made up the accumulation and the maximum distance between them (in 2017; see Supplementary Information C for details).

IV.3.3.3. Sampling of small litter at the water surface

To sample small litter items (1–20 mm) floating at the surface of rivers, a neuston net with a mesh size of 1 mm and an opening area of 27 cm x 10.5 cm (in 2013) or 35 cm x 9 cm (in 2017) was used. The net was cast with the opening facing into the current, and fixed to a jetty, a bridge, or the riverside for approximately 1 hour, remaining afloat at the surface by means of two empty plastic bottles with closed lids attached to each side of the net opening (Supplement Figure C1). To calculate the load of small plastics in the river (items m^{-3} , Supplement Formula C1), the deployment time of the net and the river flow velocity near the net were recorded. Since the discharge, velocity and width of Chilean rivers are highly variable throughout the year, it is important to reliably measure flow velocity *in situ*. Herein we used the “orange method”, i.e., measuring the time that an orange takes to float over a given length along the river (Rech et al., 2015), due to the high cost of equipping the nets with flow meters. However, some schools had problems measuring the flow velocity, and to maintain as many data points as possible small plastics abundance was finally expressed as items h^{-1} (Supplement Formula C2).

After the sampling, the net was taken back to the respective school, where the schoolchildren extracted and inspected the collected sample. For learning purposes, they first separated the litter items from the natural ones, then the small litter (1–20 mm) from the macrolitter (>20 mm), and finally classified and quantified the small litter items.

Following the schoolchildren's inspection, each sample was carefully put back together (i.e., small litter, macrolitter, and natural items), stored in a labeled hermetic plastic bag or container, and sent to the coordination team to be recounted by a professional scientist. The professional recounts were performed visually under a stereomicroscope, classifying small litter according to plastics, polystyrene, cigarette butts, glass, metals, and other items. In the cases of dubious samples or particles, identification was aided by the use of a compound microscope, a needle (for puncturing organic materials), and/or a density test in filtered water, to differentiate plastics (which most commonly float) from other materials (such as glass or natural items, which do not float). Afterward, visual recounts were verified or corrected by FTIR spectroscopy (see section 2.4). Potential contamination of the samples was accounted for by excluding fibers from analysis during both years (see Supplementary Information C for details).

IV.3.3.4. Survey of macrolitter at the water surface

In 2017, the schoolchildren also counted the floating macrolitter (i.e., litter visible to the naked eye) that passed in front of them along the river surface for approximately 30 min (as described by Kiessling et al., 2021). The schoolchildren were asked to record the observation time and register whether items were of natural or anthropogenic origin, as well as their approximate size (small: size of an apple; medium: size of a football; large: size of a bucket).

Similar visual observation protocols have considered the river width at the sampling site when counting floating macrolitter (e.g., Vriend et al., 2020; Weideman et al., 2020; Kiessling et al., 2021). Herein, however, we did not standardize the abundance of floating macrolitter by the river width, because the width of Chilean rivers varies widely throughout the year and it cannot be reliably determined; instead, we report macrolitter as items h^{-1} , similarly to other studies (e.g., van Emmerik et al., 2019a; van Emmerik et al., 2020).

IV.3.3.5. Inference of litter sources

In 2017, the schoolchildren also explored the surroundings of the sampling site to infer the most probable sources of litter in the river, following the methodology by Kiessling et al. (2019). Participants ranked on a five-point-scale the following possible sources: residents, recreational visitors, illegal dumping, industries, ship/boat traffic, and the river itself washing up litter from upstream sources. They first explored the surroundings of their sampling site and then, based on several criteria such as the use-type, size, and location of litter at the riverside, they ranked each source answering the research question “Is the respective source contributing to local litter pollution?” with the possible responses “Yes”, “Likely”, “Possibly”, “Unlikely”, and “No”. The responses “Yes” and “Likely” were grouped as a positive response, “No” and “Unlikely” as a negative response, and the answer “Possibly” was not considered. The generated data were evaluated in terms of percentage of sampling sites where a potential source was identified (i.e., received a positive response).

IV.3.4. Citizen science data verification

A main concern of citizen science studies is whether the collected data are reliable, and thus it is important to include steps to ensure or improve data quality (Hidalgo-Ruz and Thiel, 2015). Herein we employed the following strategies: (1) the sampling protocols were elaborated prioritizing easy tasks and simplicity of data recording, (2) the coordination team maintained constant contact with the participating teachers to ensure that all activities were appropriately carried out, (3) the teachers were trained prior to the sampling, (4) during the sampling activity teachers and schoolchildren were supported and guided, whenever possible, by a voluntary local scientific advisor who ensured the rigorous conduction of the sampling protocols and identified potential problems with the data collected, and (5) small floating litter items (1–20 mm) were recounted by professional scientists and verified by Fourier-transform infrared (FTIR) spectroscopy.

Regarding the latter point, all samples collected in 2017 were sorted to separate small litter items (1–20 mm, including visually identified plastics, i.e., “putative plastics”, and other litter) from macrolitter and organic material. These small litter items (with few exceptions) were subjected to FTIR spectroscopy to confirm or correct the visual recounts of small plastics, and to identify polymer types to aid determining the source(s) of the riverine litter (see Supplementary Information C for details about FTIR analysis). In the case of the 2013 samples, not all of them could be professionally recounted and none

could be analyzed by FTIR, because most samples were lost during a tsunami event that hit Coquimbo on 16th September 2015; thus, the professional recounts of plastics (when available) and the schoolchildren's recounts (in the remaining cases) were corrected according to the proportion of putative plastics from 2017 that were confirmed as such by FTIR (i.e., "FTIR correction factor"; see Supplementary Information C for details, also Supplement Tables C3 and C4).

IV.3.5. Data evaluation and statistical analyses

In this study, we compared the litter data from the rivers surveyed in 2013 and 2017 (some of the 2013 data on four main rivers had already been analyzed and interpreted in an earlier study; Rech et al., 2015). Data generated by the different samplings were evaluated to determine average abundances and composition of litter, as well as the presence of litter accumulations at surveyed sites. For calculating the abundance of small floating plastics in 2013 the categories "plastics" and "polystyrene" were grouped and corrected by the FTIR correction factor (Supplement Table C4), whereas for 2017 the data corresponding to plastics confirmed by FTIR were used. Given that the data from 2013 were corrected according to the proportion of plastics confirmed by FTIR in 2017, we assume that the data from both years are comparable (see also Supplementary Information C).

To identify the most influential factors on the abundances of riverside litter, floating macrolitter and small floating plastics in Chilean rivers, different temporal (year), geographic (zone), topographic (distance to river source), hydrologic (river width; discharge), and anthropogenic (land use; population size; wastewater treatment effluents; dams) variables were evaluated through Generalized Additive Models (Supplement Table C5; see also Supplement Table C6 for details about variables). R 4.0.2 (R Core Team, 2020) was used for the models, which were built using R package *gamlss* 5.1-7 (Rigby and Stasinopoulos, 2005), with gamma distribution for riverside litter and zero-altered gamma distributions for floating macrolitter and small floating plastics (as the proportion of zero values in the latter datasets was large and categories for the independent variables were not fully balanced; Supplement Figure C2). Several models were built for each sampling approach, using the *stepGAIC* function of *gamlss*, retaining the model with the lowest AIC (Akaike Information Criterion) for each of the three sampling approaches. Post-hoc tests for these models were conducted with R package *emmeans* 1.5.1.0006 (Lenth, 2020).

To evaluate whether there is a relationship between the abundances of riverside litter, floating macrolitter, and small floating plastics, Kendall rank correlation tests were conducted, using the R package Kendall 2.2 (McLeod, 2011). For data exploration and plotting, the R packages fitdistrplus 1.1-1 (Delignette-Muller and Dutang, 2015) and ggplot2 3.3.2 (Wickham, 2016) were used.

IV.4. Results

IV.4.1. Litter at riversides

IV.4.1.1. Abundance and composition of riverside litter

The abundance of litter at Chilean riversides was highly variable along the country, ranging from 0 to 21.8 items m⁻² per sampling circle (i.e., the circles within which litter was collected at each sampling site; Figure IV.2) and from 0.01 to 6.8 items m⁻² per sampling site, considering both years. In most sampling circles less than 4 items m⁻² were found, but in northern and central Chile much more litter was found in some circles (Figure IV.2), especially in the Arica and the Coquimbo regions (Lluta and Elqui rivers, respectively; Supplement Figure C3). Average values per geographic zone ranged from 0.95 ± 0.67 to 4.27 ± 4.77 items m⁻², and the overall national average abundance was 1.81 ± 2.49 items m⁻² (median 0.99, interquartile range IQR 1.83), being slightly higher in 2013 (1.94 ± 2.26 items m⁻², median 1.27, IQR 2.11) than in 2017 (1.66 ± 2.71 items m⁻², median 0.71, IQR 1.56; Supplement Table C7).

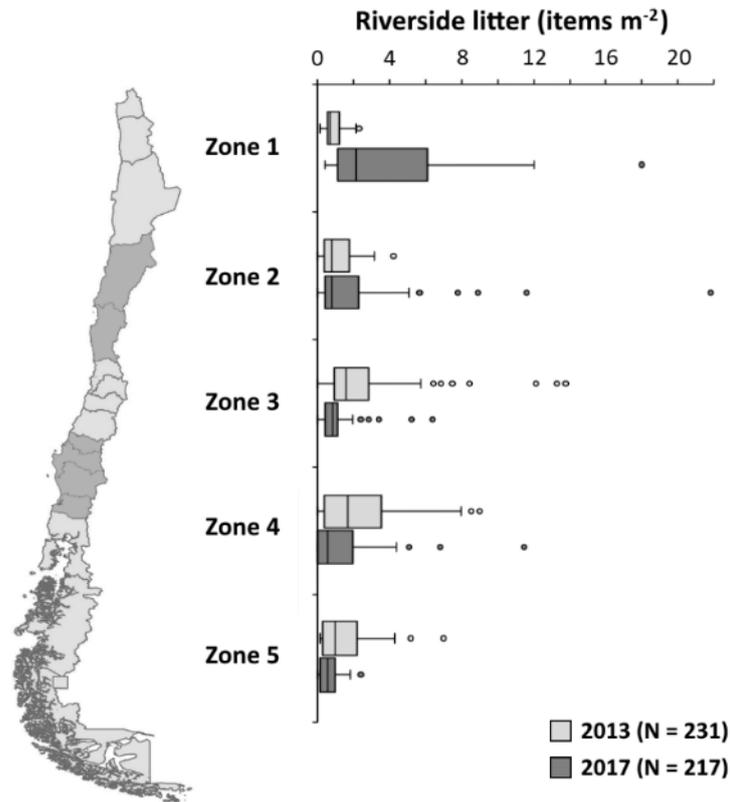


Figure IV.2. Litter abundance (items m^{-2}) on Chilean riversides determined in 2013 and 2017, per geographic zone. Each data point represents the litter abundance within one sampling circle, standardized to items m^{-2} ($N_{2013} = 231$ sampling circles, $N_{2017} = 217$); the first and third quartiles (edges of the boxes) were calculated excluding the medians when the number of observations was odd.

Notably, in both years at least one litter item was registered at all sampling sites (Supplement Table C7). The occurrence of litter (i.e., the percentage of sampling circles containing litter) was high in all zones and both years (Figure IV.3A, Supplement Table C7). At the national level and considering both years, 91% of sampling circles contained litter; 95% in 2013 and 87% in 2017 (Figure IV.3A, Supplement Table C7). The lowest value corresponded to 71% of circles with litter in zone 4 (2017), while most of the other zones presented values over 90%. In general, zones 1-3 presented the highest occurrences of riverside litter.

Riverside litter composition was very diverse, as litter from all categories was encountered (Figure IV.3B). It mostly comprised plastics, which ranged from 20% to 44%, considering all zones and both years, and averaged 29% overall. Important shares of other categories, such as paper (14%), glass (12%), cigarette butts (11%), metal (8%), and other items (23%), were also registered. In general, glass and metal items were slightly more

represented in the southernmost zone, whereas the same was true for papers in the northernmost zone (Figure IV.3B).

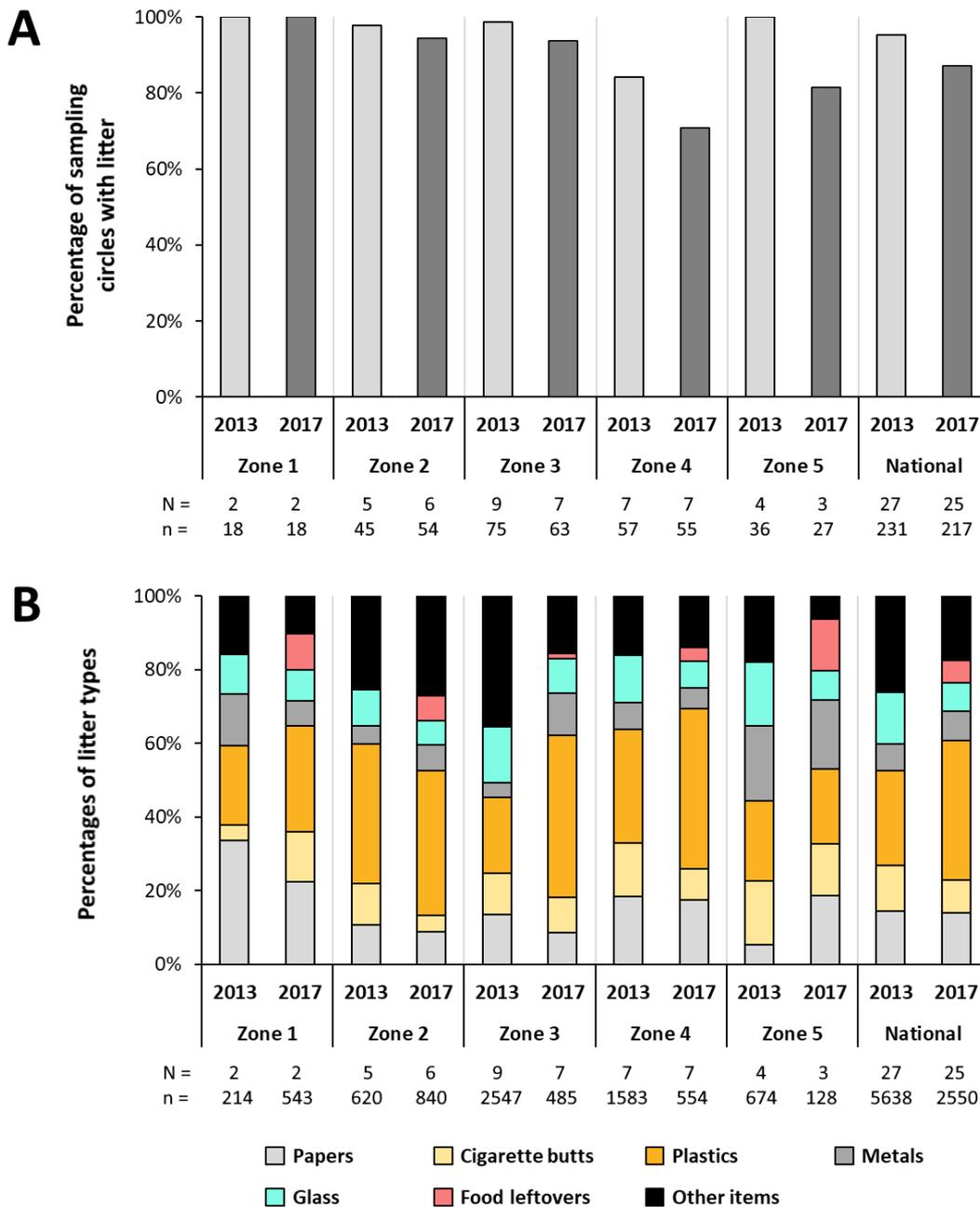


Figure IV.3. (A) Percentage of riverside sampling circles with litter, per year and geographic zone. N = number of sampling sites; n = number of total sampling circles. (B) Composition of litter on riversides, per year and geographic zone. Food leftovers were recorded as a separate category only in 2017, and were recorded as other items in 2013. N = number of sampling sites; n = number of litter items found.

IV.4.1.2. Litter accumulations

Litter accumulations of all sizes were registered during both study years. Small accumulations were more frequently encountered than medium and large ones, with 100% and 96% of surveyed sites presenting them in 2013 and 2017, respectively (Supplement Table C8). Nonetheless, medium and large accumulations were also fairly frequent: the former were registered at 62% of sites in 2013 and 81% in 2017, while large accumulations were present at 24% of sites in 2013 and 73% in 2017 (Supplement Table C8).

IV.4.2. Floating litter

IV.4.2.1. Abundance of floating macrolitter

Floating macrolitter was seen at 76% of the sites sampled in 2017, with high variability among the different sites (Figure IV.4A, Supplement Table C7). The national average abundance was 10.1 ± 13.5 items h^{-1} (median 7.0, IQR 11.6), and the highest amount (62 items h^{-1}) was registered in zone 1 (Loa river in the Antofagasta region; Supplement Figure C4A).

The majority of the floating macrolitter corresponded to the small size class (38% to 92% of the litter items registered in the different zones), followed by medium sized litter (5% to 42%), and lastly large sized litter (0% to 19%; Supplement Figure C5).

IV.4.2.2. Abundance and polymer composition of small floating plastics

During both study years, small floating litter was dominated by plastics: 58% in 2013 and 75% in 2017 (Supplement Figure C6). Overall, small floating plastics were present at 43% of all sampling sites; 31% of sites in 2013 and 57% in 2017. The abundances of small floating plastics were very variable among sampling sites, especially during 2017 (Figure IV.4B). The overall national mean was 5.8 ± 11.4 items h^{-1} (median 0.0, IQR 5.5; or 0.08 ± 0.15 items m^{-3} , albeit excluding two sampling sites due to missing information). The mean abundance was higher in 2017 (10.4 ± 15.5 items h^{-1} , median 2.0, IQR 19.7) than in 2013 (2.1 ± 3.7 items h^{-1} , median 0.0, IQR 2.5; Supplement Table C7), mainly due to several sites with particularly high abundances of small floating plastics in 2017, especially in zones 1 and 2 (Lluta and Elqui rivers, respectively; Figure IV.4B, Supplement Figure C4B).

In general, polymers collected in 2017 in Chilean rivers were not very diverse, with mostly three main types present: polyethylene (49% of total items), polypropylene (28%) and polystyrene (21%; Supplement Figure C7). Other polymers were also present in Chilean rivers, although in very low proportions (2%).

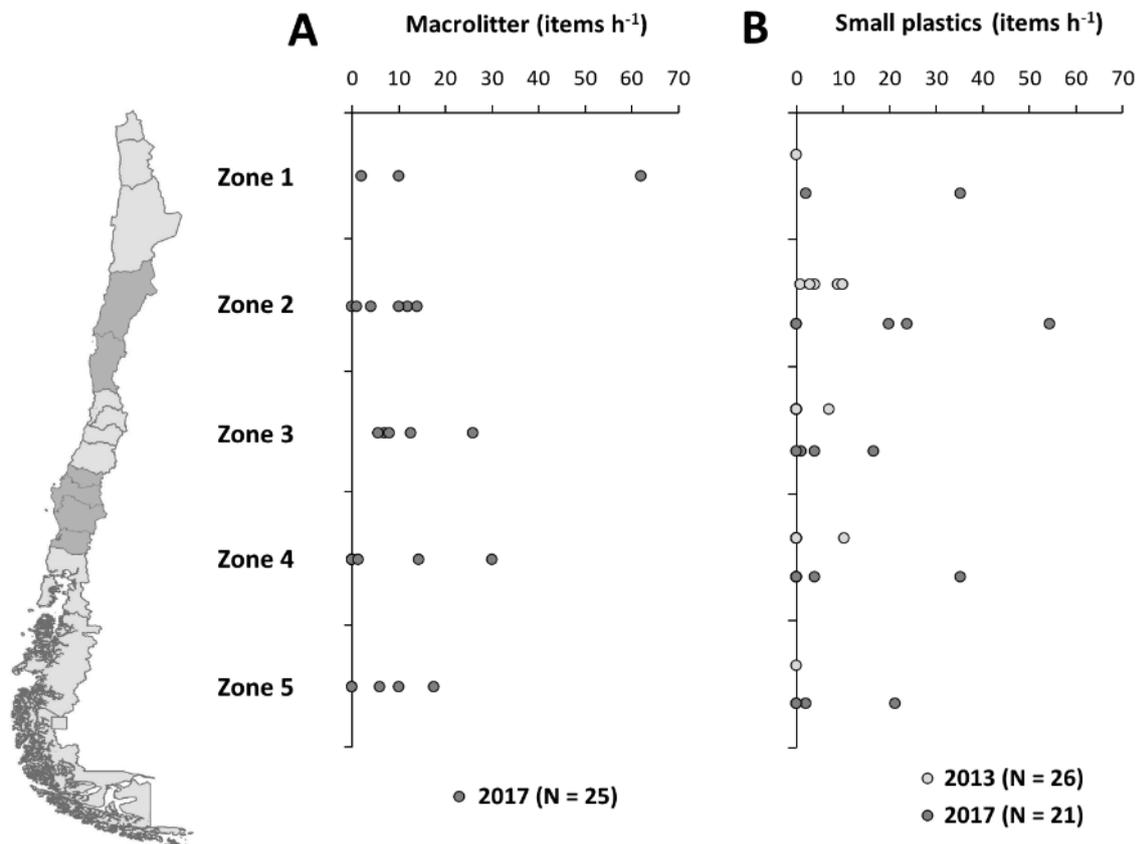


Figure IV.4. Abundances of (A) floating macrolitter on Chilean rivers in 2017, per zone (N = 25 sampling sites), and (B) small floating plastics on Chilean rivers in 2013 and 2017, per zone (N₂₀₁₃ = 26, N₂₀₁₇ = 21). Each data point represents the standardized abundance (items h⁻¹) at one sampling site.

IV.4.2.3. Inference of litter sources by the participating schoolchildren

In 2017, the schoolchildren identified four main probable sources of litter in Chilean rivers, namely recreational visitors (at 86% of sampling sites), residents (66%), illegal dumping (59%), and the river itself depositing litter from upstream sources (52%; Supplement Table C9). The remaining two categories, i.e., industry and ship/boat traffic, were considered as probable sources in only 14% and 3% of the sampling sites, respectively (Supplement Table C9).

IV.4.3. Evaluation of factors influencing abundances of riverine litter

For riverside litter, the final model considered the geographic zone and the presence of wastewater treatment effluents up to 50 km upstream as predictors for litter abundances (Supplement Figure C8). Post-hoc tests revealed significant differences between zone 1 and zones 3, 4 and 5; and further between zones 2 and 3 (see significance letters in Supplement Figure C8). Moreover, a significant difference existed between the presence and absence of upstream wastewater treatment effluents. Although differences were significant, the actual differences between categories of the above variables in terms of the abundance of litter items m^{-2} were small (Supplement Figure C8).

In contrast, the final model for floating macrolitter considered no variable as a significant predictor for macrolitter abundances. For small floating plastics, the final model considered the sampling year and the presence or absence of dams within 50 km upstream of the sampling site; however, only the year was included as a significant predictor for small floating plastics abundances (Supplement Figure C9). Post-hoc tests showed significant differences between years (higher abundances in 2017 than in 2013), but not between the presence or absence of dams (Supplement Figure C9).

When comparing the abundances of litter registered by the different sampling approaches, they were highly variable everywhere. Interestingly, however, peak and generally higher abundances always occurred in the northern zones (1-2): peak abundances of both riverside litter and small floating plastics were registered in the Lluta river (Arica region, zone 1) and the Elqui river (Coquimbo region, zone 2; Supplement Figures C3 and C4B), while the highest abundance of floating macrolitter occurred in the Loa river (Antofagasta region, zone 1; Supplement Figure C4A). In spite of these trends, there was no significant correlation between any combination of sampling approaches (riverside litter, floating macrolitter, and small floating plastics; Kendall rank correlation tests, p -values > 0.05 , Supplement Table C10).

IV.5. Discussion

IV.5.1. Anthropogenic litter at Chilean riversides

Anthropogenic litter is a pervasive problem at Chilean riversides, as reported by Rech et al. (2014, 2015) and reconfirmed by the nationwide results of the present study. The national average abundance of litter at Chilean riversides was 1.8 items m^{-2} . To our knowledge, only one study on riverside litter is directly comparable to ours, which

reported (using the same sampling protocol and units) a considerably lower national average abundance at German riversides (0.5 items m⁻²; Kiessling et al., 2019). Furthermore, we found a frequency of occurrence of litter of 91%, whereas Kiessling et al. (2019) reported a value of 61%. These differences might be partially caused by a higher environmental awareness, more adequate litter management, and a better implementation and enforcement of existing laws in Germany, as has been discussed for differences between litter abundances on Chilean and German beaches (Honorato-Zimmer et al., 2019).

In contrast, in two freshwater systems of Argentina, the average abundances of riverside litter were similar to our results (1.2 and 2.3 items m⁻²; Blettler et al., 2017, 2019), which might be partially attributed to the more similar socio-economic and educational backgrounds among South American countries (when contrasted with most European countries). Most other studies on riverside litter are difficult to compare due to very different protocols or reporting units (see Supplement Table C11), which has also been raised as a concern for citizen science studies (Zettler et al., 2017).

Within Chile, the national average abundances of litter registered at riversides (1.9 and 1.7 items m⁻² in 2013 and 2017, respectively) were similar to those reported on coastal beaches (1.7 and 2.2 items m⁻² in 2012 and 2016, respectively; Hidalgo-Ruz et al., 2018). This seems reasonable since riverine transport contributes important amounts of litter to the ocean, most of which strands on nearby beaches shortly after entering the sea (Rech et al., 2014; Ryan and Perold, 2021). Despite variations within zones and among years, in both environments (i.e., rivers and beaches) there was a tendency of peak abundances of litter in northern Chile (zone 1 for beaches, Hidalgo-Ruz et al., 2018; zones 1-2 for riversides, this study). These might be explained by (i) a lack of concern for and/or engagement in litter issues among inhabitants and governmental bodies of the Antofagasta and Coquimbo regions, as has been suggested for coastal beaches (Kiessling et al., 2017), and/or (ii) the usually low frequency and intensity of rainfall in northern zones (see e.g., Bauer-Civiello et al., 2019). The latter is consistent with the higher proportion of paper litter in those zones (since it is not often destroyed or flushed downstream by rain), and of non-buoyant litter (glass and metals) in the southernmost zone.

IV.5.2. Anthropogenic litter floating in Chilean rivers

The presence of floating macrolitter and small plastics at 76% and 43% of the sampling sites, respectively, shows that litter is also pervasive in the surface waters of Chilean

rivers. Peak and generally higher abundances of floating litter (macro and small) also occurred in northern Chile (zones 1-2), reinforcing the above discussion about the possible influence of low levels of concern/engagement among inhabitants and the lack of rainfall on the abundances of litter in rivers.

The national average abundance of floating macrolitter in Chilean rivers (10.1 items h^{-1}) was orders of magnitude lower than in rivers from South East Asia (e.g., van Emmerik et al., 2019a; van Emmerik et al., 2020; Supplement Table C12), possibly explained by considerably higher population densities and rates of mismanaged waste in South East Asian countries (Lebreton and Andrady, 2019). An additional explanation might be long-lasting retention of macrolitter in slow-flowing lowland rivers, especially in their lower parts (e.g., Acha et al., 2003; Tramoy et al., 2020), whereas litter might be rapidly flushed downstream directly into the ocean in highly dynamic Chilean mountain rivers. Importantly, litter at the riversides may also be mobilized and flushed downriver during periods of high discharge. This could be particularly relevant in northern Chile, where flushing events occur seldom, but can be highly destructive when they happen, dragging houses, crops, sediments and also litter downstream (see e.g., Wilcox et al., 2016).

Interestingly, we found a clear pattern in the size composition of floating macrolitter: a notable majority of small-sized litter, followed by medium and then large items. This trend might be caused by human behavior (e.g., larger litter items are easier to clean up), but also by the fragmentation of plastic litter in the environment, with the consequent generation of many smaller pieces from one initial large plastic item (Zhang et al., 2015). The latter has also been suggested by Crosti et al. (2018) and Castro-Jiménez et al. (2019), who reported the same size trend in other rivers originating from mountain ranges. Based on those findings, we suggest that mountain rivers might accelerate the fragmentation process of plastic litter, given their rocky substratum and the continuous contact of suspended materials with it.

Contrary to what might be expected due to the fragmentation of plastic litter, i.e., higher abundances of small floating plastics than of floating macrolitter, we obtained similar densities of small floating plastics and of macrolitter. It is likely that the fraction of small plastics was underestimated, as the mesh size of the net was 1 mm, thereby excluding even smaller plastic particles. It is also possible that small plastics move faster along the river course than macrolitter (see e.g., Nizzetto et al., 2016, who reported this behavior for small versus large microplastics), or that macrolitter might be more

frequently retained in riparian vegetation (Williams and Simmons, 1999). The average abundance of small floating plastics per volume (0.08 items m⁻³) was up to four orders of magnitude lower than in slow-flowing Asian rivers (e.g., Zhao et al., 2014; Di and Wang, 2018; Supplement Table C13), reinforcing our suggestion of rapid flushing of plastic litter in dynamic, fast-flowing mountain rivers. We acknowledge, however, that our study has limitations due to the variability of Chilean rivers, and thus all floating litter data need to be viewed critically. Reliably measuring the river flow velocity when sampling (whether visually or with a net) will be instrumental in future studies conducted in mountain rivers.

IV.5.3. Sources of anthropogenic litter in Chilean rivers

The composition of litter at riversides was very diverse and generally dominated by plastics (29%), followed by important shares of “short-term buoyant” (i.e., items that initially float and can be transported by a stream for a relatively short time before sinking or decomposing, such as papers and cigarette butts; Rech et al., 2014) and non-buoyant (glass and metals) litter items. These results are indicative of direct littering, e.g., by recreational visitors and residents, as opposed to riverine transport from upstream sources (see e.g., Bravo et al., 2009, who reported similar findings for Chilean beaches). Kiessling et al. (2019) found a very similar percentage of plastics at German riversides (31%) and also comparatively high proportions of short-term buoyant and non-buoyant items, and they identified recreational visitors as the main source of riverine litter. Several other studies have also reported that one of the main litter sources is the recreational use of these environments (e.g., Gasperi et al., 2014; Kapp and Yeatman, 2018).

Plastics were even more highly represented among the small floating litter than among the riverside litter, possibly due to the high buoyancy of most types of plastics. The polymer composition of small floating plastics, comprising mainly polyethylene, polypropylene and polystyrene, is common at the water surface and in sediments of rivers (Klein et al., 2015; Di and Wang, 2018; Kiessling et al., 2021) and also points to direct littering as a main source, given that these polymers are ubiquitous in packaging and common user products (e.g., Sadri and Thompson, 2014).

The presence of litter accumulations at the riversides has also been used to identify sources of litter, predominantly illegal dumping activities (Williams and Simmons, 1999; Rech et al., 2015). While small accumulations might originate either from intentional littering or natural events, medium and large accumulations are highly indicative of illegal dumping (Rech et al., 2015). Thus, the moderate to high percentages of sampling sites

containing medium or large accumulations in this study suggest illegal dumping as an important source of riverine litter throughout Chile, and therefore that littering is highly intentional in Chilean rivers. Similarly, illegal dumping was identified as an important source of riverside litter elsewhere (Williams and Simmons, 1999; McCormick and Hoellein, 2016). Kiessling et al. (2019), on the contrary, did not consider illegal dumping a relevant source at German rivers and reported a lower presence of medium and large litter accumulations than in Chile.

The inference of litter sources by the schoolchildren largely agreed with the above discussion and the previous findings by Rech et al. (2015): direct littering by recreational visitors, local residents and illegal dumping are the most likely sources of litter in Chilean rivers. Likewise, schoolchildren identified recreational visitors as the most likely source in German rivers (at 87% of sampling sites), which was consistent with the findings revealed by riverside litter composition (Kiessling et al., 2019).

Regarding the possible factors influencing the abundances of riverine litter, only the study year was shown to significantly influence small floating plastics, which suggests an increasing tendency nationwide over time. Interestingly, no anthropogenic variables were significant predictors of litter abundances in this study, which was also recently shown for population density elsewhere (Schuyler et al., 2021). In the case of riverside litter, no clear and consistent trends could be found between the statistical model and the significant differences identified by the post-hoc tests, and thus no final conclusion can be drawn. Two different, not mutually exclusive conditions might explain these non-conclusive findings. First, although this study was conducted at a national scale, the sample sizes (sites per river and per year) might have been too small to identify conclusive patterns of influencing factors. Thus, it would be interesting to sample wider spatial and temporal extensions to complement the present results, especially considering the strong seasonality of plastic litter transport in rivers (van Emmerik et al., 2019b) and the heterogeneity of discharge conditions in mountain areas (Viviroli et al., 2003). Second, possible complex synergies and dynamics may exist between the different factors and hydrodynamic effects (Klein et al., 2015; Mani et al., 2016), which were not considered in the models, such as differences in flushing and retention of litter between lowland and mountain rivers. Additionally, sociological aspects such as awareness, concern, engagement, territorial planning and valuation of ecosystem services, may play an important role on riverine litter. The influence of these variables on litter abundances and composition might be assessed through a mixed approach, combining quantitative litter

data and sociological surveys (e.g., Nelms et al., 2021). Therefore, relationships between different factors may be even more complex than previously suggested and need to be further investigated, considering the possible dynamics and synergies among them.

IV.6. Conclusions and Outlook

This study confirmed that anthropogenic litter is a common problem in Chilean rivers, both at the riversides and in surface waters, and that the main litter sources are riverside users, local residents and people illegally dumping litter. Littering is highly intentional, as suggested by the high prevalence of litter accumulations at the riversides.

In general, Chilean rivers are dynamic and fast-flowing mountain rivers, and our data suggested that riverine litter may be rapidly flushed downstream in these environments. During transport, plastic litter undergoes important fragmentation, and litter at the riversides may also be mobilized into the stream and flushed downriver, especially during periods of high discharge. This suggests that common tools to intercept litter in rivers such as retention booms might not be adequate in mountain rivers, since they would not catch much litter during most of the time and then might get destroyed with the first strong rains of the year.

Consequently, in Chile it is fundamental to address the issue by means of education and prevention/management measures, which should be locally driven and aimed at the identified sources. To date, many municipal ordinances and a few national laws to reduce and manage litter have been approved, but implementation, enforcement, and control efforts are still insufficient, as well as educational campaigns accompanying them. These challenges need to be urgently addressed to improve the current condition of Chilean rivers, given that rivers not only transport litter to the ocean, but are also essential water resources.

IV.7. References

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IV.8. Acknowledgements

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Chapter V: Die Plastikpiraten – Teilhabe an echter Wissenschaft durch Citizen-Science

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Eine aktive Rolle in der wissenschaftlichen Forschung einnehmen – das bedeutet meist eine langjährige akademische Ausbildung und eine tiefgehende Expertise in einem spezialisierten Fachgebiet. Citizen-Science-Projekte jedoch ermöglichen Bürgerinnen und Bürgern eine niedrighschwellige Teilhabe an wissenschaftlichen Forschungsprozessen, also z.B. der Entwicklung, Durchführung und Auswertung von wissenschaftlichen Studien. Für die Wissenschaft ergibt sich durch Einbezug der Bevölkerung die Chance Daten in größerem räumlichem und zeitlichem Umfang zu erheben und somit ganz neue Fragestellungen zu beantworten. Eine Vielzahl von Projekten bezieht dabei auch Schulen ein. Neben der Erhebung von Daten bietet sich teilnehmenden Schülerinnen und Schülern ein zusätzlicher Nutzen: Fachwissen wird vermittelt, der naturwissenschaftliche Erkenntnisweg wird erlebbar gemacht, und es wird veranschaulicht wie transdisziplinäre Forschung funktioniert. Dadurch fördern Citizen-Science-Projekte vielfach das Verständnis der Naturwissenschaften und sind eine motivierende Abwechslung zum Schullalltag (Bonney et al. 2016, Aivelo & Huovelin 2020).

In diesem Beitrag beschreiben wir das Citizen-Science-Projekt Plastikpiraten, in dem Schülerinnen und Schüler die Müllverschmutzung von Flüssen untersuchen. Möglichkeiten der Teilnahme am Projekt, sowie darüber hinausgehende Ideen für wissenschaftliche Forschung in der Schule und Möglichkeiten der Reflektion der Aktivitäten werden vorgestellt. Die Plastikpiraten bauen dabei auf dem Vorgängerprojekt „Dem Plastikmüll auf der Spur“, sowie weiteren Angeboten der Kieler Forschungswerkstatt auf, die es Schülerinnen und Schülern ermöglichen an wissenschaftlicher Forschung teilzuhaben und eine aktive Rolle gegen die Müllverschmutzung des Ozeans einzunehmen (siehe dazu auch Kruse et al. 2018; 2020; Kruse et al., in Druck).

V.1 Citizen-Science und Plastikmüll

Insbesondere das Thema Plastikmüll ist gut für einen Einstieg in Citizen-Science geeignet: In jedem Haushalt fällt Müll an und dieser wird für die Entsorgung vorsortiert. Dadurch lässt sich das Interesse für Umweltthemen wecken, zudem besteht eine Vertrautheit mit dem Studienobjekt. Für die Teilnahme an einer wissenschaftlichen Untersuchung ist daher, im Gegensatz zu vielen Biodiversitäts-Projekten, keine weitergehende fachliche Expertise nötig. Müll ist in der Regel nicht mobil und kann so gut dokumentiert werden. Das ist

wichtig für eine Überprüfung und Bestätigung der Citizen-Science-Daten, damit sie von der internationalen Forschungsgemeinschaft akzeptiert werden. Die Beseitigung von Müll aus der Landschaft ist ein positiver Nebeneffekt, der Schülerinnen und Schüler den Einfluss von Müll auf die Umwelt an einem vertrautem Ort in ihrer Nähe verdeutlicht, aber nach Abschluss der Untersuchung zudem das Gefühl vermittelt etwas für die Umwelt getan zu haben. Im Nachgang der „aktiven Feldphase“ bietet die Auswertung der Daten eine Chance Lösungsvorschläge zu diskutieren und weitergehende Forschungsfragen zu entwickeln. Eine Reflektionsphase erlaubt es Schülerinnen und Schülern das eigene Konsumverhalten zu überdenken und ihre Erfahrungen mit Familie, Freunden oder via social media zu teilen, und so eine Botschafterrolle gegen die Plastikmüllverschmutzung der Umwelt einzunehmen. Auf diese Weise kann auch die Akzeptanz der Bevölkerung für politische Maßnahmen gegen Plastikmüll erhöht werden. Besonders interessant für Schulen ist, dass das Thema mühelos Inhalte naturwissenschaftlicher und sozialwissenschaftlicher Fächer verbindet und somit erlaubt den Aspekt der Nachhaltigkeit aus verschiedenen Blickwinkeln zu betrachten.

V.2 Die Plastikpiraten

Teilnehmerinnen und Teilnehmer am Citizen-Science-Projekt Plastikpiraten erforschen die Müllverschmutzung an einem Fluss in ihrer Nähe, denn inzwischen ist bekannt, dass eine große Menge Plastikmüll über Flüsse ins Meer eingetragen wird (Infobox V.1). Dafür werden verschiedene Methoden eingesetzt: am Flussufer ermöglicht die Quantifizierung und Kategorisierung von Müll beispielsweise eine Beurteilung wie hoch der Anteil an besonders problematischem Einweg-Plastik in der Umwelt ist, und welche politischen Maßnahmen sinnvoll sein könnten, um diesen Müll zu reduzieren. Eine Beobachtung von treibendem größerem Müll und die Probennahme von Mikroplastik mit einem feinmaschigen Netz soll die Frage beantworten, wieviel Müll über Flüsse in den Ozean transportiert wird. Und eine Identifikation von Müllquellen soll letztendlich dazu beitragen diese Quellen abzustellen. Außerdem beschäftigt sich ein „Reporterteam“ mit der Öffentlichkeitsarbeit, indem sie die anderen Teilgruppen interviewt und einen Beitrag für die Schulhomepage erstellt.

Infobox V.1. Plastikmülltransport über die Flüsse in den Ozean

Nach Schätzungen von globalen Modellen sind es bis zu 2,5 Millionen Tonnen Plastikmüll, der jährlich über Flüsse in die Meere eingetragen wird (Lebreton et al. 2017). Zunächst wurde angenommen, dass nur einige wenige große Flüsse in Asien und Afrika einen Großteil dieses Mülls transportieren. Doch eine neue Studie zeigt, dass sehr viel mehr Flüsse als zunächst gedacht, darunter auch kleinere Flüsse, viel Plastikmüll mit sich führen (Meijer et al. 2019). Aus diesem Grund ist ein Fokus auf wenige Flüsse nicht ausreichend um die Verschmutzung des Ozeans durch Plastikmüll aus Flüssen zu unterbinden. Über die Mengen und Zusammensetzung von Müll in den Flüssen und an Flussufern selber – und vor allem auch über die Quellen dieses Mülls – ist weniger bekannt. Die Menge von größeren Müllteilen scheint mit der Bevölkerungsdichte zu korrelieren und Mikroplastik gelangt häufig über Klärwerke oder bei Verlusten der Kunststoffproduzenten oder –verarbeiter in die Umwelt. Diese Erkenntnisse beruhen häufig jedoch auf wenigen Datenpunkten, da insbesondere die Probennahme und Analyse von Mikroplastik sehr zeit- und ressourcenaufwändig ist.

Die Daten und gesammelten Mikroplastikproben werden anschließend im Rahmen der Möglichkeiten der Schule ausgewertet. Für eine Analyse der Mikroplastikproben (aufgrund der Netzgröße mit Partikeln > 1 mm) empfiehlt sich ein Binokular mit Auflicht und mindestens 40-facher Vergrößerung, sowie feine Pinzetten. Große Proben sollten geteilt und schrittweise untersucht werden. Partikel, die Mikroplastik darstellen können, lassen sich hauptsächlich anhand ihrer Farbe und ihrer Oberfläche unterscheiden: kräftige Farben, einfarbige Farbverläufe und eine glatte Oberfläche weisen auf Mikroplastik hin (Abbildung V.1A) - jedoch erscheint die Oberfläche von Partikeln, die sich schon länger in der Umwelt befinden, häufig verwittert. Der Großteil von industriell produzierten Plastikpellets ist weiß, transparent oder schwarz, lässt sich durch die runde oder linsenförmige Form aber gut erkennen. Natürliche Partikel in derselben Größenklasse, z.B. Steinchen, Fragmente von Blättern oder Algen oder Muschelschalen, erscheinen im Vergleich eher blassfarbig und haben eine strukturierte Oberfläche (Abbildung V.1B).

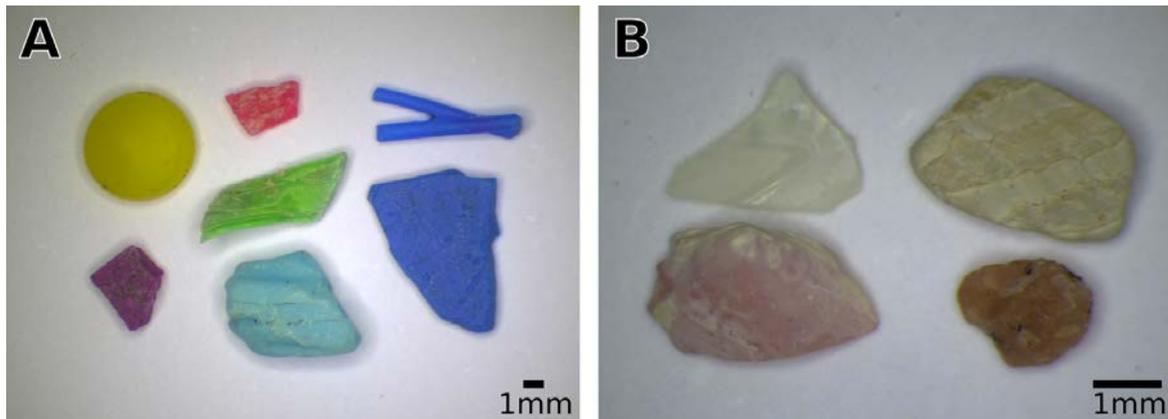


Abbildung V.1. (A) Plastik-Bruchstücke haben häufig durchgehend kräftige Farben, und glattere Oberflächen. (B) Natürliche Materialien haben blässere Farben als Mikroplastik, weisen Farbverläufe auf und haben in der Regel strukturiertere oder rauere Oberflächen. Magdalena Gatta-Rosemary/Kieler Forschungswerkstatt, Creative Commons-Lizenz CC BY 4.0.

Nach der Auswertung werden die Daten auf der Webseite der Plastikpiraten hochgeladen, dadurch lassen sie sich auch mit anderen teilnehmenden Schulen vergleichen. Die Mikroplastikproben werden zur weiteren Analyse an die Kieler Forschungswerkstatt geschickt und dort mit einem ATR-Infrarotspektroskop untersucht. Die aufgenommenen Spektren erlauben nach einem Vergleich mit Spektren einer Datenbank zu beurteilen, ob es sich bei dem Partikel wirklich um Mikroplastik handelt und aus welchem Polymer es besteht. Eine vorläufige Auswertung hat ergeben, dass sich in über der Hälfte der Proben kleine Plastikpartikel befanden. Auch die Daten zu größeren Müllfunden am Flussufer werden hier im Anschluss weiter von Wissenschaftlerinnen und Wissenschaftlern bearbeitet, zusammengeführt und für ganz Deutschland ausgewertet. So konnte in einer ersten Veröffentlichung gezeigt werden, dass der Müll an Flussufern in Deutschland zu einem Großteil aus Plastikmüll und Zigarettenstummeln besteht, und dass Flussbesucherinnen und Flussbesucher eine Hauptquelle für den Müll darstellen (Kiessling et al. 2019). Dazu wurden 250 Datensätze berücksichtigt. Eine so umfangreiche Studie wäre ohne die über 5.000 beteiligten Schülerinnen und Schüler und über 350 Lehrkräfte nicht möglich gewesen!

V.3 Teilnahme an den Plastikpiraten

Konkret gliedert sich das Projekt für teilnehmende Lehrkräfte und deren Schulklassen in drei Arbeitsphasen: (1) Vorbereitung in der Schule: Das Projektheft für Lehrerinnen und Lehrer („Lehr- und Arbeitsmaterial“) bietet Informationen, Aufgaben, Kopiervorlagen

und Experimente zu den Themen Lebensraum Ozean und Flüsse, Nahrungsnetze, Nutzung der Meere durch den Menschen, Kunststoffe und Plastikmüllverschmutzung des Ozeans. Auch die Probennahme am Fluss wird hier vorbereitet: die Schülerinnen und Schüler suchen einen Ort aus, teilen sich in Gruppen ein, besorgen das benötigte Material und üben die Probennahme. (2) Wissenschaftliche Probennahme am Fluss: ein Aktionstag am Fluss. Je nach Gruppe werden unterschiedliche Aspekte erforscht, der Müll wird gesammelt, klassifiziert und protokolliert. Zudem werden Fotos angefertigt, die später zur Bestätigung der Daten dienen. (3) Datenauswertung: Die Schülerinnen und Schüler analysieren die erhobenen Daten und Mikroplastikproben, beantworten die Forschungsfragen und vergleichen ihre Daten mit denen anderer Schulen. Im Anschluss werden die Daten auf der Webseite des Projekts hochgeladen.

Eine Teilnahme ist während Aktionszeiträumen möglich (jeweils vom Mai bis Juni und September bis November). Die Eingrenzung der Aktivität auf diese Aktionszeiträume konzentriert die Datensammlungen aller Schulen auf einen engeren Zeitraum und macht dadurch eine wissenschaftliche Auswertung erst möglich. Für die Probennahme am Fluss sollten drei bis vier Stunden eingeplant werden, erfahrungsgemäß dauert das Orientieren vor Ort und Sortieren des Materials eine gewisse Zeit. Die Nachbereitung dauert etwa zwei Schulstunden, je nachdem wie tiefgehend die Daten analysiert und vor allem die Mikroplastikproben untersucht werden (je nach Ausstattung der Schule und Anforderungen an die Schülerinnen und Schüler). Die Datenübermittlung dauert etwa 20 Minuten, kann jedoch auch von der Lehrkraft im Nachgang erledigt werden. Die Vorbereitungsphase kann beliebig gestaltet werden. Für notwendigen fachlichen Input und der Organisation der Probennahme empfiehlt sich mindestens eine Doppelstunde. Für eine intensivere Beschäftigung, beispielsweise innerhalb einer Projektwoche, gibt das „Lehr- und Arbeitsmaterial“ jedoch ebenfalls genug Stoff her. Die Plastikpiraten sind für größere Gruppen von Jugendlichen, ab ca. 12 Jahren, konzipiert worden. Die meisten Teilnehmerinnen und Teilnehmer waren zwischen 12 und 16 Jahre alt, jedoch haben inzwischen auch viele jüngere Schülerinnen und -schüler erfolgreich am Projekt teilgenommen. Die Lehrkräfte reduzieren dann entsprechend die Komplexität des Projekts und führen z.B. nur eine der Gruppen durch. Das zur Verfügung stehenden Material ist kostenlos erhältlich (Infobox V.2).

Infobox V.2. Plastikpiraten-Material und Links zu Citizen-Science und dem Plastikmüllproblem

- *Download und Bestellung des Lehr- und Arbeitsmaterials, Aktionshefts und Netzes der Plastikpiraten:* <https://bmbf-plastik.de/de/plastikpiraten/aktionsmaterialien> oder plastikpiraten@forschungs-werkstatt.de
 - *Informationen über den aktuellen Stand der Forschung der Plastikpiraten:* <https://bmbf-plastik.de/de/plastikpiraten/ergebnisse> und auf facebook unter <https://www.facebook.com/plastikpiraten>
 - *Angebote des ozean:labors der Kieler Forschungswerkstatt, darunter das Angebot „Plastikmüll im Ozean – Wer bringt den Müll raus?“* <https://www.forschungs-werkstatt.de/labore/ozeanlabor/>
 - *Überblick über Citizen-Science-Projekte in Deutschland:* <https://www.buergerschaffenwissen.de/projekte>
 - *Überblick über internationale Citizen-Science-Projekte (englischsprachig):* <https://scistarter.org/> und <https://www.zooniverse.org/>
 - *Heft mit vielen Informationen zum Plastikmüllproblem, der Plastikatlas der Heinrich Böll Stiftung:* <https://www.boell.de/de/plastikatlas>
-

Falls eine Teilnahme an den Plastikpiraten nicht (in den Aktionszeiträumen) möglich ist, oder weitergehende Untersuchungen durchgeführt werden sollen, kann in der Schule ein eigenes Forschungsprojekt entwickelt werden. Fragestellungen könnten dabei sein: Welcher Müll fällt hauptsächlich in der Schule an? Mit welcher Aktivität ist dieser Müll verbunden? Wie sehen verschiedene Akteure (Mitschülerinnen und Mitschüler, Schulleitung, Eltern, Supermärkte, etc.) das Müllproblem? Diese Studie muss also nicht auf naturwissenschaftliche Fragestellungen begrenzt sein, dadurch ergibt sich auch ein Anschluss an weitere Fächer. In einer wissenschaftlichen Untersuchung ist es wichtig, dass die erhobenen Daten einem Zweck dienen, d.h. der Öffentlichkeit zugänglich gemacht werden oder mit ihnen Veränderungen herbeigeführt werden sollen. Bereits die Fragestellungen sollten durch die Citizen-Scientists, d.h. Schülerinnen und Schüler entwickelt werden, um sie so weit wie möglich am wissenschaftlichen Erkenntnisweg teilhaben zu lassen. Forschungsfragen zur (Plastik)Müllverschmutzung sollten dabei auch immer auf Müllquellen eingehen, nur so ist eine Reduktion des Eintrags in die Umwelt zu verwirklichen. Im Anschluss wird eine einheitliche Methode entwickelt, um die Fragestellung beantworten zu können (als Inspiration kann auch die Plastikpiraten-Methode dienen) und diese Methode ausprobiert und verbessert. Bei diesem Schritt

erfahren die Schülerinnen und Schüler, dass Forschung nicht nach einem vorgegebenen Rezept erfolgen kann und immer wieder auf Überraschungen reagiert und Probleme gelöst werden müssen. Nach der Durchführung und Datenerhebung erfolgt die Datenanalyse (je nach Anforderungen an die Schulklasse mit statistischen Methoden), und letztendlich die Zusammenfassung, Bewertung und Publikation der Ergebnisse (beispielsweise auf der Schulwebseite).

V.4 Reflektionsphase

Nach der Auswertung der Daten bietet sich eine Reflektionsphase an. Dafür können in Gruppen Projekte entwickelt werden, um unseren Umgang mit Müll zu überdenken und zu diskutieren. Eine Orientierung bieten die englischsprachigen R-Wörter, die sich auf den Umgang mit Müll beziehen: Reduce (Reduzieren), Reuse (Wiederverwenden), Recycle (Wiederverwerten). Diese Begriffe können auch erweitert werden, z.B. um Rethink (Umdenken), Refuse (Ablehnen), Repair (Reparieren). Zu jedem R-Wort lassen sich zugehörige Projekte verwirklichen: die Allgemeinheit über die erhobenen Daten und Lösungsvorschläge informieren, aus Müll neue und höherwertige Objekte herstellen (Upcycling), oder ein Interview mit den Großeltern führen, um den Umgang mit Müll und Verpackungen in der Vergangenheit zu erarbeiten (Details finden sich im „Lehr- und Arbeitsmaterial“ der Plastikpiraten).

Als weitere Möglichkeit im Nachgang des Projekts kann eine Diskussionsrunde zu Lösungsansätzen des Müllproblems organisiert werden. Dabei werden zunächst Akteure gesammelt, die gegen die Umweltverschmutzung durch (Plastik)Müll aktiv werden können oder sollten. Diese Akteure werden anschließend gruppiert. Dies kann, je nach Fokus, grob aufgelöst (Gesellschaft, Industrie, Politik) oder kleinteiliger erfolgen (Landwirtschaft, lebensmittelverarbeitende Industrie, Supermärkte, kleine Lebensmittelläden). Jede Akteur-Gruppe wird dann von einer Gruppe Schülerinnen und Schüler bearbeitet. Diese versetzen sich in die Rolle des Akteurs und entwickeln Maßnahmen zur Lösung des (Plastik)Müllproblems. Es ist sinnvoll hier wenige Maßnahmen konkreter auszuarbeiten und innerhalb der Gruppe zu diskutieren (vergleiche z.B. „Verbot von Plastik“ und „Verbot von Einweg-Plastik für das es eine nachhaltige Alternative gibt“). Fragen, die eine solche Diskussion anregen sind u.a.: „Ist die Maßnahme sinnvoll um den Müll in der Umwelt zu reduzieren?“, „Ist die Maßnahme finanzierbar?“, „Wer würde davon profitieren und wer müsste mit Einschränkungen

leben?“ oder „Fände eine solche Maßnahme Akzeptanz in der Gesellschaft und Wirtschaft?“. Als Abschluss können die Gruppen ihre Lösungsvorschläge präsentieren und auf einer grafischen Darstellung der Abfallhierarchie verorten (Abbildung V.2). Häufig ergibt sich dann das Bild, dass technisch-orientierte Lösungsvorschläge, die oft sehr präsent in den Medien sind, „end of pipe“-Lösungen darstellen, d.h. Lösungsvorschläge, die ansetzen wenn der Müll bereits angefallen oder gar in die Umwelt gelangt ist. Darunter fallen beispielsweise das Recycling-System, Mikroplastik-Siebe in Kläranlagen, oder die Konstruktion von Müllsammel-Vorrichtungen in den Meeren. Lösungen, die den Müll von vornherein reduzieren, finden sich weiter oben in der Müllhierarchie, z.B. ein Redesign von Verpackungen, Entwicklungen von Pfandsystemen oder eine gesellschaftliche Veränderung des Einkaufsverhaltens. Das verdeutlicht wiederum, dass ein tiefgreifender gesellschaftlicher Diskurs und eine Akzeptanz in der Bevölkerung für einen Wandel des Konsumverhaltens notwendig ist, um das Plastikmüllproblem zu lösen.



Abbildung V.2. (A) Die Müllhierarchie, vom sinnvollsten Umgang mit Müll bis hin zur Ansammlung von Müll in der Umwelt. Tim Kiessling/Kieler Forschungswerkstatt, modifiziert nach der Grafik zur Müllprävention der Europäischen Abfallrahmenrichtlinie auf <https://ec.europa.eu/environment/waste/framework/>. (B) Lösungsvorschläge, die von Schülerinnen und Schülern während der BNE-Konferenz „Schule macht Zukunft – Impulse für ein nachhaltiges Leben“ an der Universität Kiel (Februar 2020) entwickelt und der Müllhierarchie gemäß Müllvermeidungs-Potential zugeordnet wurden. Magdalena Gatta-Rosemary/Kieler Forschungswerkstatt, Creative Commons-Lizenz CC BY 4.0.

V.5. Literatur

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Chapter VI: Synthesis

Anthropogenic litter, and especially plastics, are ubiquitous pollutants, found almost everywhere. The studies presented here show that plastic pollution by large and small items alike is a common problem at riversides and within the rivers themselves in Germany and Chile. In Germany, litter items at the riverside have been discovered at 91% of the investigated 179 sites, with an overall density of 0.5 litter items m^{-2} . Plastics and cigarette butts have been found most frequently. Items potentially dangerous to human health (i.e. glass shards, sharp metallic objects, used hygienic articles, and chemicals) have been sighted at 89% of 387 investigated sites, emphasizing that litter pollution is not only a relevant environmental pollutant but can endanger the well-being of people as well. Larger litter items floating in the river have been spotted less frequently; at 54% of the 282 sampling sites with averages of 0.3 items per hour and meter of river width. Similarly, smaller plastic particles (i.e. mesoplastics and microplastics with a size range of 1 to 24.99 mm) have been sampled at 57% of 164 sites, averaging 6.9 particles per hour. An interesting result was the discovery of six pollution hotspots accounting for more than half of all mesoplastics and microplastics found in the entire study. The most likely source for larger litter items at German riversides were recreational visitors consuming food (making picnics and barbecues), while the plastic producing industry and possibly wastewater treatment plants are likely responsible for most of the pollution of small plastics in rivers.

For rivers in Chile, similar to riversides in Germany, larger litter items have been found at 100% of investigated sites. Litter quantities were higher than in Germany with an overall average of 1.8 litter items per m^2 , with plastics being the most frequently found items. Regarding litter items located within rivers, larger floating items have been observed at 76% of sites with average densities of 10 items per hour (the river width was not considered in this analysis, as rivers in Chile vary greatly in width according to season and water flow). Small plastic particles have been found in 43% of samples, with an average of 5.8 items per hour. In addition to recreational visitors as a major litter source (similarly to Germany), residents and the illegal dumping of large quantities of litter by people also are relevant sources of litter at riversides.

Comparing the density of larger litter objects at riversides, more litter has been found in Chile. While litter production per capita is lower in Chile compared to Germany (1.15 kg per capita and day and 1.72 kg per capita and day, respectively, Kaza et al. 2018), a larger fraction of it ends up in the environment (this has not only been shown for

riversides but also for beaches in the two countries, Honorato-Zimmer et al. 2019). This illustrates the problem of “unseen” waste streams and the excess waste production of countries with a high gross domestic product (Kaza et al. 2018). A substantial share of their plastic waste is exported (e.g. countries of the European Union export 46% of collected polyethylene waste), often to countries with a small gross domestic product and without adequate recycling infrastructure, thereby contributing to ocean pollution by plastic litter (Bishop et al. 2018).

To address this issue as well as to limit the production and use of single-use plastics several legislations have been adopted on an international scale in recent years: in 2019 the Basel Convention was amended to include plastic litter as a regulated material, requiring documentation of exported material and restricting exports to plastics deemed capable of recycling (UNEP 2019). The European Union passed legislation to ban certain single-use plastic items (e.g. plastic straws, plates and cutlery) as well as aiming to reduce the consumption of several single-use food containers (European Commission 2018). Further, the European Union formulated the “European Strategy for Plastics in a Circular Economy”, aiming at facilitating the design of plastics that can be reused, repaired and recycled as well as considering more sustainable materials to replace plastics (Penca 2018). Concerning microplastics, strict regulation is equally necessary, for example requiring the plastic-producing and plastic-processing industry to hermetically transport and store pellets (during these processes much plastic is lost, Karlsson et al. 2018). A first step is a proposal by the European Chemicals Agency to limit the use of plastic particles that are intentionally added to products (e.g. as exfoliates in cosmetic products; ECHA 2019).

To address the issue of plastic pollution in a holistic way, true circular economy models are necessary, focusing on the entire life cycle of a product (Figure VI.1A). Especially plastic packaging should be addressed (making up 40% of plastics produced in Europe, PlasticsEurope 2020), for example by stimulating local production and consumption of food, thereby reducing transport processes. For all solutions to the global plastic litter problem, the waste hierarchy (Figure VI.1B) should be respected, primarily promoting the reduction of single-use plastics and not overly funding the implementation of elaborate waste and recycling infrastructure or solutions located towards the end of the waste hierarchy.

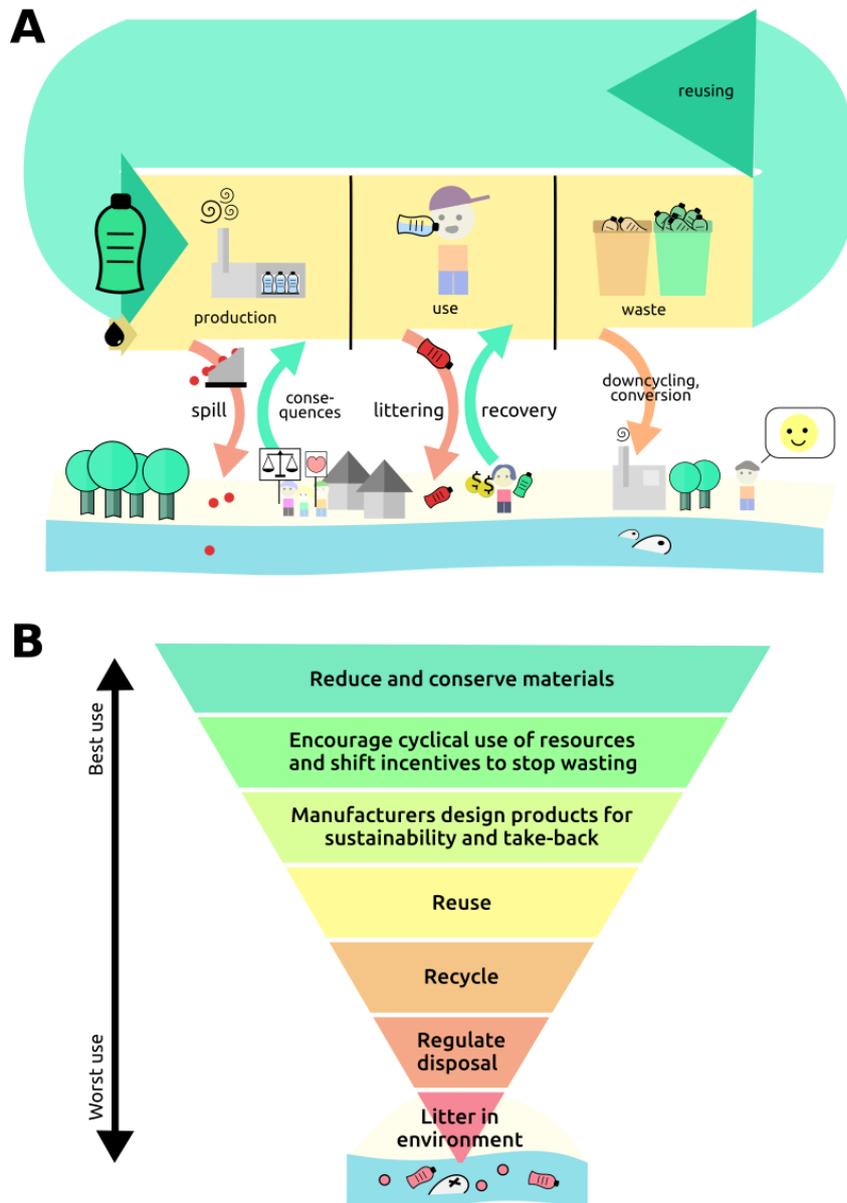


Figure VI.1. Circular economy model and waste hierarchy. (A) In an ideal circular scenario, food packaging (exemplified by a plastic bottle) would be mostly reused. Poor practices along the life cycle of a product (red arrows) would be mitigated by effective legislation and consequences as well as recovery of products (returnable packaging). The small amount of products being phased out in each cycle would be used for recycling or disposed of responsibly. Modified from Eriksen et al. 2018. (B) The waste hierarchy, sorted from the best possible use of materials (reducing the amount of plastics needed) to the worst possible use of materials (recovery of litter from the environment). From Penca 2018.

The studies presented herein involved the general public in the research of plastic pollution in the environment (in this case schoolchildren and their teachers). Data from citizen science studies are not often published in peer-reviewed scientific journals. According to Theobald et al. 2015 only 12% of biodiversity citizen science projects they

assessed contributed data to peer-reviewed journals. Similarly, obtaining relevant results from the Plastic Pirates involved some challenges and required specific measures: before the start of the project it was not clear if enough teachers (and their schoolchildren) would be interested in participating in the project, and therefore whether enough relevant datasets would be collected. This phase was facilitated by the contacts to schools of the funding agency (the Federal Ministry for Education and Research) and also the existing network of teachers of Kiel Science Factory. Another challenge was to adapt the complexity of the sampling methods to the capacity of the participants, i.e. their knowledge, available time and possibilities to visit rivers in their vicinity. In one such instance, a subgroup of the initial sampling campaign in 2016 proved to be too complex and many participants misunderstood instructions and results could not be used (in this case litter accumulations at the riverside were not quantified as intended, see Chapter II.4.1.). The educational material was subsequently edited and the method was simplified. Further challenges were incomplete datasets, missing photographs (used for data verification) and missing microplastic samples, resulting in the fact that many data could not be used for analysis (see details in Chapter II.2.6. and Chapter III.4.1.). Due to the large interest in the project, however, enough datasets were still available for analysis.

In general, teachers mentioned that the educational material and field sampling activity fitted the school curricula well and were adequate in terms of complexity. This is a result of developing the project as a cooperation between scientists and school teachers, adapting the material according to the feedback by participants, and also results from the experience of working with schools in the context of a school laboratory (Kiel Science Factory) as well as previous citizen science projects (run by the Científicos de la Basura citizen science program in Chile and Kiel Science Factory in Germany).

The findings presented in this thesis could not have been obtained without the enthusiastic support of the schoolchildren and their teachers. The citizen science approach allowed to gain a national overview of several different aspects of litter pollution of rivers in two different countries. Based on the feedback by schoolchildren and teachers, at times requesting more information about the plastic pollution problem, developing their own projects addressing plastic pollution in schools or in their spare time, and promising results of an evaluation of the precursor project “Following the Pathways of Plastic Litter” (Kruse et al. 2020) the citizen science approach is not only valuable to answer novel research questions. Several studies indicated that participating in citizen science projects can increase the understanding of the scientific process as such (scientific literacy), raise

environmental awareness as well as the knowledge about the studied subject (e.g. Cronje et al. 2011, Toomey and Domroese 2013, Bela et al. 2016, Bonney et al. 2016, Ruiz-Mallen et al. 2016, Den Broeder et al. 2017, Queiruga-Dios et al. 2020), and increase the well-being of communities (e.g. Den Broeder et al. 2017, King et al. 2017, Blake et al. 2018). Citizen science can therefore play an important role in the democratization of science (see Eitzel et al. 2017, Mahr and Dickel 2019 for further discussion), allowing each individual regardless of formal scientific education to participate in research processes.

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Supplementary material

Supplementary material A for Chapter II

A1. Excerpts from the project booklet 'Plastic Pirates – Science Year 2016*17 Seas and Oceans' version English-2017

Excerpts from the project booklet 'Plastic Pirates – Science Year 2016*17 Seas and Oceans' version English-2017. © German Federal Ministry of Education and Research 2016/2017. The full project booklet, the German version, and workbooks in both languages with background information about litter and the riverine and marine environment are available at:

- English: <https://www.wissenschaftsjahr.de/2016-17/weiterfuehrende-informationen/englisch/plastic-pirates/downloads.html>
- German: <https://www.wissenschaftsjahr.de/2016-17/mitmachen/junge-wissenschaftsinteressierte/plastikpiraten/downloads.html>



A2. Data quality control and stepwise verification protocol of citizen science data

A2-1. Datasets received, rejected, and accepted

To verify data it was first checked whether a school or organization that conducted the sampling submitted all vital information (e.g. date and place of sampling). Afterwards, data for each group were assessed individually (see also section II.2.6 and II.3.1 as well as Figure II.4 in the main text of the manuscript). In total 408 project groups participated in the sampling and between 314 and 387 datasets were received for the different aspects of litter pollution. Of those between 20% and 83% could be accepted and analysed (Table A2-1).

Table A2-1: Number of datasets received, rejected, and accepted for analysis for each investigated litter aspect per river system and sampling year. For details on why groups were rejected see text below.

	Riverside litter			Litter accumulations			Dangerous materials			Inference of litter sources		
	Datasets received	Datasets rejected	Datasets accepted	Datasets received	Datasets rejected	Datasets accepted	Datasets received	Datasets rejected	Datasets accepted	Datasets received	Datasets rejected	Datasets accepted
All riversides, both years	360	88	179 (50%)	335	269	66 (20%)	387	67	320 (83%)	314	53	261 (83%)
Per Year												
2016	176	81	95	158	158	0	167	7	160	160	26	134
2017	184	100	84	177	111	66	220	60	160	154	27	127
Per river system												
Rhine	165	74	91	150	120	30	161	11	150	147	24	122
Weser	46	23	23	43	38	5	46	3	43	37	5	32
Elbe	68	38	30	67	54	13	68	7	61	62	7	55
North Sea, other	6	3	3	7	7	0	8	2	6	5	0	5
Baltic Sea	23	9	14	22	17	5	24	0	24	23	4	19
Danube	37	19	18	36	23	13	39	3	36	31	4	27
(Not identified)	15	15	0	10	10	0	41	41	0	9	9	0

A2-2. Verification of riverside litter data

Riverside litter was assessed by 360 groups, however datasets from 73 groups were rejected because vital information about the sampling was missing, the method was not followed (e.g. no zones were established or litter counts were pooled across transects or zones), the group did not submit legible data, or it was not clearly indicated how many stations had been sampled (Table A2-2). For groups that complied with these criteria, each individual sampling circle was assessed separately (in total 2,487 data points; see Figure II.4 in the main text of the manuscript for a graphic representation of the verification process):

If no litter was recorded, the respective data point was accepted without photographic evidence (though some groups submitted photos of the sampling site without litter). 820 sampling stations contained no litter (a total of 16 groups did not encounter any litter at all).

If litter was recorded but no photo was available (or assignable because of unclear labelling) the data point could not be verified. Subsequently, it was evaluated whether a group submitted at least one photograph, and all groups without any photographic evidence were rejected. Overall, 656 stations remained without photographic evidence. 58 groups submitted incomplete photo sets and 80 groups submitted no photo and their data were rejected.

Table A2-2: Reasons for the rejection of datasets from groups assessing riverside litter in sampling circles.

	Number of datasets
Groups that conducted riverside litter sampling	360
– schools and organizations that did not provide vital information about sampling	21
– groups that did not follow methodology	17
– groups that did not submit legible data	10
– groups that did not communicate how many sampling stations they had surveyed	25
– groups that did not submit at least one photograph for any sampling circle	80
– groups with inexplicable differences between litter counts and material composition on photographs upon comparison to submitted data sheets	28
Datasets accepted	179

If the photo showed the exact same count and material composition of litter items as had been recorded by the participants, the data point was accepted (Figure A2-2A, B). This was the case for 309 data points.

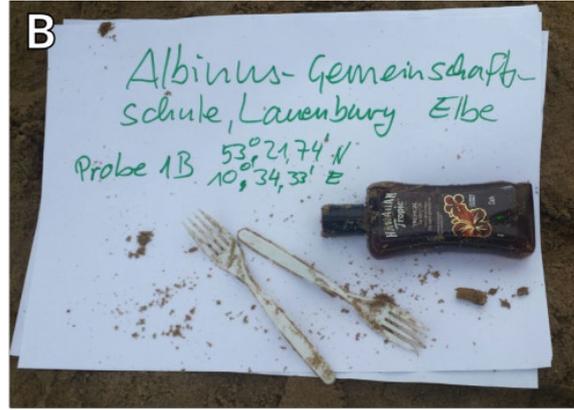
If count or material composition did not match exactly, we evaluated whether this was because of the composition of the photo or because of a miscount or misclassification of items by the participants: often overlapping items complicated count and identification of items on the photographs (Figure A2-2C, D, E, F). For several photographs the quality of the images did not allow to identify single items (especially the case with smaller litter and flat items, making it difficult to differentiate between many paper, plastic or aluminum foil fragments; Figure A2-2G, H). Further complications were for example presented by litter items found within a bag (Figure A2-2I) or items that were likely broken upon handling by the participants (Figure A2-2J). These complications due to the photographic composition of the images affected data for 642 sampling stations. Only in rare cases (approx. 3%) were the data submitted by the schoolchildren changed by the

reviewer and only if the photograph allowed the unambiguous identification of litter objects.

If the difference in count and/or material composition of litter items remained inexplicable, all data from the respective group (not only individual data points) were rejected (Figure A2-2K, L): this was the case for 60 data points out of 1,011 available photographs (6%), originating from 28 groups (Table A2-2). For some of these 60 data points the difference between submitted data and litter on the photograph was small, for example 14 of the data points differed by just one litter item.



Station 2C by Werdenfels-Gymnasium Garmisch-Partenkirchen. All litter items recorded by participants (7 cigarette butts, 1 metal object and two glass items) could be identified on the photograph. This datapoint was accepted.



Station 1B by Albinus-Gemeinschaftsschule Lauenburg. The litter items recorded by participants (1 cigarette butt and 3 plastic objects) could be identified on the photograph. This datapoint was accepted.



Station 3C by Geschwister-Scholl-Gymnasium Nossen. Overlapping litter (right) and several unidentifiable objects (left side) complicated the identification of 3 cigarette butts, 3 plastic and 3 metal objects, 16 glass shards, and 2 other items. This datapoint was accepted.



Station 1A by Lessing Schule Bochum with Ruhr-Universität Bochum. Overlapping plastic items obstruct the view of underlying items. Participants had recorded a total of 8 items (6 plastic, 1 metal, 1 glass object), while upon review only 7 objects could be counted. This datapoint was accepted.



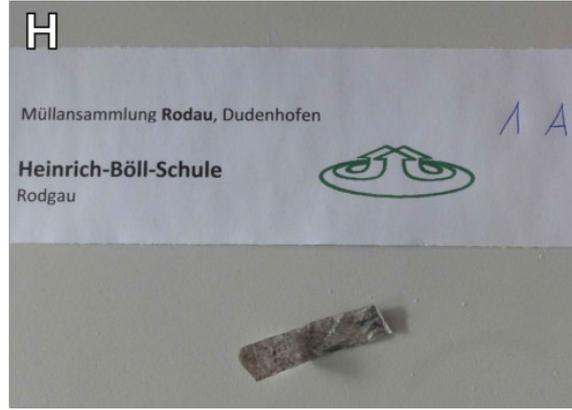
Station 1A by Frida-Levy-Gesamtschule Essen. A total of 37 litter objects were recorded (most of them plastics). Upon revision 35 objects could be counted but the exact material composition could not always be inferred. This datapoint was accepted.



Station 1B by Gymnasium am Wirteltor Düren. 114 litter items were recorded at this station, among them 75 cigarette butts. The piled up litter, the zoomed-out photo, and the presence of dirt allowed the identification of only 50 items. This datapoint was accepted.



Station 1C by Grund- und Gemeinschaftsschule im Quellental Pinneberg. The photo shows 1 cigarette butt and 3 paper-like objects. The participants identified the latter items as plastic objects (a correct classification, assuming they are wet wipes). This datapoint was accepted.



Station 1A by Heinrich-Böll-Schule Rodgau. The object on the photo was identified as a metal object by the students, and as a plastic fragment by the reviewer. This datapoint was accepted.



Station 2C by Rotteck-Gymnasium Freiburg. All items within the plastic bag have been counted by participants, resulting in 21 litter items (most of them consisting of paper and glass). The bag prevented the count of items upon review, only 3 bottles and the plastic bag itself could be quantified. This datapoint was accepted.



Station 3B by Käte-Lassen-Schule Flensburg. The broken cookie in the photograph (top left) had been classified by the participants as 1 food leftover but now consists of 7 parts or more. It may have been broken upon handling by the participants. This datapoint was accepted.



Station 1A of this group shows 3 plastic objects. This did not coincide with the recorded litter (1 plastic object, 1 food leftover). This datapoint, and therefore all data of this group were rejected.



Station 2C of this group shows 5 hardly identifiable objects but the participants recorded 15 glass shards, and 5 other litter items. This datapoint, and therefore all data of this group were rejected.

A2-3. Verification of litter accumulation data

Litter accumulations were surveyed by 335 groups, however all data taken in 2016 had to be discarded as the methodology was too complex (see details in the Material & Methods part in the manuscript). Datasets from 2017 were rejected because no vital information about the sampling was provided, the dataset for litter accumulations was incomplete, or the established sampling area was too small. Further data were rejected because no photos had been submitted (at least one photo was required), or the submitted photos showed that the respective group misidentified (e.g. single litter objects were counted as accumulations) or misclassified litter accumulations (e.g. less than 10 litter items were classified as a medium-sized accumulation; Table A2-3). The remaining 66 groups identified 638 litter accumulations, of which 43% were documented with photographs (at least one litter accumulation per group). 10 groups did not record any litter accumulations and were therefore not required to submit photographs.

Table A2-3: Reasons for the rejection of datasets from groups assessing litter accumulations.

	Number of datasets
Groups that conducted litter accumulation sampling	335
– groups that conducted the sampling in 2016 with more complex methodology	158
– schools and organizations that did not provide vital information about sampling	10
– groups that submitted unlegible or incomplete data	6
– groups that did not sample an area of at least 1000 m ² or that did not submit any measurement of their area	19
– groups that did not submit at least one photograph of any litter accumulation	68
– groups that misidentified or misclassified the size of litter accumulations	8
Datasets accepted	66

A2-4. Verification of data for dangerous materials at the riverside

The survey of dangerous materials (within the same sampling area as litter accumulations) was conducted by 387 groups. 67 groups had to be discarded because no vital information about the sampling was provided, or because the submitted data was not legible or ambiguous (e.g. a cross was located between two response fields). A total of 320 datasets were accepted for this analysis.

A2-5. Verification of data for the inference of litter sources

Litter sources were inferred by 314 groups. Datasets of 53 groups were rejected because vital information about the sampling was missing, or because the data sheets were

illegible, remained ambiguous, or were incomplete (i.e. not all potential litter sources had been evaluated). The remaining 261 datasets were accepted for analysis.

Additionally, we reviewed available photos of litter accumulations (from the valid 66 datasets from 2017) to identify likely sources of these accumulations. 277 litter accumulations could be assessed this way, considering mainly the composition and use-type of objects within these accumulations to assign a likely source (Table A2-5A). In some cases the size of the accumulation or the location of litter deposition could be assessed as well. The most likely source of the litter accumulations on the photographs were visitors, followed by residents, people dumping litter illegally, and industry. Very few litter accumulations were assigned to ship/boat traffic or the river itself depositing the litter (Table A2-5B).

Table A2-5A: Sources assigned to litter accumulations based on the use-type of individual litter items within the accumulation.

Litter items in litter accumulation	Use type	Potential sources
Cigarette butts, cigarette packs, plastic wrapper of cigarette packs	Smoking	Visitors
Larger identifiable glass bottles, metallic bottle caps, glass shards of identifiable bottles	Alcohol consumption	Visitors
Food wrapping, drink packages, candy wraps, coffee to go-cups, beverage cans, food leftovers	Food consumption	Visitors
Plastic cutlery, paper plates, aluminium trays, grills, coal fragments or ashes	Picnic/Barbecue, food consumption	Visitors
Paper tissues/handkerchiefs, wet wipes, diapers, medication	Personal care	Visitors, residents
Balloons, plastic toys	Toy	Visitors, residents, illegal dumping
Plastic gloves, detergent bottles	Household product	Residents, illegal dumping, industry, ship/boat traffic
Concrete bags, cables, PVC pipes, large metallic objects, plastic sheeting	Construction, agriculture	Industry
Clothes	Clothing	Illegal dumping, residents
Tents, bicycle tires	Outdoor activity	Illegal dumping, residents, visitors
Fish traps	Fishing	Industry, ship/boat traffic, residents
Weathered plastic fragments	(unknown)	River depositing litter
Unidentifiable items (small plastic fragments, non-identifiable glass shards)	(not assigned)	(not assigned)

Table A2-5B: Number of litter accumulations assigned to each source upon review of submitted photos of litter accumulations. The sum exceeds the total of 277 litter accumulations assessed as a single accumulation could be attributed to several sources.

Source	Number (and percentage) of litter accumulations assigned to each source
Visitors	243 (88%)
Residents	35 (13%)
River depositing litter	2 (1%)
Illegal dumping	31 (11%)
Ship/boat traffic	1 (< 1%)
Industry	12 (4%)

A3. Statistical tests and additional data tables for riverside litter, litter accumulations, and the inference of litter sources

A3-1. Litter accumulation densities per river system, and statistical analysis of litter accumulations

Table A3-1: Number of litter accumulations in the main river systems of Germany in 2017 and statistical analysis (no datasets have been analysed for 2016 and for other rivers flowing into the North Sea, see main text of manuscript for details). Variances were homogeneous across river systems for the total number of litter accumulations (Levene's test, $df = 4$, $F\text{-value} = 0.90$, $p\text{-value} = 0.47$) and each litter accumulation size class (small: Levene's test, $df = 4$, $F\text{-value} = 1.28$, $p\text{-value} = 0.29$; medium: Levene's test, $df = 4$, $F\text{-value} = 0.47$, $p\text{-value} = 0.75$; large: Levene's test, $df = 4$, $F\text{-value} = 0.40$, $p\text{-value} = 0.81$).

	Total area surveyed in m^2 (Number of datasets considered)	Small litter accumulations * 1000 m^2	Medium litter accumulations * 1000 m^2	Large litter accumulations * 1000 m^2	Total litter accumulations * 1000 m^2
Litter accumulations per river system					
Rhine	185,420 (30)	1.4 ± 1.5	0.2 ± 1.3	0.1 ± 0.3	1.7 ± 2.4
Weser	22,200 (5)	0.8 ± 1.1	0.6 ± 0.8	0.2 ± 0.4	1.5 ± 1.9
Elbe	112,890 (13)	0.7 ± 0.6	0.2 ± 0.2	0.2 ± 0.2	1.1 ± 0.9
North Sea other	0 (0)	na	na	na	na
Baltic Sea	33,375 (5)	0.7 ± 1.2	$< 0.1 \pm 0.1$	$< 0.1 \pm 0.3$	0.7 ± 1.4
Danube	64,990 (13)	1.7 ± 1.4	0.4 ± 0.5	0.2 ± 0.5	2.2 ± 2.0
All river systems	418,875 (66)	1.2 ± 1.3	0.2 ± 1.0	0.1 ± 0.3	1.5 ± 2.0
One-way ANOVAs testing for differences of litter accumulations between river systems					
		Small litter accumulations	Medium litter accumulations	Large litter accumulations	Total litter accumulations
df		65	65	65	65
F-ratio		1.75	0.51	0.40	1.26
p-value		0.15	0.73	0.81	0.30

A3-2. Tukey-adjusted posthoc test for the zero-altered negative binomial (hurdle) model for riverside litter data

Table A3-2: Results of pairwise posthoc tests (with Tukey-HSD p-value adjustment) for river systems, sampling years, and the interaction between river systems and sampling years comparing litter densities in sampling circles at riversides (for the zero-altered negative binomial (hurdle) model River system * Sampling year with theta count = 0.251, number of iterations in BFGS optimization = 23, log-likelihood = -3499, df = 21). Significant contrasts are marked in bold.

	Estimate	Standard error	df	t-ratio	p-value
River systems					
Baltic Sea – Danube	-2.20	0.41	1516	-5.39	<0.01
Baltic Sea – Elbe	-1.28	0.37	1516	-3.51	<0.01
Baltic Sea – Rhine	-1.97	0.32	1516	-6.21	<0.01
BalticSea – Weser	-0.69	0.38	1516	-1.79	0.38
Danube – Elbe	-0.91	0.36	1516	2.55	0.08
Danube – Rhine	0.23	0.31	1516	0.73	0.95
Danube – Weser	1.51	0.39	1516	3.99	<0.01
Elbe – Rhine	-0.69	0.25	1516	-2.71	0.05
Elbe – Weser	0.60	0.33	1516	1.79	0.38
Rhine – Weser	1.29	0.28	1516	5.58	<0.01
Sampling years					
2016 – 2017	-0.69	0.22	1516	-3.10	<0.01
Interactions between river systems for 2016					
Baltic Sea – Danube	-0.81	0.54	1516	-1.51	0.97
Baltic Sea – Elbe	-1.14	0.44	1516	-2.60	0.21
Baltic Sea – Rhine	-3.27	0.38	1516	-8.65	<0.01
BalticSea – Weser	-0.89	0.49	1516	-1.81	0.84
Danube – Elbe	-0.33	0.51	1516	-0.66	1.00
Danube – Rhine	-2.46	0.46	1516	-5.36	<0.01
Danube – Weser	-0.09	0.56	1516	-0.16	1.00
Elbe – Rhine	-2.13	0.34	1516	-6.27	<0.01
Elbe – Weser	0.25	0.46	1516	0.53	1.00
Rhine – Weser	2.38	0.41	1516	5.83	<0.01
Interactions between river systems for 2017					
Baltic Sea – Danube	-3.59	0.63	1516	-5.73	<0.01
Baltic Sea – Elbe	-1.42	0.58	1516	-2.44	0.31
Baltic Sea – Rhine	-0.67	0.51	1516	-1.33	0.99
BalticSea – Weser	-0.48	0.59	1516	-0.81	1.00
Danube – Elbe	2.16	0.51	1516	4.22	0.00
Danube – Rhine	2.91	0.43	1516	6.73	<0.01
Danube – Weser	3.11	0.52	1516	5.95	<0.01
Elbe – Rhine	0.75	0.38	1516	1.99	0.70
Elbe – Weser	0.95	0.48	1516	1.98	0.71
Rhine – Weser	0.20	0.39	1516	0.51	1.00
Interactions between sampling years for river systems					
Baltic Sea 2016 – 2017	-0.66	0.58	1516	-1.13	1.00
Danube 2016 – 2017	-3.44	0.58	1516	-5.97	<0.01
Elbe 2016 – 2017	-0.94	0.44	1516	-2.14	0.57
Rhine 2016 – 2017	1.94	0.26	1516	7.46	<0.01
Weser 2016 – 2017	-0.24	0.50	1516	-0.48	1.00

A3-3. Item count of riverside litter in sampling circles for river width

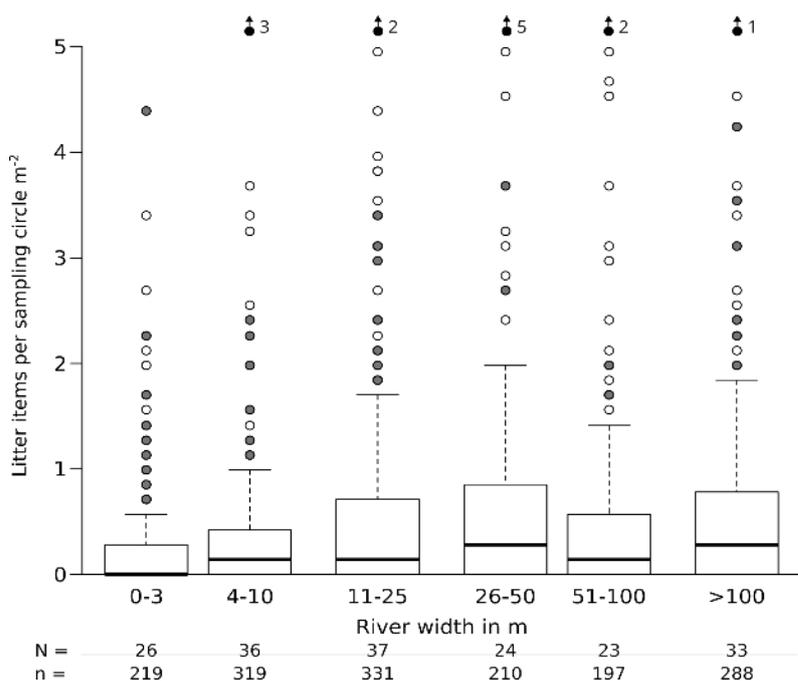


Figure A3-3: Boxplot of litter items per sampling circle m^{-2} for the different size classes (widths) of rivers. Whiskers represent the 1.5 interquartile range. Outliers are represented by dots (filled if multiple dots have the same value). The number of outliers exceeding the scale are indicated by the number next to arrows at the top of the boxplot. N = Number of datasets considered, n = number of sampling circles surveyed.

A3-4. Litter sources identified at each river system and sampling year

Table A3-4: Percentage of sources identified as a likely origin for litter pollution according to riverside and sampling year, and river size/width.

	Number of datasets analysed	Visitors	Residents	River depositing litter	Illegal dumping	Ship/boat traffic	Industry
Per riverside and year							
All riversides, both years	261	87%	38%	31%	23%	17%	10%
2016	134	90%	40%	31%	22%	19%	10%
2017	127	84%	36%	31%	23%	15%	9%
Rhine 2016	62	92%	52%	32%	27%	19%	6%
Rhine 2017	61	89%	38%	26%	28%	15%	13%
Weser 2016	16	75%	13%	19%	19%	38%	13%
Weser 2017	16	69%	44%	31%	13%	13%	6%
Elbe 2016	31	87%	39%	32%	16%	16%	23%
Elbe 2017	24	71%	29%	29%	21%	17%	13%
North Sea, other 2016	4	100%	50%	0%	50%	0%	0%
North Sea, other 2017	1	100%	0%	100%	100%	0%	0%
Baltic Sea 2016	12	92%	33%	33%	17%	17%	0%

Baltic Sea 2017	7	86%	43%	43%	29%	57%	0%
Danube 2016	9	100%	22%	44%	11%	11%	11%
Danube 2017	18	100%	33%	39%	11%	0%	0%
Per river size/width							
All riversizes/widths	261	87%	38%	31%	23%	17%	10%
0 – 3 m	30	80%	30%	27%	40%	0%	7%
4 – 10 m	63	79%	54%	25%	22%	2%	10%
11 – 25 m	47	91%	38%	30%	23%	6%	9%
26 – 50 m	39	87%	21%	31%	15%	8%	13%
51 – 100 m	31	90%	32%	13%	23%	19%	3%
> 100 m	51	94%	41%	51%	18%	63%	16%

A4. List of participating schools, institutions and organizations

We are grateful to all participating students, teachers, and other volunteers – without them this project would not have been possible. The name of participating schools and organizations can be found in Table A4.

Table A4: List of schools, institutions and organizations that participated in the Plastic Pirates sampling campaigns of 2016 and 2017.

Abraham-Frank-Sekundarschule Velen, Adolf-Reichwein-Schule Limburg, Agnes-Wenke-Schule Arnsberg, Albert-Einstein-Gymnasium Hameln, Albert-Schweitzer-Gymnasium Sömmerda, Albinus-Gemeinschaftsschule Lauenburg, Alexander-S.-Puschkin-Gymnasium Hennigsdorf, Alexander-von-Humboldt-Realschule Bayreuth, Alexander-von-Humboldt-Schule Kiel, Ammersee-Gymnasium Diessen, Amplonius-Gymnasium Rheinberg, Angelaschule Osnabrück, Anna-Schmidt-Schule Frankfurt am Main, Anton-Heilingbrunner-Schule Wasserburg am Inn, Auguste-Viktoria Schule Flensburg, Auguste-Viktoria Schule Itzehoe, Augustin Wibbelt Gymnasium Warendorf, Bärbel-von-Ottenheim Gemeinschaftsschule Schwanau, Bergstraßen Gymnasium Hemsbach, Bertha-von-Suttner Gymnasium Berlin, Bertha-von-Suttner-Gymnasium Andernach, Bertolt-Brecht Oberschule Berlin, Bertolt-Brecht-Gesamtschule Löhne, Berufsbildungszentrum Rendsburg-Eckernförde, Berufskolleg Kaufmännische Schulen Düren, Biologiedidaktik Martin-Luther-Universität Halle, Bischof Neumann Schule Königstein im Taunus, Bismarckschule Elmshorn, Boje-C.-Steffen-Gemeinschaftsschule Elmshorn, Brüder-Grimm-Schule Calvörde, BUND Naturschutz Jugendgruppe Günzburg, BUNDjugend Brandenburg, Burgsitzschule Spangenberg, Carl-Fuhlrott-Gymnasium Wuppertal, Carl-Kraemer-Grundschule Berlin, Christian von Mannlich-Gymnasium Homburg, Christliches Gymnasium Jena, Christoph-Jacob-Treu-Gymnasium Lauf an der Pegnitz, CJD Christopherus Gymnasium Elze, CJD Christopherus Gymnasium Rostock, CJD Christophorusschule Königswinter, Copernicus-Gymnasium Philippsburg, Corsten Jugendhilfe GmbH Hellenthal, Creatives Zentrum “Haus am Anger” Falkensee, Dathe-Gymnasium Berlin, David Schuster Realschule Würzburg, Deutsch-Französisches-Gymnasium Freiburg im Breisgau, Diakonische Jugendhilfe Region Heilbronn, Die Fürther Wasserratten Fürth (Ferienbetreuung), Domgymnasium Verden, Dominik-Brunner-Realschule Poing, Dr.-Johann-Stadler-Schule Parkstetten, Dr.-Samuel-Hahnemann-Schule Köthen, Edith-Stein-Realschule Lipstadt, Eichendorffschule Veitshöchheim, Elbe-Jeetzel-Schule Dannenberg, Emanuel-von-Seidl-Grundschule Murnau, Emil-Fischer-Gymnasium Schwarzeide, Emile Montessorischule Neubiberg, Erasmus-Gymnasium Rostock und Leibniz-Institut für Ostseeforschung Warnemünde, Erich-Kästner Schule Bürstadt, Erich-Kästner-Gemeinschaftsschule Elmshorn, Erich-Kästner-Hauptschule Bergheim, Erich-Kästner-Realschule Offenburg, Ernst-Reuter-Schule Frankfurt am Main, Ernst-Sigle-Gymnasium Kornwestheim, Erzbischöfliche Mädchenrealschule Heilig Blut Erding, Erzbischöfliche Maria Ward Mädchenrealschule Berg am Laim, Erzbischöfliche Realschule Vinzenz von Paul Markt Indersdorf, Europaschule “Marie & Pierre Curie” Guben, Evangelisches Gymnasium Werther, Fasia-Jansen-Gesamtschule Oberhausen, Felix-Klein-Gymnasium Göttingen, Franz-Sales-Wocheler Schule Überlingen, Franziskus Gymnasium Nonnenwerth Remagen, Franziskus-Schule Neunkirchen-Seelscheid, Freie Aktive Schule Esslingen – Kin-

derkosmos, Freie Christliche Gesamtschule Siegburg, Freie Christliche Schule Schirgiswalde, Freie demokratische Schule "Kapriole" Freiburg im Breisgau, Freie Montessori-Gemeinschaftsschule Bad Lobenstein, Freie Montessori-Schule Westerwald Westerburg, Freie Schule Altmark Salzwedel, Freie Schule Kierspe, Freie Schule Potsdam, Freie Waldorfschule Christian Morgenstern Werder/Havel, Frida-Levy-Gesamtschule Essen, Friedrich von Bodelschwingh-Schulen Bielefeld, Friedrich-Abel-Gymnasium Vaihingen, Friedrich-Bährens-Gymnasium Schwerte, Friedrich-List-Schule Ulm, Friedrich-Schiller-Gymnasium Marbach am Neckar, Friedrich-Schiller-Gymnasium Preetz, Gemeinschafts- und Sekundarschule Harzgerode, Gemeinschaftsschule am Seminarweg Bad Segeberg, Gemeinschaftsschule Hermann Neuberger Völklingen, Gemeinschaftsschule In den Fliesen Saarlouis, Gemeinschaftsschule St. Wendel, Gemeinschaftsschule Sulzbach, Georg Heinsius von Mayenburg-Grundschule Schlausitz, Georg-Christoph-Lichtenberg-Gesamtschule Göttingen, Gertrud-Bäumer-Gymnasium Remscheid, Gesamtschule Aldenhoven-Linnich, Gesamtschule Bonns Fünfte Bonn, Gesamtschule Bremen Mitte, Gesamtschule Eifel Blankenheim, Gesamtschule Eiserfeld, Gesamtschule Emsland Lingen, Gesamtschule Gangelt-Selfkant, Gesamtschule Harsewinkel, Gesamtschule Kaarst Büttgen, Gesamtschule Kürten, Gesamtschule Langerfeld, Gesamtschule Niederkassel, Gesamtschule Peter Joseph Lenné Potsdam, Gesamtschule Sankt Augustin, Gesamtschule Stadtmitte Mönchengladbach, Gesamtschule Troisdorf Sieglar, Geschwister-Scholl-Gymnasium Fürstenwalde, Geschwister-Scholl-Gymnasium Nossen, Geschwister-Scholl-Gymnasium Waldkirch, Geschwister-Scholl-Schule Heidelberg, Gewerbliche und Hauswirtschaftliche Schulen Emmendingen, Greenpeace Halle und Sekundarschule Heinrich Heine Halle (Saale), Greenpeace Halle und Martin-Luther-Universität Halle-Wittenberg, Greenpeace Nordrhein-Westfalen, Grimmelschule Renchen, Grund und Gemeinschaftsschule im Quellental Pinneberg, Grund- und Mittelschule Eggolsheim, Grund- und Mittelschule Merching, Grund- und Oberschule Johannes Clajus Herzberg Elster, Grund- und Realschule plus St. Martin Kelberg, Grundschule im Beerwinkel Berlin, Grundschule im Eliashof Berlin, Grundschule Lonnerstadt, Grundschule Sonntal Hessisch Oldendorf, Grundschule Veitshöchheim, Grüner Campus Malchow Berlin, Grünschnäbel Pullach (Bund Naturschutz), Gustav-Heinemann-Schule Mülheim, Gustav-Leutelt-Schule Neugablonz Kaufbeuren, Gymnasium "Am Breiten Teich" Borna, Gymnasium Altona Hamburg, Gymnasium am Kurfürstlichen Schloss Mainz, Gymnasium am Wirteltor Düren, Gymnasium Bruckmühl, Gymnasium der Stadt Alsdorf, Gymnasium Ernestinum Celle, Gymnasium Fabritianum Krefeld, Gymnasium Glinde, Gymnasium Harksheide Norderstedt, Gymnasium Harsewinkel, Gymnasium Herkenrath Bergisch Gladbach, Gymnasium Hochrad Hamburg, Gymnasium Hoffmann-von-Fallersleben-Schule Braunschweig, Gymnasium Hohenlimburg Hagen, Gymnasium Lilienthal, Gymnasium Martineum Halberstadt, Gymnasium Max-Josef-Stift München, Gymnasium Michelstadt, Gymnasium Miesbach, Gymnasium Münchberg, Gymnasium Nordhorn, Gymnasium Othmarschen Hamburg, Gymnasium Penzberg, Gymnasium Philippinum Weilburg, Gymnasium Ritterhude, Gymnasium Schloss Plön, Gymnasium Schramberg, Gymnasium Schwarzenbek, Gymnasium Stolzenau, Gymnasium Sulingen, Gymnasium Thomaeum Kempen, Gymnasium Trudering München, Gymnasium Wellingdorf Kiel, Gymnasium Wesermünde Bremerhaven, Gymnasium-Bildungszentrum Markdorf, Halepaghen-Schule Buxtehude, Hardbergschule Mosbach, Hebel-Gymnasium Lörrach, Heinrich-Böll-Schule Rodgau, Heinz-Nixdorf-Gesamtschule Paderborn, Helene-Lange-Schule Oldenburg, Hellenstein-Gymnasium Heidenheim, Helmholtz-Gymnasium Hilden, Herderschule Gießen, Herderschule Rendsburg, Hohenbergschule Rottenburg, Hör-Sprachzentrum Heidelberg/Neckargemünd, Humboldt-Gymnasium Eichwalde, Humboldt-Gymnasium Solingen, Integrative Montessorischule an der Balanstraße München, Integrierte Gesamtschule Aurich, Integrierte Gesamtschule Buchholz, Integrierte Gesamtschule Delmenhorst, Integrierte Gesamtschule Georg Friedrich Kolb Speyer, Integrierte Gesamtschule Gifhorn, Integrierte Gesamtschule Heidberg Braunschweig, Integrierte Gesamtschule Landau, Integrierte Gesamtschule Lüneburg, Integrierte Gesamtschule Morbach, Integrierte Gesamtschule Volkmarode Braunschweig, Jenaplanschule Lobeda Jena, Jenaplanschule Rostock, Jodocus Nünning Gesamtschule Borken, Johann-Gottfried-Herder-Gymnasium Berlin, Johann-Pachelbel-Realschule Nürnberg, Johann-Schöner-Gymnasium Karlstadt, Johann-Steingruber-Realschule Ansbach, Johannes-Brahms-Gymnasium Hamburg, Johannes-Butzbach-Gymnasium Miltenberg, Johannes-Scharrer-Realschule Hersbruck, Johannisberg-Schule Witzenhausen, Jungmannschule Eckernförde, Kardinal-Frings-Gymnasium Bonn, Karl-Kessler-Schule Aalen, Karolinen-Gymnasium Rosenheim, Käte-Lassen-Schule Flensburg, Kepler-Gymnasium Weiden, Kieler Forschungswerkstatt Kiel, Kolleg St. Sebastian Stegen, König-Wilhelm-Gymnasium Hötter, Konrad-Adenauer-Gymnasium Kleve, Kopernikus-Gymnasium Lintorf, Kopernikus-Realschule Langenfeld, Kreisgymnasium Neuenburg, Kurfürst-Balduin-Gymnasium Münstermaifeld, Landschulheim Schloss Heessen Hamm, Leibniz Universität Hannover, Leibniz-Institut für Ostseeforschung Warnemünde, Leibnizschule Frankfurt am Main, Leonardo-da-Vinci-Gesamtschule Willich, Lernwerft Club of Rome-Schule Kiel, Lessing-Gymnasium Köln, Lessing-Gymnasium Winnenden, Lore-Lorentz-Schule Düsseldorf, Lornsenschule Schleswig, Lothar-Kahn-Schule Rehlingen-Siersburg, Ludwig Leichhardt Oberschule Neuendorf am See, Mädchenrealschule St. Ursula Augsburg, Mandelberg-Grundschule Dertingen Wertheim am Main, Maria-Theresia-Mittelschule Günzburg, Maria-Ward-Schule

Aschaffenburg, Marie-Curie-Gymnasium Neuss, Mariengymnasium Warendorf, Marienschule Münster, Max-Delbrück-Gymnasium Berlin, Max-Planck-Schule Kiel, Michael-Ende-Schule Raubling, Mittelschule Albert-Schweitzer-Straße München, Mittelschule an der Pestalozzistraße Ingolstadt, Mittelschule Miesbach, Montessori Gymnasium Köln, Montessori-Schule Göttingen, Musisch-aktive Montessori-Schule Bad Tölz, NABU Stadthagen e.V., NEST Naturerkundungsstation Wolfsburg, Nymphenburger Schulen München, Oberlandsschulen Weilheim, Oberschule an der Ronzelenstraße Bremen, Oberschule Bevern, Oberschule im Park Bremen, Oberschule Rockwinkel Bremen, Offene Schule Köln, Offene Schule Waldau Kassel, Otto-Graf-Realschule Leimen, Otto-Hahn-Gymnasium Geesthacht, Pädagogium Schwerin, Peeneschule Groß Gievitze, Poligenius Private Schule Ulm, Private Realschule St. Katharina Landstuhl, Ratsgymnasium Peine, Realschule Bissingen, Realschule Hamborn II Duisburg, Realschule Maria Stern Nördlingen, Realschule plus Altenglan, Realschule Vechelde, Reichswald-Gymnasium Ramstein-Miesenbach, Rhein-Wied-Gymnasium Neuwied, Rheingau-Gymnasium Berlin, Ricarda-Huch-Schule Kiel, Richard-Wossidlo-Gymnasium Ribnitz-Damgarten, Riesschule Ritterhude, Robert-Bosch-Gesamtschule Hildesheim, Robert-Bosch-Gymnasium Langenau, Rotteck-Gymnasium Freiburg, Ruhr-Universität Bochum, Rupert-Neß-Gymnasium Wangen im Allgäu, SBBZ St. Fridolin, Schillerschule Hannover, Schloss-Schule Pfullingen, Schubart-Gymnasium Aalen, Schubart-Gymnasium Ulm, Schule Altstadt Rendsburg, Schule am Andreasried Erfurt, Schule am Fennpfuhl Berlin, Schule an der Alten Feuerwache Berlin, Schule St. Christina Ravensburg, Sekundarschule Altena/Nachrodt-Wiblingwerde, Sekundarschule Schkopau, Selma-Lagerlöf-Gemeinschaftsschule Ahrensburg, Sophie-Scholl-Gesamtschule Hamm, Sprachheilschule-Rohräckerschulzentrum Esslingen, St. Laurentius Schule Attendorn, St.-Franziskus-Schule Olpe, Staatliche Realschule Memmingen, Staatliche Realschule Naila, Staatliche Realschule Zirndorf, Staatliche Regelschule Weimar-Schöndorf, Staatliches Berufliches Schulzentrum Kelheim, Staatliches St. Josef Gymnasium Dingelstädt, Städtische Gesamtschule Delbrück, Städtische Gesamtschule Lippstadt, Städtisches Gymnasium St. Leonhard Aachen, Städtisches Gymnasium Thusneldastraße Köln, Städtisches Hölderlin-Gymnasium Köln, Städtisches Von-Müller-Gymnasium Regensburg, Stadtteilschule Bahrenfeld Hamburg, Stadtteilschule Poppenbüttel Hamburg, Stadtteilschule Rissen Hamburg, Stadtverwaltung Saalfeld – Amt für Jugendarbeit, Stiftsgymnasium Sindelfingen, Stormarnschule Ahrensburg, Tannenbusch-Gymnasium Bonn, Teamschule – Sekundarschule der Stadt Drensteinfurt, Trave-Gymnasium Lübeck, Ursulinen-Gymnasium Mannheim, Viktor-Karell-Realschule Landau an der Isar, Vogelsbergschule Schotten, Warnowschule Papendorf, Weibelfeldschule Dreieich, Werdenfels-Gymnasium Garmisch-Partenkirchen, Werner-von-Siemens Gymnasium Gronau, Werner-von-Siemens-Grundschule Augsburg, Werner-von-Siemens-Gymnasium Bad Harzburg, Wiedtal-Gymnasium Neustadt/Wied, Wilhelm-Fabry-Realschule Hilden, Wilhelm-Focke-Oberschule Bremen, Wilhelm-Leuschner-Schule Niestetal, Wilhelm-Olbers-Schule Bremen, Wilhelm-Raabe-Schule Lüneburg, Wilhelm-von-Oranien-Schule Dillenburg, Ysenburgschule Geinhausen

Supplementary material B for Chapter III

B1. Excerpts from the project booklet ‘Plastic Pirates – Science Year 2016*17 Seas and Oceans’ version: English-2017

Excerpts from the project booklet ‘Plastic Pirates – Science Year 2016*17 Seas and Oceans’ (version: English-2017). © German Federal Ministry of Education and Research 2016/2017. The full project booklet, the German version, and workbooks in both languages with background information about litter and the riverine and marine environment are available at:

- English: <https://www.wissenschaftsjahr.de/2016-17/weiterfuehrende-informationen/englisch/plastic-pirates/downloads.html>
- German: <https://www.wissenschaftsjahr.de/2016-17/mitmachen/junge-wissenschaftsinteressierte/plastikpiraten/downloads.html>

The more recent versions of this booklet and the educational material can be found at (© German Federal Ministry of Education and Research 2020):

- English: <https://www.plastic-pirates.eu/en/material/download>
- German: <https://www.plastic-pirates.eu/de/material/download>

WORKING LIKE SCIENTISTS

When you think of scientists, you might have an image in your mind of old men in white coats with crazy hair. The reality is very different.

Researchers do not spend all day in the lab, performing experiments and gathering data. They also attend specialist conferences, supervise students, produce charts and communicate with colleagues. It's a highly exciting and often professional life for you!



Now that you have learnt so much about our systems and how and how to plan and conduct research, it's time to research the issue once again. It's time to be a scientist!

In the next few hours, you should have new work through the LEOPARD of any scientific experiment.

On the hunt for waste It is now time to plan the sampling process. The aim is to get a wide range of samples to test in the river and around the catchment to see if there are any hotspots.

River sampling - let's get started! It is now time to plan the sampling process. The aim is to get a wide range of samples to test in the river and around the catchment to see if there are any hotspots.

Requirements for our group's sampling site. Includes a table for recording site details like latitude, longitude, and a section for describing the site.

Table with 2 columns: Problem and Solution. It is used for recording issues encountered during the pilot phase.

The pilot phase A scientific study also includes a pilot phase. This is a trial run of the sampling procedure that helps you prepare for the actual sampling.

PREPARING TO TAKE SAMPLES

To enable you to compare your results with other groups at a later stage, it is important that all groups across the country apply the same method.

Have read your sampling method carefully on the worksheet and fill in the blanks. Start by assigning the five tasks to members of your group.

Form for 'MY GROUP' with fields for Name and Job. Includes a section for 'What you like to do in the following job' and 'Write down the most important aspects of your method in bullet point form'.

The sample site

Look at the map and think about where to take your samples. When you have decided, think about the following questions:

- How long will it take to get to the site?
• What does the riverbank look like?
• What are the main uses of the area?
• How is the area close to the riverbank used to be used?
• How is the area close to the riverbank used to be used?

You will soon realize that every river and every location are different. Try to think about what you will need to find a suitable site for your research that allows you to compare different types of water. Please remember that safety always comes first when you are out in the field.

Notes section with a grid for recording observations and a small illustration of a person taking a sample.

GROUP 4

Floating waste! Your group needs to use different types of floats for your floating items and microplastics.

A NET FOR MICROPLASTIC SAMPLING

If you wish to take part in microplastic sampling, you need a special net. You can borrow this net free using the following contact details.

METHOD

- 1 Find a suitable spot for casting your microplastic net.
2 Cast your microplastic net with the opening facing the opposite direction to the flow of current.
3 Search for microplastics by looking through the opening. Keep over the net for 10 minutes.

RESEARCH QUESTIONS

- 1 How many types of waste do you find along the river?
2 How many types of floating waste do you find along the river?
3 How many microplastics do you find along the river?

RESEARCH QUESTIONS section with a small illustration of a person and a list of questions.

AIMS OF THE SAMPLING section with a target icon and a list of aims.

REQUIRED MATERIAL section with a list of materials and a small illustration of a net.

INFO! IDENTIFYING MICROPLASTIC section with a list of instructions for identifying microplastics.

- 1 Place a bucket for floating waste.
2 Place the entire contents of the net into the bucket.
3 As soon as the net has been emptied, take a photo of it and make the other members of your group aware of it.

Table for recording data, including a section for 'Number of microplastic fragments per net'.

Calculating the number of microplastic fragments per litre of river water. This will need the following data to calculate the number of microplastic fragments per litre of river water.

Visual guide for identifying microplastics. Includes images of white pellets, microplastics in different colors, small stones, and a magnifying glass over a red fragment.

Visual guide for river sampling. Includes diagrams for 'DRY MICROPLASTICS NET', 'CONTENTS ON A TRAY', 'SORT AND NOTE DOWN', and 'RESULTS LOG'. Also includes a photo of a person sampling a river.

Visual guide for data recording. Includes 'GROUP 4' and 'EXTRA GROUP' worksheets for recording sampling data and a 'RESULTS LOG' table.

B2. List of participating schools, institutions and organizations

The present study would not have been possible without the support of schoolchildren, teachers and other engaged individuals from the following schools and organizations, participating in the Plastic Pirates sampling campaigns of 2016 and 2017 (see Table A4)!

B3. Citizen science data verification

B3-1. Problems during litter sampling as reported by 52 groups of citizen scientists. Their responses were grouped. Some groups reported more than one problem, therefore the total does not add up to 52.

Description of problem	Number of groups reporting problem
General problems	
Sampling site: not well accessible (mostly due to vegetation), people at work, selection of sampling site difficult, space constraints	17
Weather: rain, cold, wind, heat	9
Social or motivational problems: “group dynamics”, no motivation because of few litter findings, not much to do	9
Time constraints	1
Problems specific to meso-/microplastic sampling, measurement of flow velocity, and observation of macrolitter	
Factors primarily influencing the measurement of flow velocity: ship traffic, presence of weir, slow flowing river, rainfall, waves, obstacles in river	8
Data handling and sampling instructions: analyzing or calculating data, understanding instructions	7
Accessibility of river: space constraints to measure flow velocity, no good vantage point to observe macrolitter	5
Deployment of net: no place to attach, net loosened during sampling	4
Material: equipment did not work or was not brought in sufficient supply	2

B3-2. Evaluation of the data submitted by the citizen scientists regarding the quantity of meso-/microplastics within their samples. Only the data by the 164 groups for which samples were considered are listed (see main text for details). The total number of meso-/microplastics confirmed via FTIR analysis in the present study was 1128. The total number of meso-/microplastics estimated by the 164 groups was 1744. Participants estimated the quantity of meso-/microplastics by separating suspect particles from other material (using visual aids if available), based on a guide provided in the project booklet (see Supplement B1).

	Number of groups
Participants did not submit an estimate of meso-/microplastics	30
Participants correctly identified that there were no meso-/microplastics within the sample	41
Participants detected the correct quantity of meso-/microplastics in the sample	8
Participants overestimated the quantity of meso-/microplastics in the sample	43
Participants underestimated the quantity of meso-/microplastics found in sample	42

B4. Results of floating macrolitter and floating meso-/microplastic pollution for each sampling site

Results of floating macrolitter and floating meso-/microplastic pollution for each sampling site (empty cells = respective sampling was not conducted or considered for analysis; see main text for details). Go to <https://doi.org/10.5281/zenodo.4600790> for a downloadable and editable version of this table.

Dataset number	Sampling period	Sampling date	Approximate latitude	Approximate longitude	Floating macrolitter $m^{-1} h^{-1}$	Floating meso-/microplastics h^{-1}	Floating meso-/microplastics m^{-3}
2	Autumn 2016	21/09/2016	54.7922222	009.4561111	1.33	0.00	0.00
5	Autumn 2016	23/09/2016	53.1625000	008.6752778	0.10		
6	Autumn 2016	20/10/2016	50.6452050	011.3705700	0.10	0.00	0.00
7	Autumn 2016	06/10/2016	50.1905556	011.7897222	0.00	0.00	0.00
8	Autumn 2016	25/09/2016	53.1722222	008.7425000	0.05		
9	Autumn 2016	12/10/2016	53.7447222	009.4388889	0.00		
10	Autumn 2016	16/09/2016	53.7500000	009.6488889	0.00		
13	Autumn 2016	24/09/2016	53.1644444	008.7527778	0.00		
15	Autumn 2016	29/09/2016	50.4394611	007.4452778	0.15	9.00	0.13
16	Autumn 2016	04/10/2016	49.9488889	011.5663889	0.67	1.00	0.02
17	Autumn 2016	28/10/2016	51.8847222	006.9169444	0.00	0.00	0.00
18	Autumn 2016	23/09/2016	53.1591667	008.7005556	0.05	1.00	0.04
19	Autumn 2016	24/10/2016	48.9350000	008.9505556	0.00	0.00	0.00
20	Autumn 2016	24/10/2016	47.9916667	007.8380556	0.59		
21	Autumn 2016	19/09/2016	51.1613889	011.1152778	0.50	0.00	0.00
23	Autumn 2016	21/10/2016	49.2230556	008.3866667	0.00		
24	Autumn 2016	03/11/2016	54.3180556	010.2088889	0.00	0.00	
25	Autumn 2016	31/10/2016	50.2272222	007.4200000	0.10	3.00	
26	Autumn 2016	12/11/2016	53.2241667	010.4222222	0.00	0.00	0.00
27	Autumn 2016	03/11/2016	52.3550000	014.0625000	0.19	0.00	0.00
28	Autumn 2016	30/09/2016	51.7705556	009.3805556	0.10	6.00	
29	Autumn 2016	08/11/2016	51.6713889	008.3091667	0.30	3.69	0.10
30	Autumn 2016	11/10/2016	50.1055556	008.7158333		1.82	0.05
31	Autumn 2016	17/10/2016	47.5880556	009.5558333	0.10	2.00	0.06
32	Autumn 2016	07/11/2016	48.9275000	008.9552778	0.00	3.00	0.04
33	Autumn 2016	01/11/2016	52.2955556	008.0305556	0.00		
35	Autumn 2016	08/11/2016	50.3891667	008.0663889	0.00		
37	Autumn 2016	10/11/2016	51.1583333	006.9216667	0.00		
38	Autumn 2016	10/11/2016	48.7052778	009.4197222	0.00		
39	Autumn 2016	14/10/2016	54.3005556	009.6472222	0.00		
40	Autumn 2016	09/11/2016	53.9561111	010.3091667	0.00		
41	Autumn 2016	30/09/2016	53.1336111	008.8980556	0.00		
42	Autumn 2016	11/11/2016	52.3933333	013.0713889	0.07		
43	Autumn 2016	01/11/2016	52.2594444	010.3669444	0.00	1.00	0.03
44	Autumn 2016	03/11/2016	51.6975000	007.8516667	0.00		
45	Autumn 2016	01/11/2016	51.8277778	009.4433333	0.00	0.00	0.00
46	Autumn 2016	09/11/2016	51.1602778	007.1336111	0.30		
48	Autumn 2016	11/11/2016	50.8400000	006.0972222	0.00	2.00	
49	Autumn 2016	14/10/2016	50.5019444	009.1275000	0.00		
50	Autumn 2016	11/11/2016	50.0988889	008.5625000	0.05	0.00	0.00
53	Autumn 2016	27/10/2016	51.0561111	013.3080556	0.00	7.00	

54	Autumn 2016	25/10/2016	51.0508333	013.3111111	0.00		
55	Autumn 2016	11/11/2016	51.5266667	009.9233333	0.00	1.00	0.02
56	Autumn 2016	18/10/2016	52.2522222	010.5205556	0.00	0.00	
57	Autumn 2016	31/10/2016	51.9558333	007.9891667	0.44	2.00	0.02
58	Autumn 2016	08/11/2016	50.7755556	006.0463889	0.00		
60	Autumn 2016	05/11/2016	50.9950000	007.8319444	0.00		
61	Autumn 2016	03/11/2016	53.1194444	008.2044444	0.00		
64	Autumn 2016	07/10/2016	53.5541667	010.3141667	0.12	0.00	
65	Autumn 2016	04/11/2016	52.4375000	010.7991667	0.08	0.00	0.00
67	Autumn 2016	04/11/2016	51.1713889	006.9622222	0.67		
68	Autumn 2016	10/11/2016	51.8883333	010.5475000	0.00	0.00	0.00
69	Autumn 2016	26/10/2016	51.6972222	007.8441667	0.00		
70	Autumn 2016	04/10/2016	54.7916667	009.4594444	0.00		
71	Autumn 2016	31/10/2016	52.2226000	007.0193000	0.53	0.95	
73	Autumn 2016	11/11/2016	50.8733333	007.0488889	0.50		
74	Autumn 2016	17/11/2016	49.8361111	009.8686111	0.25		
75	Autumn 2016	24/10/2016	48.9486111	009.1025000	0.30		
76	Autumn 2016	11/11/2016	52.6241667	010.0961111	0.00		
78	Autumn 2016	27/10/2016	48.1261111	011.5752778	0.10		
79	Autumn 2016	02/11/2016	53.6377778	010.0563889	0.00	0.00	0.00
80	Autumn 2016	17/11/2016	51.2047222	012.3977778	0.40		
81	Autumn 2016	07/11/2016	51.3125000	010.3288889	0.00		
82	Autumn 2016	11/11/2016	47.8255556	007.5522222	0.00	0.00	0.00
84	Autumn 2016	23/10/2016	53.4144444	010.2569444	0.00		
85	Autumn 2016	23/10/2016	53.5352778	010.1805556	0.00	0.00	
87	Autumn 2016	18/11/2016	51.4955556	013.9686111	0.30		
88	Autumn 2016	14/10/2016	47.7602778	011.5566667		0.00	0.00
91	Autumn 2016	08/11/2016	51.3388889	006.3630556	0.20	37.00	0.54
92	Autumn 2016	14/11/2016	48.3955556	009.9936111	0.10	0.00	0.00
93	Autumn 2016	15/11/2016	50.6855556	007.1813889	0.10		
94	Autumn 2016	14/11/2016	54.5130556	009.5847222	0.67	3.00	
95	Autumn 2016	09/11/2016	48.3438889	010.9372222	0.00	0.00	0.00
96	Autumn 2016	15/11/2016	47.9916667	007.8813889	0.67		
97	Autumn 2016	01/11/2016	53.6063889	009.6169444	0.10		
98	Autumn 2016	17/11/2016	52.3680556	009.7216667	0.25		
99	Autumn 2016	16/11/2016	51.9502778	014.7200000	0.00		
100	Autumn 2016	08/11/2016	49.9594444	009.7605556		2.77	0.06
101	Autumn 2016	11/11/2016	54.2861111	010.0733333	2.00	0.00	0.00
102	Autumn 2016	14/11/2016	52.4800000	010.5500000	0.00		
103	Autumn 2016	15/11/2016	52.4800000	010.5500000	0.00		
105	Autumn 2016	09/11/2016	53.5377778	008.5763889	0.00		
106	Autumn 2016	21/10/2016	48.8652778	009.3922222		0.88	0.01
107	Autumn 2016	16/11/2016	51.4244000	007.5587000	0.25		
109	Autumn 2016	06/11/2016	51.4341667	007.5744444	0.00		
110	Autumn 2016	16/11/2016	53.3652778	010.5600000	0.15	1.00	0.07
111	Autumn 2016	07/11/2016	54.2380556	010.2675000	0.00		
112	Autumn 2016	11/11/2016	49.2455556	008.4563889	0.00		
113	Autumn 2016	08/11/2016	53.9161111	009.5213889	0.00	0.00	0.00
114	Autumn 2016	28/10/2016 and 30/11/2016	52.2458700	010.5215810	0.05	0.46	
115	Autumn 2016	11/11/2016	49.3452778	009.1008333	0.30	6.00	0.12
116	Autumn 2016	11/11/2016	49.4783333	008.4608333	0.50	0.00	0.00
117	Autumn 2016	16/11/2016	53.2650000	008.4805556	0.10	1.00	0.04

118	Autumn 2016	09/11/2016	54.2369444	010.2858333	0.50	0.00	0.00
119	Autumn 2016	12/11/2016	48.4450000	010.2825000	0.00	2.00	
120	Autumn 2016	18/11/2016	49.7725000	011.0613889	1.33		
121	Autumn 2016	31/10/2016	51.0458333	006.9497222	0.00	0.00	0.00
122	Autumn 2016	11/11/2016	48.7058333	009.0069444	3.00		
123	Autumn 2016	25/10/2016	49.4125000	008.6883333	0.45	60.00	1.10
124	Autumn 2016	09/11/2016	48.8730556	009.2744444	0.10		
125	Autumn 2016	09/11/2016	48.8038889	009.2102778	0.20		
126	Autumn 2016	09/11/2016	48.8741667	009.2752778	0.10		
127	Autumn 2016	11/10/2016	48.9550000	009.1305556	0.00		
128	Autumn 2016	14/11/2016	53.4708333	009.6952778	0.14	0.00	0.00
129	Autumn 2016	10/11/2016	48.9400000	009.2525000	0.00		
130	Autumn 2016	09/11/2016	48.4450000	010.2825000	0.00	0.00	0.00
131	Autumn 2016	17/11/2016	47.7525000	011.5572222	0.10	0.00	0.00
132	Autumn 2016	09/11/2016	47.6147222	007.6522222	0.53	1.00	0.08
133	Autumn 2016	31/10/2016	49.3172222	008.4411111	0.10	0.00	0.00
135	Autumn 2016	15/11/2016	51.2947222	006.7269444	0.07	1.00	
136	Autumn 2016	15/11/2016	51.2947222	006.7269444	0.00	0.00	0.00
137	Autumn 2016	09/11/2016	51.3369444	006.8100000	0.00	0.00	0.00
138	Autumn 2016	15/11/2016	53.2605278	010.4165833	0.20	0.00	0.00
139	Autumn 2016	31/10/2016	51.0405556	006.9502778	0.00	10.00	0.10
140	Autumn 2016	26/10/2016	50.8350000	007.9844444	0.62		
141	Autumn 2016	11/11/2016	51.9861111	007.7863889	0.27	0.00	0.00
142	Autumn 2016	14/11/2016	49.4438889	007.5711111	0.80	0.00	0.00
143	Autumn 2016	17/11/2016	49.5647222	008.6491667	2.14		
144	Autumn 2016	31/10/2016	50.6786111	007.1930556	0.00		
145	Autumn 2016	09/11/2016	53.3055556	009.9561111	0.00		
146	Autumn 2016	18/11/2016	50.8552778	007.0036111	0.00		
148	Autumn 2016	08/11/2016	51.4058333	007.1683333	0.00	1.00	0.01
150	Autumn 2016	16/11/2016	53.3613889	010.5730556	0.20	8.00	
151	Autumn 2016	11/11/2016	54.2261111	010.2844444	0.00		
152	Autumn 2016	26/10/2016	52.2027778	008.7213889	0.05	2.00	0.11
153	Autumn 2016	15/11/2016	51.4427778	007.9586111	0.00		
154	Autumn 2016	07/11/2016	49.9530556	009.1186111	0.05		
155	Autumn 2016	24/10/2016	49.9561111	009.1255556	0.00		
156	Autumn 2016	04/11/2016	47.5283333	011.1111111	0.20		
157	Autumn 2016	03/11/2016	50.7955556	006.4733333	1.00	3.00	0.03
158	Autumn 2016	17/11/2016	50.7247222	007.1247222	0.50	14.00	0.50
160	Autumn 2016	26/10/2016	48.3988889	009.9716667	0.21		
161	Autumn 2016	18/11/2016	50.7891667	007.2005556	0.00	0.00	0.00
162	Autumn 2016	03/11/2016	52.6075000	013.0822222	0.25		
163	Autumn 2016	03/11/2016	51.5200000	013.4047222	0.00		
164	Autumn 2016	18/11/2016	51.3900000	011.9816667		220.00	5.46
165	Autumn 2016	17/11/2016	51.1250000	009.5366667	0.20		
166	Autumn 2016	18/11/2016	50.8940680	006.9982350	0.04	0.80	
167	Autumn 2016	14/11/2016	50.9311111	006.3458333	0.00		
168	Autumn 2016	09/11/2016	48.1272222	011.5766667	0.00		
170	Autumn 2016	10/11/2016	53.9163889	009.5233333	0.00	2.00	
172	Autumn 2016	07/11/2016	49.9936111	008.8705556	0.25		
174	Autumn 2016	02/11/2016	50.1025580	008.6710970	0.05		
175	Autumn 2016	24/10/2016	52.0755556	008.4250000	0.00		
176	Autumn 2016	18/11/2016	52.1807481	009.9190472		62.00	
179	Autumn 2016	11/11/2016	52.4402778	007.0544444	0.00		

180	Autumn 2016	26/10/2016	53.0666667	008.8175000	0.00	0.00	
183	Spring 2017	08/05/2017	50.9705556	007.0661111		0.00	0.00
186	Spring 2017	08/05/2017	51.3436111	009.8516667	0.10	1.00	0.01
187	Spring 2017	18/05/2017	48.8502778	010.4766667	0.00	2.00	0.13
188	Spring 2017	26/05/2017	49.8361111	009.8686111	0.90	7.00	0.61
190	Spring 2017	23/05/2017	52.1403820	009.2097522	0.00	2.00	0.03
192	Spring 2017	22/05/2017	47.826944	007.5536111	0.05		
193	Spring 2017	10/05/2017	51.9002778	010.5416667		9.00	
196	Spring 2017	24/05/2017	48.9138889	011.8375000	0.16		
197	Spring 2017	10/05/2017	47.7777778	009.5963889	0.00		
198	Spring 2017	16/05/2017	52.5847222	013.2111111	0.20		
199	Spring 2017	24/05/2017	49.2977778	007.0602778	3.60	1.00	
200	Spring 2017	28/05/2017	47.6680556	011.2450000	0.60	0.00	
201	Spring 2017	23/05/2017	52.5216667	013.3388889	3.30		
202	Spring 2017	22/05/2017	53.5952778	011.4922222	0.30	0.00	
203	Spring 2017	30/05/2017	53.1105556	008.7436111	0.35		
204	Spring 2017	30/05/2017	47.8622222	011.1416667	0.00	1.00	
206	Spring 2017	10/05/2017	48.1908333	011.8627778	3.33		
209	Spring 2017	29/05/2017	49.4355556	010.9538889	0.47		
213	Spring 2017	31/05/2017	49.6913889	009.2244444	0.00	1.00	
214	Spring 2017	01/06/2017	51.8941667	011.0247222	0.00		
216	Spring 2017	16/05/2017	52.5141667	009.0791667	0.00		
217	Spring 2017	01/06/2017	48.1327778	011.5877778	0.00	0.00	0.00
218	Spring 2017	31/05/2017	50.2913889	006.9230556	0.00	0.00	
219	Spring 2017	31/05/2017	47.9908333	007.8902778	0.11	1.00	0.01
220	Spring 2017	30/05/2017	50.3894444	008.0658333	0.06		
222	Spring 2017	01/06/2017	49.5100000	011.4400000	0.00	1.00	0.04
223	Spring 2017	30/05/2017	47.7841667	011.8308333	0.00		
224	Spring 2017	31/05/2017	49.7480361	009.5697389	0.30	12.00	0.45
225	Spring 2017	06/06/2017	48.8758333	010.1005556	0.40	58.00	0.93
226	Spring 2017	31/05/2017	51.7983333	007.7447222	0.16	13.00	0.52
227	Spring 2017	29/05/2017	51.1452778	007.6183333	0.00	16.00	0.43
228	Spring 2017	01/06/2017	51.4844444	009.9536111	0.67	0.00	0.00
229	Spring 2017	30/05/2017	52.6819444	008.7986111	0.67	0.00	0.00
232	Spring 2017	30/05/2017	52.1711111	009.9258333	0.29	4.00	0.22
233	Spring 2017	08/06/2017	53.0786333	011.0942833	0.00	0.00	0.00
235	Spring 2017	01/06/2017	53.9024370	010.8346460	0.00	0.00	0.00
237	Spring 2017	09/06/2017	49.4707330	011.0113810	1.30		
238	Spring 2017	02/06/2017	51.4080556	006.8911111	0.05	0.00	
240	Spring 2017	13/06/2017	54.3200000	010.2088889	0.00		
246	Spring 2017	13/06/2017	51.3105556	009.5030556	0.20		
247	Spring 2017	02/06/2017	52.6316667	013.2158333	0.20		
248	Spring 2017	01/06/2017	51.3144444	009.5569444	0.00		
249	Spring 2017	08/06/2017	51.5208333	009.9247222	2.22		
250	Spring 2017	14/06/2017	52.1222222	009.7586111		0.00	
254	Spring 2017	30/05/2017	52.5705380	013.3951610	0.00	19.00	0.23
256	Spring 2017	13/06/2017	52.2850000	010.5125000	0.05	0.98	0.05
258	Spring 2017	19/06/2017	51.4727778	007.2877778	0.00	0.00	0.00
259	Spring 2017	14/06/2017	52.3794444	012.9388889	0.10	0.00	
260	Spring 2017	13/06/2017	51.1680556	007.0213889	0.67		
261	Spring 2017	30/05/2017	51.4486111	007.9525000	0.00	5.00	0.12
263	Spring 2017	15/05/2017	50.4902778	006.6275000	1.00		
264	Spring 2017	02/06/2017	50.9469444	006.9705556	0.00		

265	Spring 2017	15/06/2017	54.3077778	009.6752778	0.12	0.94	
267	Spring 2017	14/06/2017	52.4430556	013.6177778	0.00		
270	Spring 2017	20/06/2017	50.6228600	007.4233900	0.00	0.00	0.00
271	Spring 2017	20/06/2017	51.6722222	008.3305556		1.00	0.01
272	Spring 2017	30/05/2017	52.6086111	013.1211111	0.00		
273	Spring 2017	10/06/2017	51.6777778	011.2297222	1.00	0.00	0.00
274	Spring 2017	29/05/2017	50.8027778	007.1755556	0.43	3.00	0.12
276	Spring 2017	22/06/2017	51.1430556	007.6202778	0.00	11.00	0.50
277	Spring 2017	20/06/2017	51.0558333	013.3086111		7.00	0.13
278	Spring 2017	21/06/2017	51.0505556	013.3113889	0.00	13.00	0.36
279	Spring 2017	19/05/2017	51.7688889	008.7736111	0.00	2.00	0.03
280	Spring 2017	19/06/2017	50.6744444	009.5658333	0.00	0.00	
286	Spring 2017	22/06/2017	51.8266667	006.2358333	0.10		
287	Spring 2017	21/06/2017	48.905000	012.6219444	0.09		
288	Spring 2017	16/06/2017	50.4475000	011.6961111	0.00	0.00	0.00
289	Spring 2017	21/06/2017	51.4113889	007.2463889	0.40		
290	Spring 2017	16/06/2017	51.4730556	007.2875000	0.00	1.00	0.02
291	Spring 2017	01/06/2017	51.4730556	007.2872222	0.00		
292	Spring 2017	14/06/2017	54.0900000	012.1400000	0.40		
293	Spring 2017	22/06/2017	51.3809950	006.9971620	0.16		
295	Spring 2017	21/06/2017	51.4500000	013.7300000	0.18		
300	Spring 2017	14/06/2017	51.8644444	012.0752778	0.40	10.00	
301	Spring 2017	22/06/2017	51.3502778	006.6613889	0.60	2.00	
302	Spring 2017	23/05/2017	48.4683333	009.2219444	1.40		
304	Spring 2017	21/06/2017	48.3575000	010.9358333	0.50		
305	Spring 2017	01/06/2017	52.3769444	009.7133333	0.20	0.00	0.00
306	Spring 2017	21/06/2017	50.7825000	006.4811111	0.00		
308	Spring 2017	22/06/2017	53.5441667	009.9083333	0.40	0.00	
309	Spring 2017	22/05/2017	50.7350000	008.2913889	0.00	0.00	0.00
311	Spring 2017	26/06/2017	50.1847222	008.4572222	0.00	1.00	0.03
312	Spring 2017	20/06/2017	48.0891667	007.9427778	0.00		
313	Spring 2017	28/06/2017	49.3880556	006.6741667	0.60		
314	Spring 2017	21/06/2017	50.7825000	006.4811111	0.40		
315	Spring 2017	20/06/2017	53.2272222	008.8877778	0.03	0.00	
316	Spring 2017	21/06/2017	51.0086111	011.0075000	0.11		
317	Spring 2017	23/06/2017 and 25/06/2017	48.1266950	011.5764090		3.00	0.03
319	Spring 2017	21/06/2017	51.1983333	006.7344444	0.00		
320	Spring 2017	26/06/2017	48.4975000	010.1186111	0.80		
322	Spring 2017	09/06/2017	51.0966667	006.8783333	0.05	20.00	0.29
323	Spring 2017	18/05/2017	47.8775000	011.9200000	0.00	0.00	0.00
324	Spring 2017	08/06/2017	50.1113889	008.7611111		0.00	0.00
325	Spring 2017	21/06/2017	49.3952778	009.0688889		1.00	0.03
326	Spring 2017	28/06/2017	49.3236111	006.7444444	0.15	9.00	0.61
327	Spring 2017	27/06/2017	50.3333333	011.7088889	0.00		
328	Spring 2017	28/06/2017	48.8580556	010.4788889	2.00	5.00	0.17
329	Spring 2017	27/06/2017	49.9994444	008.3111111	0.00	0.00	0.00
330	Spring 2017	27/06/2017	50.9475000	006.6333333	0.17		
331	Spring 2017	27/06/2017	48.4588889	008.9008333		1.00	0.07
332	Spring 2017	15/06/2017	52.3725000	013.6530556	0.00		
333	Spring 2017	08/06/2017	54.3863889	010.1605556	3.11		
334	Spring 2017	28/06/2017	51.4316000	006.8743667	0.05		
335	Spring 2017	23/06/2017	48.6757833	012.6922167	0.00	3.00	0.05

336	Spring 2017	27/06/2017	49.6780556	012.1738889	0.00	0.00	
337	Spring 2017	25/06/2017	51.3575000	007.5616667	0.15	0.00	0.00
338	Spring 2017	28/06/2017	51.6713889	008.3091667	1.17	11.00	0.32
340	Spring 2017	28/06/2017	49.5502778	007.4691667	0.00	2.00	0.02
341	Spring 2017	28/06/2017	49.5508333	007.4708333	3.50	0.00	0.00
344	Spring 2017	21/06/2017	52.5766667	013.4122222	2.34		
346	Spring 2017	29/06/2017	49.3286111	007.3497222	8.00		
347	Spring 2017	12/06/2017	51.6722222	007.7286111	0.00	0.00	
349	Spring 2017	29/06/2017	50.8258333	007.0072222	0.00		
351	Spring 2017	30/06/2017	52.3936111	013.0697222	0.33	4.00	0.11
352	Spring 2017	27/06/17	48.0594444	012.2325000		147.00	
354	Spring 2017	23/06/2017	52.0266667	008.5783333		126.00	3.46
356	Spring 2017	27/06/2017	54.2861111	010.0736111	0.00		
359	Spring 2017	12/06/2017	54.3641667	009.8266667	0.00	0.00	0.00
364	Spring 2017	29/06/2017	50.9997222	007.1700000	0.00		
365	Spring 2017	21/06/2017	51.7605556	008.5686111	1.00	2.00	0.05
366	Spring 2017	29/06/2017	51.4113889	007.2461111	0.60		
368	Spring 2017	29/06/2017	51.2669444	007.1800000	0.00	4.00	
369	Spring 2017	08/06/2017	50.7327778	007.0477778	0.00	0.00	0.00
371	Spring 2017	29/06/2017	47.6750000	009.8191667	0.48		
372	Spring 2017	22/06/2017	51.6897222	007.7800000	2.00		
373	Spring 2017	21/06/2017	50.9172222	006.9763889	0.20	7.00	
374	Spring 2017	26/06/2017	49.4230556	007.5688889	0.50		
378	Spring 2017	30/06/2017	53.5475000	009.8636111	0.15		
380	Spring 2017	25/06/2017	48.0444444	011.5166667	0.00		
381	Spring 2017	21/06/2017	48.2983333	011.9038889	0.00		
384	Spring 2017	30/06/2017	51.6813889	007.7730556	0.00		
385	Spring 2017	19/06/2017	47.8666667	012.6522222	0.05		
387	Spring 2017	22/06/2017	53.6750000	010.2511111		26.00	0.55
389	Spring 2017	02/06/2017	48.6791667	010.1575000	0.00	2.00	0.04
390	Spring 2017	29/06/2017	50.7818356	007.1299256	0.05	9.00	0.10
392	Spring 2017	27/06/2017	47.5155556	011.1069444	0.13	1.00	
393	Spring 2017	20/06/2017	53.1222222	008.6469444	0.20	6.00	0.53
394	Spring 2017	28/06/2017	53.6752778	009.8222222	0.00	1.00	0.03
396	Spring 2017	30/06/17 and 06/07/2017	47.6255556	008.3308333	0.67	1.94	
398	Spring 2017	16/06/2017	52.5700000	013.3922222	8.25	18.00	0.32
401	Spring 2017	13/06/2017	48.2141667	008.3852778	1.20	0.00	0.00
402	Spring 2017	26/06/2017	51.5669444	006.6194444	0.00		
403	Spring 2017	19/06/2017	51.9625000	008.2188889	0.00	1.00	0.07
404	Spring 2017	17/07/2017	51.6966667	013.2465167	0.09		
407	Spring 2017	21/06/2017	48.5675270	008.0263330		17.00	1.30
408	Spring 2017	23/06/2017	53.6855556	010.2319444	0.25	2.00	0.05
409	Spring 2017	02/06/2017	47.7869444	011.8369444	0.00	0.00	
410	Spring 2017	20/06/2017	47.7869444	011.8369444	0.86		
411	Spring 2017	22/06/2017	47.8586111	012.1358333	0.40	0.00	
413	Spring 2017	23/06/2017	53.6813889	010.2411111	0.14	0.00	0.00
415	Spring 2017	23/05/2017	51.0666667	007.3180556	0.00		
417	Spring 2017	28/06/2017	48.0983333	007.8611111	0.00		
424	Spring 2017	29/05/2017	50.0130556	008.8919444	0.00	6.00	0.11
425	Spring 2017	26/06/2017	50.0261111	008.8813889	0.00		

B5. Map of Germany with floating macrolitter and floating meso-/microplastic quantities

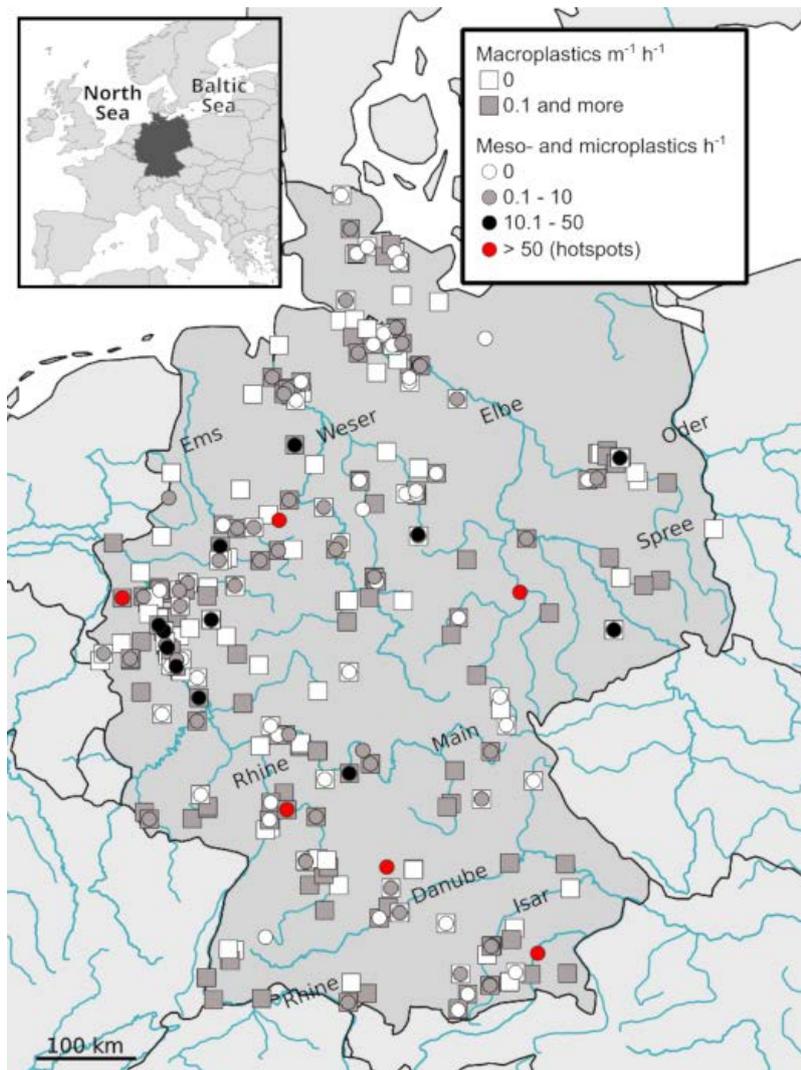


Figure B5: Map of Germany with major rivers and sampling spots of the Plastic Pirates in 2016 and 2017. Squares represent macrolitter observation sites, circles represent microplastic sampling sites.

B6. Results of statistical tests and models

B6-1. Final gamlss models (in bold) for floating macrolitter and floating meso-/microplastics for all sampling sites and for sampling sites located at the Rhine river system, respectively, and the effect on the Akaike Information Criteria (AIC) by adding further variables to the model or removing variables included in the model. Variables in *italic* were included in the model as they lowered the AIC but were not a significant predictor in themselves.

	Degrees of freedom	AIC
Model for floating macrolitter (Macrolitter ~ river system + sampling year + river width + population density at sampling site)		433.48
Adding variable artificial barriers upstream of sampling site	1	434.93
Adding variable natural barriers upstream of sampling site	1	435.12
Removing variable river system	5	441.62
Removing variable population density at sampling site	2	446.68
Removing variable sampling year	1	449.88
Removing variable river width	5	524.74
Model for floating macrolitter for the Rhine river system (Macrolitter ~ sampling year + river width)		229.68
Adding variable distance of sampling site to source of river	1	229.76
Adding variable population density at sampling site	2	232.10
Adding variable total population upstream of sampling site	3	234.85
Removing variable sampling year	1	230.80
Removing variable river width	5	272.96
Model for floating meso-/microplastics (Meso-/microplastics ~ river system + river width + population density at sampling site + artificial barriers upstream of sampling site + natural retention basins upstream of sampling site)		821.69
Adding variable sampling year	1	822.92
Removing variable natural retention basins upstream of sampling site	1	821.98
Removing variable artificial barriers upstream of sampling site	1	824.53
Removing variable river system	5	828.84
Removing variable population density at sampling site	2	831.38
Removing river width	5	838.38
Model for floating meso-/microplastics, for the Rhine only (Meso-/microplastics ~ river width + population density at sampling site + population density upstream of sampling site)		377.84
Adding variable artificial barriers upstream of sampling site	1	379.27
Adding variable distance of sampling site to source of river	1	379.47
Adding variable natural retention basins upstream of sampling site	1	379.52
Removing variable total population upstream of sampling site	3	378.02
Removing variable river width	5	380.20
Removing variable population density at sampling site	2	390.90

B6-2. Results of posthoc tests of the gamlss models for floating macrolitter and floating meso-/microplastics.

Contrast	estimate	SE	z-value	p-value
Floating macrolitter model				
River system				
Danube – Elbe	-0.302	0.255	-1.182	0.846
Danube – North Sea other	-0.517	0.520	-0.993	0.920
Danube – Baltic Sea	-0.481	0.375	-1.280	0.796
Danube – Rhine	-0.478	0.224	-2.136	0.269
Danube – Weser	0.411	0.270	1.519	0.652
Elbe – North Sea other	-0.215	0.502	-0.428	0.998
Elbe – Baltic Sea	-0.179	0.349	-0.513	0.996
Elbe – Rhine	-0.176	0.180	-0.980	0.924
Elbe – Weser	0.713	0.233	3.063	0.027
North Sea other – Baltic Sea	0.036	0.579	0.062	1.000
North Sea other – Rhine	0.038	0.486	0.079	1.000
North Sea other – Weser	0.928	0.519	1.787	0.474
Baltic Sea – Rhine	0.002	0.324	0.007	1.000
Baltic Sea – Weser	0.892	0.359	2.482	0.129
Rhine – Weser	0.889	0.202	4.397	0.000
Sampling campaign				
Autumn 2016 – Spring 2017	-0.534	0.140	-3.805	0.000
River width				
0-3 – 4-10	0.651	0.256	2.541	0.112
0-3 – 11-25	1.860	0.248	7.500	0.000
0-3 – 25-50	1.955	0.265	7.388	0.000
0-3 – 51-100	2.129	0.287	7.406	0.000
0-3 – >100	2.083	0.244	8.526	0.000
4-10 – 11-25	1.209	0.219	5.521	0.000
4-10 – 25-50	1.304	0.237	5.498	0.000
4-10 – 51-100	1.478	0.267	5.528	0.000
4-10 – >100	1.432	0.216	6.639	0.000
11-25 – 25-50	0.095	0.226	0.420	0.998
11-25 – 51-100	0.269	0.259	1.038	0.905
11-25 – >100	0.223	0.205	1.087	0.887
25-50 – 51-100	0.174	0.274	0.632	0.989
25-50 – >100	0.128	0.224	0.570	0.993

51-100 – >100	-0.046	0.256	-0.179	1.000
Population density at sampling site				
5,000 - 20,000 – < 5,000	0.259	0.141	1.832	0.159
5,000 - 20,000 – 20,001 - 100,000	-0.865	0.330	-2.617	0.024
< 5,000 – 20,001 - 100,000	-1.124	0.322	-3.488	0.001
Floating meso-/microplastic model				
River system				
Danube – Elbe	-0.826	0.641	-1.289	0.791
Danube – North Sea other	-0.689	0.875	-0.787	0.970
Danube – Baltic Sea	1.713	0.958	1.787	0.474
Danube – Rhine	0.475	0.482	0.987	0.922
Danube – Weser	-0.273	0.669	-0.408	0.999
Elbe – North Sea other	0.137	0.764	0.179	1.000
Elbe – Baltic Sea	2.538	0.886	2.865	0.048
Elbe – Rhine	1.301	0.398	3.267	0.014
Elbe – Weser	0.553	0.540	1.024	0.910
North Sea other – Baltic Sea	2.402	1.104	2.174	0.250
North Sea other – Rhine	1.164	0.735	1.584	0.610
North Sea other – Weser	0.416	0.850	0.490	0.997
Baltic Sea – Rhine	-1.237	0.872	-1.419	0.720
Baltic Sea – Weser	-1.985	0.993	-1.999	0.343
Rhine – Weser	-0.748	0.422	-1.774	0.483
River width				
0-3 – 4-10	-0.0615	0.508	-0.121	1.000
0-3 – 11-25	1.5440	0.540	2.859	0.049
0-3 – 25-50	0.4931	0.599	0.823	0.963
0-3 – 51-100	1.8332	0.586	3.126	0.022
0-3 – >100	-0.2012	0.507	-0.397	0.999
4-10 – 11-25	1.6054	0.379	4.240	0.000
4-10 – 25-50	0.5546	0.407	1.362	0.750
4-10 – 51-100	1.8947	0.544	3.483	0.007
4-10 – >100	-0.1397	0.410	-0.341	0.999
11-25 – 25-50	-1.0509	0.477	-2.202	0.237
11-25 – 51-100	0.2893	0.563	0.514	0.996
11-25 – >100	-1.7452	0.441	-3.957	0.001
25-50 – 51-100	1.3401	0.606	2.212	0.232
25-50 – >100	-0.6943	0.486	-1.427	0.710

51-100 – >100	-2.0344	0.492	-4.135	0.001
Population density at sampling site				
5,000 - 20,000 – < 5,000	-1.032	0.266	-3.878	0.000
5,000 - 20,000 – 20,001 - 100,000	-1.200	0.620	-1.935	0.129
< 5,000 – 20,001 - 100,000	-0.167	0.609	-0.275	0.959

B6-3. Interactions between variables of gamlss models

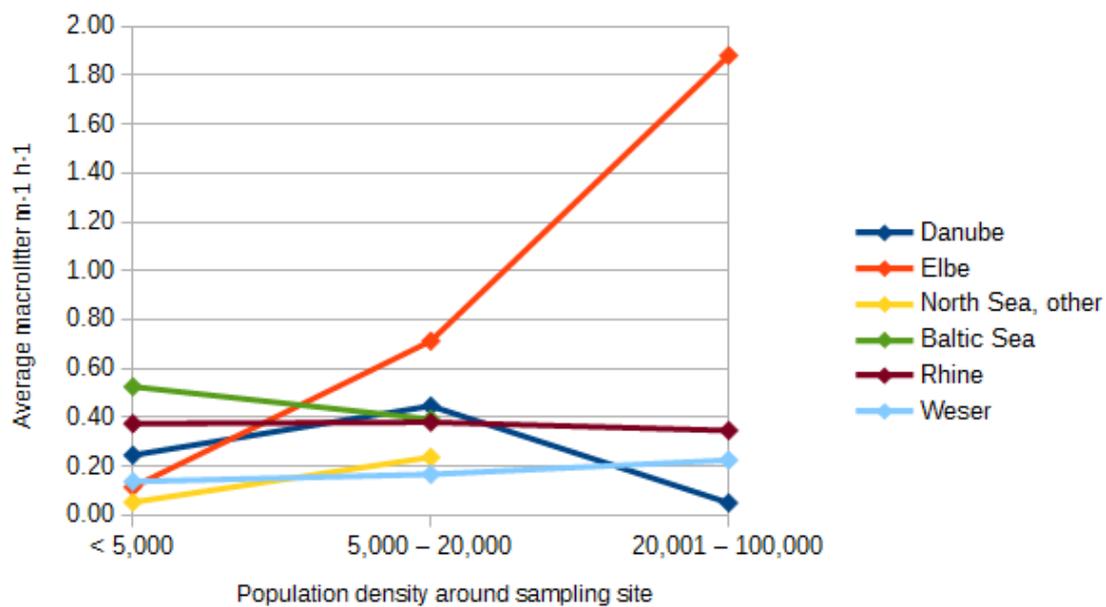


Figure B6-3.1: Average macrolitter $m^{-1} h^{-1}$ over the categories for populated places, grouped by river systems.

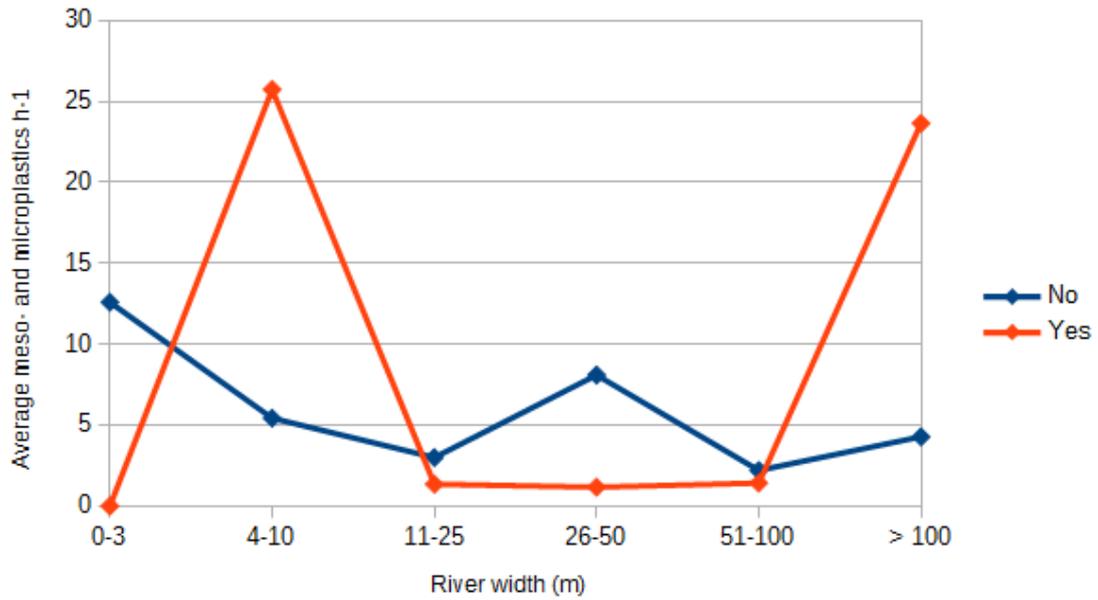


Figure B6-3.2: Average meso-/microplastics h⁻¹ over river width categories, grouped according to whether an artificial barrier was located within 2 km upstream (Yes) or not (No).

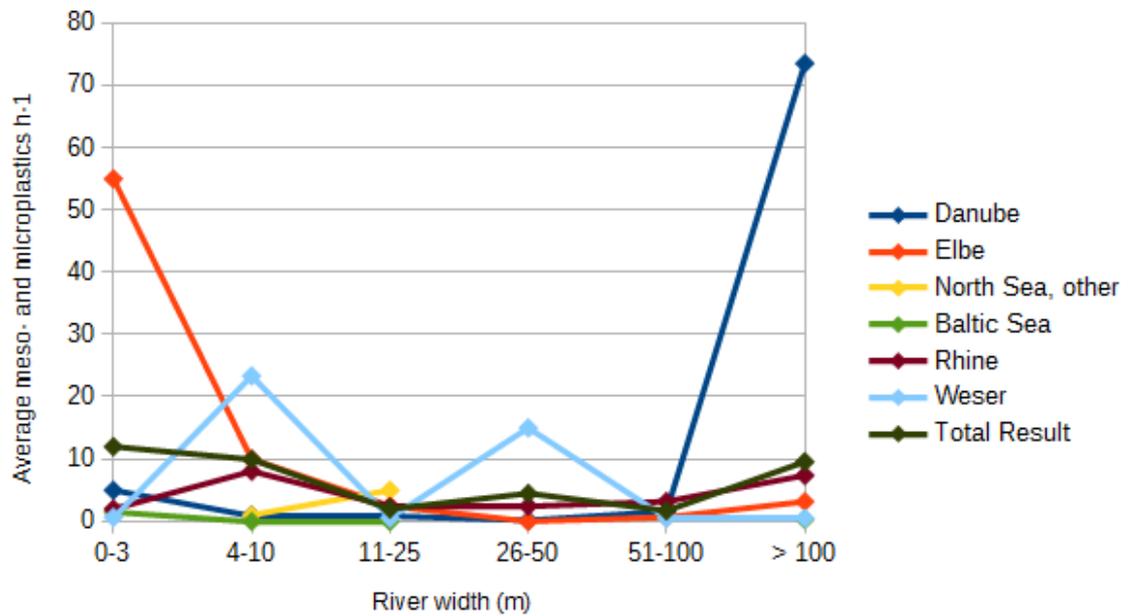


Figure B6-3.3: Average meso-/microplastics h⁻¹ over river width categories, grouped according to river system.

B6-4: Results of Kendall rank correlation tests between floating macrolitter, floating meso-/microplastics, litter at riversides, and accumulations at riversides (the data from the latter two samplings originates from Kiessling et al. 2019). Significant relationships with p-value marked bold.

Comparison between samplings	Number of sampling sites where data for both samplings was available	Kendall's tau	p-value
Floating macrolitter $m^{-1} h^{-1}$ with Floating microplastics h^{-1}	145	0.14	0.04
Floating macrolitter $m^{-1} h^{-1}$ with Riverside litter m^{-2}	228	0.11	0.02
Floating macrolitter $m^{-1} h^{-1}$ with Riverside accumulations $1000 m^{-2}$	53	0.16	0.12
Floating microplastics h^{-1} with Riverside litter m^{-2}	137	-0.04	0.50
Floating microplastics h^{-1} with Riverside accumulations $1000 m^{-2}$	41	-0.15	0.21
Riverside litter m^{-2} with Riverside accumulations $1000 m^{-2}$	55	0.11	0.25

B7. Size class, types, polymers, and colors of meso-/microplastics found in the study

A total of 1128 meso-/microplastics were identified in the present study). Polymers marked as composites consist of multiple polymers.

	Number of particles (percentage of particles)
Size class	
Microplastics (1 – 4.99 mm)	850 (75.4%)
Mesoplastics (5 – 24.99 mm)	278 (24.6%)
Type	
Soft fragments	478 (42.4%)
Hard fragments	319 (28.3%)
Pellets	151 (13.4%)
Films	101 (9.0%)
Monofilaments	79 (7.0%)
Polymers	
Polystyrene (PS)	429 (38.0%)
Polyethylene (PE)	353 (31.3%)
Polypropylene (PP)	298 (26.4%)
Ethylene vinyl acetate/Ethylene vinyl alcohol	16 (1.4%)
Ethylene propylene	9 (0.8%)
Polyester	7 (0.6%)

Nylon	5 (0.4%)
Polyamide	3 (0.3%)
Cellulose acetate	1 (~0.1%)
Composite plastic: PE and Polyester	1 (~0.1%)
Composite plastic: PS and PE	1 (~0.1%)
Ethylene acrylic acid	1 (~0.1%)
Polyethylene terephthalate (PET)	1 (~0.1%)
Silicone rubber	1 (~0.1%)
Styrene acrylonitrile	1 (~0.1%)
Styrene isoprene	1 (~0.1%)
Colours	
White	589 (52.2%)
Dark (black and brown)	237 (21.0%)
Transparent	108 (9.6%)
Red	61 (5.4%)
Blue	45 (4.0%)
Green	41 (3.6%)
Grey	41 (3.6%)
Yellow	5 (0.4%)
Several colors	1 (~0.1%)

Supplementary material C for Chapter IV

Study area and period

According to the “Water Atlas of Chile” (DGA, 2015), the Chilean hydrographic network comprises 101 river basins, >1,200 rivers, >12,700 lakes and lagoons, and >24,000 glaciers (including icefields, mountain glaciers, valley glaciers, ice aprons, and rocky glaciers). Rivers are distributed all along the country from north to south, most of them flowing in an east-west direction, from the Andes Mountains to the Pacific Ocean. They are generally short and fast-flowing, but present variable regime and discharge characteristics, given the wide climatic and geographic variations within Chile. The rivers in the northernmost regions are mostly intermittent, they have low water volumes and discharges, and are mainly fed by rainfall during the “Altiplanic winter” (austral summer). In central Chile, rivers have higher volumes and discharges and their feeding regime is mostly by rainfall (during austral winter) and snow melting (during austral spring). In the southern and austral regions, rivers are permanent year-round, they have the highest volumes and discharges, and are mainly fed by rainfall, snow and glaciers (Ferrando, 1992). Adding to these latitudinal characteristics, Chilean Andean rivers might also present large inter-annual streamflow variation due to the influence of El Niño Southern Oscillation (ENSO, Masiokas et al., 2019), as well as variations due to high levels of fragmentation caused by the presence of several barriers (e.g., dams), which are expected to increase in the near future (Díaz et al., 2019).

To account for Chile’s climatic, geographic, and socio-economic latitudinal variability, and to allow comparability with marine litter studies conducted along the Chilean coast (e.g., Hidalgo-Ruz et al., 2018), herein the country was also subdivided into different zones from north to south (zones 1 to 5, following the classification by Bravo et al., 2009; Figure 1). Interestingly, these zones also correspond roughly with the Chilean regions identified by Masiokas et al. (2019) based on streamflow variations in Andean rivers.

The samplings were conducted in 2013 and again in 2017 to determine possible general spatial and temporal tendencies at the national level, given that (i) the general climatic conditions were similar in those two years, i.e., ENSO neutral-conditions, during an extensive drought in central Chile (30°–38°S) since 2010 (Garreaud et al., 2020), and (ii) important changes in public awareness and litter policies occurred in the country during 2013-2017 (Amenábar Cristi et al., 2020).

Sampling of litter accumulations at riversides

Litter accumulations were sampled according to the methodology described by Rech et al. (2015) for the 2013 part of the study, whereas the slightly improved methodology described by Kiessling et al. (2019) was used in 2017. The former consisted in identifying and counting small, medium, and large litter accumulations, defined by the area they covered (small: $<1 \text{ m}^2$, medium: $1\text{--}10 \text{ m}^2$, large: $>10 \text{ m}^2$; named as “litter patches”, “small dumping sites”, and “large dumping sites”, respectively, by Rech et al., 2015). As indicated by Kiessling et al. (2019), this protocol was later improved to allow an easier identification of accumulations, due to some complications caused by the measurement of the occupied area (reported by Rech et al., 2015). Consequently, the improved methodology was used in the 2017 sampling, which also consisted in identifying and counting small, medium, and large litter accumulations, but their identification was not based on the area covered, but rather on the number of litter items that made up the accumulation and the maximum distance between them, i.e., accumulations contained at least three litter items separated from each other by not more than 50 cm (see Figure 2B in Kiessling et al., 2019). A small accumulation contained 3–10 total litter items, a medium accumulation 11–25 items, and a large accumulation more than 25 items. To representatively sample the potential litter accumulations, the participants had to conduct this sampling within a considerable area at the riverside (ideally 1000 m^2). Given the differences among methodologies and the consequent difficulty to standardize the number of litter accumulations per sampling effort unit, the results of this sampling are presented in terms of presence/absence of litter accumulations at each sampling site.

Sampling of small litter at the water surface

Small litter items (1–20 mm) floating at the surface of rivers were sampled using a neuston net with a mesh size of 1 mm. Mesh sizes $<1 \text{ mm}$ have been most frequently used in other studies (Hidalgo-Ruz et al., 2012), but for the purposes of simplicity and to ensure that samplings were correctly conducted and samples appropriately manipulated by the schoolchildren, herein we decided to sample small litter $\geq 1 \text{ mm}$.

Regarding the professional recounts of the net samples, in the case of 2013 only the samples from four main Chilean rivers were recounted (i.e., Elqui, Maipo, Maule and Biobío; data published by Rech et al., 2015), whereas the samples from the other surveyed rivers were unfortunately lost during a tsunami event that hit the city of Coquimbo on 16th September 2015; therefore, professional recounts of the latter samples are not

available. In the case of 2017, professional recounts are available for all the samples that were collected and appropriately sent to the coordination team ($n = 22$ samples). To homogenize and standardize the data, all professional recounts were conducted following the same protocol in terms of small litter size (1–20 mm) and categories (plastics, polystyrene, cigarette butts, glass, metals, and other items). Polystyrene was initially considered separately from plastics because it is an easily recognizable polymer and comprises an important proportion of marine litter in the austral zone of Chile (Hinojosa and Thiel, 2009). Given that fibers are ubiquitous and might originate from the very clothes of the schoolchildren, teachers and scientists, during both study years they were not considered and quantified, except for aggregated and tangled fibers, which are less likely to come from airborne contamination.

Citizen science data verification

All samples from the water surface collected in 2017 were sorted out to separate small litter items (1–20 mm, including visually identified plastics, i.e., “putative plastics”, and other litter) from macrolitter and organic material, which was abundant in some samples. These small litter items were sent to Kiel Science Factory (Germany) where most of them were subjected to FTIR spectroscopy to identify polymer types. The only exceptions to this were two samples: one sample was inadequately stored and, due to destruction of non-plastic items, only putative plastics were sent to Germany for FTIR analysis (sample from Biobío river by the school “Liceo San Juan Bautista de Hualqui”, Table C3); another sample contained more than 300 visually identical objects, from which only 10 items were analyzed (more details about this particular sample are provided below).

The device used was an Agilent Cary 630 FTIR spectrometer with an ATR (attenuated total reflectance) module. The program siMPle 1.0.1 (Primpke et al., 2020) was used for analysis with the ATR single spectra IR library 1.0.2 (Primpke et al., 2018), after output files from the device were transformed using SpectraGryph 1.2.13 (Menges, 2019). Prior to FTIR analysis, each item had its physical dimensions measured and was photographed under a microscope. Each item was then measured by FTIR at least three times, and it was confirmed as plastic if it complied with any of the following criteria: (i) three measurements indicated the same plastic polymer with a score equal or greater than 0.7, which is a value used elsewhere to accept FTIR results (Obbard et al., 2014), or (ii) it was visually identical to a confirmed plastic in the same sample (confirmed by the first criterium) and its highest measurement corresponded with the polymer of the confirmed

item. In the cases of items that did not comply with any of these criteria but one or more of their measurements indicated a plastic polymer, they were cleaned with ethanol and re-subjected to FTIR, re-evaluating whether they met the acceptance criteria after new measurements.

As indicated above, fibers were excluded, except for aggregated and tangled fibers. It is also worth noting that since the samples were sent from Chile to Germany to be analyzed by FTIR, due to their material type some non-plastic items were accidentally pulverized during transport and could not be analyzed. Additionally, one extreme outlier from 2017 was excluded from subsequent analyses, because the litter items (more than 300 identical, transparent and very brittle particles) corresponding to this extreme value appeared to come from one macrolitter item that was ingested, fragmented and regurgitated by a bird. We analyzed 10 items of this sample by FTIR and the results indicated that all the fragments possibly corresponded to polypropylene; although the polymer could not be confirmed according to the established criteria, this sample serves as an example of the fragmentation process of litter in living organisms and the environment (if it would have passed more time within the river, the bird pellet might have separated and dispersed in the river while moving in downstream direction). For information purposes, nonetheless, this outlier sample is included in Table C3 (sample from Loa river by school “Escuela Bernardo O’Higgins”).

After FTIR analysis and evaluation, the small litter items were primarily classified into the following categories: confirmed plastics (including all items that complied with either acceptance criterium), likely plastics (items that looked and scored like plastic, but did not comply with the acceptance criteria, possibly due to excessive dirtiness that could not be entirely removed with ethanol), confirmed non-plastics (items that scored differently from plastic polymers [e.g., chitin] and also items that scored as plastic with only values below 0.5), and NA (items that could not be measured three times due to their loss or destruction during manipulation). However, since the likely plastics could not be definitely and rigorously confirmed as plastics, for reporting and analyses purposes they were included in the category non-plastics. As reported in Figure C6B, 75% of small litter items were confirmed as plastic at the national level, whereas 17% were considered non-plastic, and 8% got lost or were destroyed during manipulation and could not be analyzed by FTIR (all these proportions exclude the outlier sample detailed above). Subsequently, small floating litter data from 2017 were corrected accordingly (see Table C3 for differences between the visual counting and FTIR results) and the data corresponding to

plastics confirmed by FTIR were used for all calculations and analyses of small floating plastics.

On the other hand, not all the samples collected in 2013 could be professionally recounted, and none could be analyzed by FTIR due to their loss (as indicated above). Thus, in the case of 2013 data, the professional recounts were used for analyses when available, while the schoolchildren's recounts were used in the remaining cases. However, for comparability among 2013 and 2017 data, the putative plastics recounts from 2013 (including the categories "plastics" and "polystyrene") were corrected according to the proportion of putative plastics from 2017 that were confirmed as such by FTIR, which we have termed "FTIR correction factor" herein. This FTIR correction factor corresponded to 0.78 (i.e., 217 confirmed plastics out of 278 putative plastics; see Table C3), and the resulting values of multiplying 2013 data by this correction factor were rounded to the nearest lower unit, in order to be conservative and avoid overestimating the abundances and the proportions of small plastics (see Table C4 for the original 2013 small plastics data and their correction for further analyses).

Unfortunately, due to transmission problems most schools did not submit photographic evidence of their litter findings. Therefore, a stepwise verification process of the data such as that performed by Kiessling et al. (2019) was not possible. Nevertheless, based on the verification by Kiessling et al. (2019), who applied all the same citizen science protocols as in the present study (except for litter at the water surface) and rigorously validated the data of a large percentage of participating groups, we assume that most of the Chilean schools also conducted the sampling protocols correctly. Furthermore, the Chilean coordinating team had much closer contact and communication with the participating teachers (thereby ensuring correct sampling) than was possible in Kiessling et al. (2019), given the massive participation of schools in Germany.

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Tables

Table C1. Details about the litter samplings performed by the participating schools in each of the surveyed Chilean rivers. RL = Riverside litter, LA = Litter accumulations, FMa = Floating macrolitter, FSm = Small floating litter, I = Inference of litter sources

Zone	River system	Surveyed river ^a	No. of sampling	Year of sampling	Date of sampling ^b	Coordinates of sampling site	School	Sampling(s) conducted ^c				
								RL	LA	FMa	FSm	I
1	Lluta	Lluta	1	2013	May 15 / June 5	18° 24' 29" S, 70° 14' 30" W	Escuela Humberto Valenzuela García	X	X		X	
			2	2017	June 29	18° 24' 29" S, 70° 14' 30" W	Escuela Humberto Valenzuela García	X	X	X	X	X
1	Loa	Loa	3	2017	June 29	22° 23' 49.8" S, 69° 31' 43.6" W	Escuela Bernardo O'Higgins	X	X	X	X ^e	X
			4	2017	June 17	22° 30' 17.0" S, 68° 58' 47.4" W	Escuela Armando Carrera González F-60		X	X	X	X
1	Quebrada La Negra	Vertiente Carrizo	5	2013	May 15 / July 13	23° 42' 03.6" S, 70° 23' 38.7" W	Colegio Santa Emilia	X	X			
2	Copiapó	Copiapó	6	2013	May 25	27° 22' 48.4" S, 70° 19' 34.3" W	Liceo Tecnológico de Copiapó	X	X		X	
2	Huasco	Huasco	7	2017	June 14	28° 35' 3.30" S, 70° 45' 2.30" W	Liceo José Santos Ossa	X	X	X		X
2	Elqui	Elqui	8	2013	May 2 / June 5	29° 53' 40.39" S, 71° 15' 34.45" W	Colegio Claudio Arrau	X	X		X	
			9	2013	May 2 / June 6	29° 53' 37.75" S, 71° 16' 24.74" W	Colegio Eusebio Lillo	X	X		X	
			10	2013	April 30 / June 4	29° 53' 41.20" S, 71° 15' 26.23" W	Colegio Los Carrera	X	X		X	
			11	2017	June 20	29° 53' 37" S, 71° 16' 14" W	Colegio Eusebio Lillo	X	X	X	X	X
			12	2017	June 1	29° 53' 41.20" S, 71° 15' 26.23" W	Colegio Los Carrera	X	X	X	X	X
			13	2013	May 3 / June 7	30° 02' 09.56" S, 70° 44' 09.37" W	Escuela Lucila Godoy Alcayaga	X	X		X	
			14	2017	May 23 / May 29	30° 02' 26" S, 70° 42' 47" W	Escuela Lucila Godoy Alcayaga	X	X	X	X	X

		Elqui-Claro	15	2013	April 29 / June 6	30° 06' 02.41" S, 70° 29' 27.10" W	Escuela Gabriela Mistral	X		X		
			16	2017	July 5	30° 06' 02.41" S, 70° 29' 27.10" W	Escuela Gabriela Mistral	X		X	X	
2	El Culebrón	El Culebrón	17	2017	July 6	29° 57' 45.7" S, 71° 19' 16.9" W	Escuela José Agustín Alfaro	X	X	X	X	X
2	Quebrada Camaronés	Estero Tongoy	18	2017	July 4	30° 15' 39.2" S, 71° 28' 57.8" W	Liceo Carmen Rodríguez Henríquez	X		X	X ^f	X
3	La Ligua	La Ligua	19	2013	May 9 / June 7	32° 25' 13.2" S, 71° 23' 22.2" W	Escuela Básica Papudo	X	X		X ^f	
			20	2017	June 6	32° 24' 43.3" S, 71° 24' 36.3" W	Liceo Técnico Profesional de Papudo	X	X	X	X	X
3	Aconcagua	Aconcagua	21	2017	June 19	32° 55' 10.0" S, 71° 30' 30.9" W	Escuela Pacífico E-271	X	X	X	X	X
3	Maipo	Maipo	22	2013	May 17 / June 14	33° 37' 06.52" S, 71° 37' 30.91" W	Colegio Espíritu Santo	X	X		X	
			23	2013	May 14 / June 11	33° 42' 55.69" S, 71° 12' 40.72" W	Colegio San Agustín	X	X		X	
			24	2013	May 9 / June 13	33° 42' 23.85" S, 70° 20' 06.51" W	Colegio El Melocotón		X		X	
			25	2017	June 30	33° 36' 58.0" S, 71° 37' 37.1" W	Colegio Fénix	X	X	X	X ^f	X
			26	2017	June 8	33° 43' 30.3" S, 70° 55' 09.4" W	Colegio San Adrián de Quilicura	X	X	X	X	X
		Maipo- Angostura	27	2013	May 4 / June 8	33° 52' 03.1" S, 70° 45' 02.9" W	Liceo Gregorio Morales	X	X		X	
		Maipo- Quebrada Macul	28	2013	May 24	33° 30' 03.8" S, 70° 30' 44.0" W	Colegio San Francisco del Alba	X	X		X	
3	Lago Vichuquén	Estero Llico	29	2017	June 27	34° 46' 06.1" S, 72° 04' 05.8" W	Liceo Entre Aguas de Llico	X	X			X
3	Maule	Maule	30	2013	May 2 / May 29	35° 19' 28.64" S, 72° 24' 26.59" W	Colegio Eduardo Martín Abejón	X	X		X	

			31	2013	May 8 / May 29	35° 19' 28.64" S, 72° 24' 26.59" W	Escuela Superior Nueva Bilbao	X	X		X	
			32	2017	June 2	35° 19' 11.4" S, 72° 24' 40.9" W	Colegio Eduardo Martín Abejón	X	X	X	X	X
		Maule- Achibueno	33	2013	June 5	35° 52' 25.2" S, 71° 35' 57.5" W	Escuela Maitenes	X			X	
			34	2017	Aug 1	35° 52' 25.2" S, 71° 35' 57.5" W	Escuela Maitenes	X	X _d			X
		Maule- Loncomilla	35	2013	May 16 / June 17	35° 35' 37.9" S, 71° 44' 57.0" W	Liceo Manuel Montt de San Javier	X	X		X ^f	
4	Biobío	Biobío	36	2013	May 8 / July 1	36° 48' 21.21" S, 73° 10' 08.47" W	Escuela Básica Villa Centinela Sur	X	X		X	
			37	2013	May 23 / June 25	36° 48' 36.96" S, 73° 10' 24.84" W	Escuela Rosita Renard	X	X		X	
			38	2013	May 2 / June 6	36° 58' 40.8" S, 72° 56' 49.2" W	Liceo San Juan Bautista de Hualqui	X	X		X	
			39	2013	May 2 / June 20	37° 17' 07.5" S, 72° 42' 56.9" W	Liceo Politécnico Héroes de la Concepción	X	X		X	
			40	2017	June 29	36° 48' 21.21" S, 73° 10' 08.47" W	Colegio Básico Los Lobos	X	X	X	X	X
			41	2017	May 24	36° 58' 40.8" S, 72° 56' 49.2" W	Liceo San Juan Bautista de Hualqui	X	X	X	X	
4	Carampangue	Carampangue	42	2017	Aug 4	37° 14' 40.3" S, 73° 15' 53.2" W	Liceo Filidor Gaete Monsalve de Llico		X _d	X	X	X
4	Tirúa	Tirúa	43	2017	Aug 3	38° 20' 26.6" S, 73° 30' 03.5" W	Escuela Particular Aillinco N° 234	X	X	X	X	X
4	Imperial	Imperial	44	2013	May 13 / June 10	38° 47' 24.6" S, 73° 24' 26.5" W	Escuela Básica Calof	X	X		X	
			45	2017	July 10	38° 47' 04.2" S, 73° 23' 59.6" W	Liceo Reino de Suecia	X	X	X	X	X
		Imperial- Cautín	46	2017	July 7	38° 45' 05.8" S, 72° 35' 40.0" W	Liceo Particular Comercial Temuco	X	X			X
		Imperial- Purén	47	2017	June 8	38° 02' 55.9" S, 73° 05' 15.0" W	Liceo Bicentenario Indómito de Purén	X	X	X	X	X
4	Valdivia	Valdivia	48	2013	May 8 / Aug 14	39° 52' 18.1" S, 73° 22' 55.7" W	Escuela Rural Curiñanco	X	X		X	

			49	2017	June 12	39° 50' 01.1" S, 73° 15' 19.7" W	Colegio Aliwen	X		X ^f	X
4	Chaihuín	Chaihuín	50	2013	May 6 / June 13	39° 57' 11.8" S, 73° 34' 46.8" W	Escuela Rural Chaihuín	X	X		X
5	Bueno	Rahue	51	2017	July 4	40° 34' 07.7" S, 73° 09' 26.5" W	Colegio San José		X	X	X
5	Chamiza	Chamiza	52	2013	May 7 / June 18	41° 29' 02.2" S, 72° 50' 45.3" W	Escuela Melipulli	X	X		X
5	Mauñín	Mauñín	53	2017	June 13	41° 19' 31.8" S, 73° 01' 57.3" W	Colegio Antares de Alerce	X	X	X	X
5	Chepu	Las Compuertas	54	2013	May 15 / June 19	42° 19' 53.8" S, 73° 44' 50.5" W	Colegio Charles Darwin	X	X		X
5	Coastal systems between Cucao and Medina rivers	Collil	55	2017	Aug 4 / Sept 25	42° 33' 14.0" S, 73° 57' 15.8" W	Instituto del Mar Capitán Williams	X	X	X	X ^f
5	Coastal systems between Puelo river and Punta Trentelhue	Contao	56	2013	May 15 / June 17	41° 47' 32.4" S, 72° 42' 47.6" W	Liceo Mauricio Hitchcock		X		
		Laguna Rolecha	57	2013	May 16 / June 13	41° 55' 08.1" S, 72° 50' 47.8" W	Escuela Rural Semillero	X	X		X
			58	2017	June 8	41° 55' 08.1" S, 72° 50' 47.8" W	Escuela Rural Semillero		X	X	X
5	Aysén	Aysén	59	2013	May 13 / June 21	45° 24' 20.8" S, 72° 41' 05.7" W	Escuela Litoral Austral	X	X		X
			60	2017	Aug 4	45° 24' 20.8" S, 72° 41' 05.7" W	Escuela Litoral Austral	X	X	X	X

^a In the river systems where more than one river/tributary were surveyed, the tributaries are identified as "Name of main river-Name of tributary".

^b Several schools in 2013 performed the litter accumulations sampling on a given date, while conducting the riverside litter and small floating litter samplings on a later day; consequently, two different sampling dates may be indicated for them. In 2017, two schools also conducted the samplings in two different days.

^c The "X" denotes that the respective type of sampling was conducted by the respective school.

^d Two participating schools conducted the sampling of litter accumulations and erroneously recorded the accumulations data, but correctly recorded the presence of dangerous items (performed within the same protocol). Therefore, only their dangerous items data was considered for analysis.

^e One school did conduct the sampling of small floating litter, but their sample was not included in the analyses, because it corresponded to an extreme outlier possibly affected by a process of fragmentation and accumulation of plastics external to the riverine system (see section “Citizen science data verification” for details).

^f Six schools did conduct the sampling of small floating litter, but no data of them are available for analysis due to one of two reasons: (i) the school did not send their sample to the coordination team, so no professional recount could be performed (in the case of 2017 samplings), or (ii) the deploy time of the net was not recorded, and thus the small litter recounts could not be standardized for analysis.

Table C2. Main characteristics of Chilean surveyed rivers and their river systems. NA = data not available or data not found.

Zone	River system	Surveyed river	Total basin surface area (km ²)	Annual average discharge (m ³ /s)	Length of river (km) *	Source elevation (masl) *	Flow regime	Presence of dams in course	Presence of lakes in course
1	Lluta	Lluta	3437	~ 1.7	167	5100	Rainfall, snow and glacial	No	No
1	Loa	Loa	33083	~ 0.3 - 0.9	440	4000	Rainfall and snow	Yes	No
1	Quebrada La Negra	Vertiente Carrizo	11348	NA	95	2390	Rainfall	No	No
2	Copiapó	Copiapó	18703	~ 2.6	239	4260	Rainfall and snow	Yes	No
2	Huasco	Huasco	9813	~ 7.7	178	3480	Rainfall and snow	Yes	No
2	Elqui	Elqui and tributaries	9825	~ 11	152	3760	Rainfall and snow	Yes	No
2	El Culebrón	El Culebrón	1083	~ 0.4	18	85	Rainfall and coastal mist	No	No
2	Quebrada Camarones	Estero Tongoy	1217	NA	33	680	Rainfall and coastal mist	Yes	No
3	La Ligua	La Ligua	1980	~ 1.4	106	3190	Rainfall	No	No
3	Aconcagua	Aconcagua	7334	~ 33	177	2920	Rainfall, snow and glacial	No	No
3	Maipo	Maipo	15273	~ 117	255	3100	Rainfall, snow and glacial	Yes	No
		Maipo-Angostura	15273	~ 20	177	3000	Rainfall, snow and glacial	No	No
		Maipo-Quebrada Macul	15273	NA	151	2300	Rainfall, snow and glacial	No	No
3	Lago Vichuquén	Estero Llico	614	NA	34.5	330	Rainfall	No	Yes
3	Maule	Maule and tributaries	21054	~ 252	214	1800	Rainfall, snow and glacial	Yes	No
4	Biobío	Biobío	24371	~ 412	380	1160	Rainfall, snow and	Yes	No

							glacial		
4	Carampangue	Carampangue	1262	NA	70	1170	Rainfall	No	No
4	Tirúa	Tirúa	427	NA	30	710	Rainfall	No	No
4	Imperial	Imperial-Cautín	12669	~ 135	237	1500	Rainfall, snow and glacial	No	No
		Imperial-Purén	12669	NA	220	480	Rainfall	No	No
4	Valdivia	Valdivia	10245	~ 800	220	660	Rainfall, snow and glacial	No	Yes
4	Chaihuín	Chaihuín	308	~ 27	50	700	Rainfall	No	No
5	Bueno	Rahue	15367	~ 141	225	930	Rainfall, snow and glacial	No	Yes
5	Chamiza	Chamiza	814	~11	45	1000	Rainfall, snow and glacial	Yes	Yes
5	Mauullín	Mauullín	3972	~ 73	130	1400	Rainfall, snow and glacial	No	Yes
5	Chepu	Las Compuertas	1079	NA	70	150	Rainfall	No	No
5	Coastal systems between Cucao and Medina rivers	Collil	1421	NA	47	560	Rainfall	No	Yes
5	Coastal systems between Puelo river and Punta Trentelhue	Contao	521	NA	21	800	Rainfall, snow and glacial	No	No
		Laguna Rolecha	521	NA	1	5	Rainfall, snow and glacial	No	No
5	Aysén	Aysén	11457	~ 548	180	1170	Rainfall and snow	No	No

* The sources of the rivers and their total lengths from source to mouth were established considering and including the most important tributary upstream of the uppermost sampling site within each river system.

** Sources of information to elaborate Table C2:

Dirección General de Aguas (DGA). Official Hydrometeorological and Water Quality Information (Online). Ministerio de Obras Públicas (MOP), Gobierno de Chile. <https://snia.mop.gob.cl/BNAConsultas/reportes>, Accessed on November 2020.

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Table C3. Comparison between visual recount of small floating litter performed in Chile and results of the FTIR analysis conducted in Germany (data from 2017 sampling). Large within-sample differences are mainly due to pulverization of some non-plastic particles during their transport from Chile to Germany, which could not even be found within the samples by the German team upon arrival. The proportion of putative (visually

identified) plastics that were confirmed as such by FTIR, i.e., “FTIR correction factor”, is indicated in the last row. NA = small litter items that could not be correctly analyzed by FTIR due to their loss or destruction during manipulation for the analysis.

School	Surveyed river	Visual recount			FTIR			
		Plastics	Non-plastics	Total	Plastics	Non-plastics	NA	Total
Escuela Humberto Valenzuela García	Lluta	44	2	46	35	8	1	44
Escuela Bernardo O'Higgins ^a	Loa	308	0	308	0	10	0	10
Escuela Armando Carrera González F-60	Loa	1	2	3	2	1	0	3
Colegio Eusebio Lillo ^c	Elqui	64	0	64	54	9	3	66
Colegio Los Carrera ^c	Elqui	37	3	40	22	4	16	42
Escuela Lucila Godoy Alcayaga	Elqui-Turbio	36	5	41	23	7	0	30
Escuela Gabriela Mistral	Elqui-Claro	0	6	6	0	6	0	6
Escuela José Agustín Alfaro	El Culebrón	0	0	0	0	0	0	0
Liceo Técnico Profesional de Papudo	La Ligua	1	0	1	1	0	0	1
Escuela Pacífico E-271	Aconcagua	14	20	34	11	2	1	14
Colegio San Adrián de Quilicura	Maipo	0	2	2	0	2	0	2
Colegio Eduardo Martín Abejón	Maule	4	0	4	4	0	0	4
Colegio Básico Los Lobos	Biobío	0	0	0	0	0	0	0
Liceo San Juan Bautista de Hualqui ^b	Biobío	9	17	26	4	5	0	9
Liceo Filidor Gaete Monsalve de Llico ^c	Carampangue	2	0	2	0	3	0	3
Escuela Particular Aillinco N° 234	Tirúa	0	4	4	0	0	0	0
Liceo Bicentenario Indómito de Purén	Imperial-Purén	2	0	2	0	1	0	1
Liceo Reino de Suecia	Imperial	39	2	41	38	1	0	39
Colegio San José	Rahue	2	2	4	2	0	0	2
Colegio Antares de Alerce	Maullín	0	18	18	0	1	0	1
Escuela Rural Semillero	Laguna Rolecha	22	0	22	21	0	0	21
Escuela Litoral Austral	Aysén	1	0	1	0	0	1	1
Sum of items ^d		278	83	361	217	50	22	289
FTIR correction factor ^e		217/278 = 0.78						

^a Outlier sample that was excluded from analyses and from which 10 items were analyzed by FTIR, indicating that the totality of the particles in the sample possibly corresponded to a plastic polymer (polypropylene), although this could not be confirmed (see text in Supplementary Information for details).

^b Sample inadequately stored in Chile from which only 9 items visually identified as “plastics” were sent to Germany for FTIR analysis.

^c In three samples the number of total particles analyzed by FTIR was slightly higher than the particles counted in Chile, which was likely caused by fragmentation of particles during transport to Germany or during manipulation, but the variation was negligible.

^d Sum of items in each category, excluding the outlier sample.

^e Proportion of visually identified plastics that were confirmed as plastics by FTIR, excluding the items that scored as plastics but could not be confirmed (which were thus counted as non-plastics), as well as those that could not be analyzed (NA).

Table C4. Original small plastics data recorded by participating schoolchildren and professional scientists in water surface samples collected in 2013, and their correction based on the “FTIR correction factor” (i.e., the proportion of 2017 visually identified plastics that were confirmed as such by FTIR = 0.78). Schools’ and professionals’ recounts correspond to the sum of items in the 2013 categories “plastics” and “polystyrene”. In the nine cases where professional recounts existed, these were corrected instead of the schools’ recounts; see column “Visual recounts consolidated” for the values per sampling site/school that were corrected and subsequently used for the calculation of small floating plastics abundance (items h⁻¹) and for further analyses. All the corrected values were rounded to the nearest lower value in order to be conservative and avoid overestimates.

School	Surveyed river	Schools’ recounts	Professional recounts	Visual recounts consolidated	Corrected and rounded recounts (* 0.78)
Escuela Humberto Valenzuela García	Lluta	0	---	0	0
Liceo Tecnológico de Copiapó	Copiapó	2	---	2	1.56 ~ 1
Colegio Claudio Arrau	Elqui	3	6	6	4.68 ~ 4
Colegio Eusebio Lillo	Elqui	5	13	13	10.14 ~ 10
Colegio Los Carrera	Elqui	6	12	12	9.36 ~ 9
Escuela Lucila Godoy Alcayaga	Elqui-Turbio	0	4	4	3.12 ~ 3
Escuela Gabriela Mistral	Elqui-Claro	4	7	7	5.46 ~ 5
Escuela Básica Papudo ^a	La Ligua	0	---	0	0
Colegio Espíritu Santo	Maipo	1	9	9	7.02 ~ 7
Colegio San Agustín	Maipo	0	---	0	0
Liceo Gregorio Morales	Maipo-Angostura	0	---	0	0
Colegio El Melocotón	Maipo	0	0	0	0
Colegio San Francisco del Alba	Maipo-Quebrada Macul	0	---	0	0
Colegio Eduardo Martín Abejón	Maule	0	---	0	0
Escuela Superior Nueva Bilbao	Maule	0	---	0	0
Escuela Maitenes	Maule-Achibueno	0	---	0	0
Liceo Manuel Montt de San Javier ^a	Maule-Loncomilla	4	---	4	3.12 ~ 3
Escuela Básica Villa Centinela Sur	Biobío	0	0	0	0
Escuela Rosita Renard	Biobío	14	16	16	12.48 ~ 12
Liceo San Juan Bautista de Hualqui	Biobío	0	---	0	0
Liceo Politécnico Héroes de la Concepción	Biobío	0	---	0	0
Escuela Básica Calof	Imperial	0	---	0	0
Escuela Rural Curiñanco	Valdivia	0	---	0	0
Escuela Rural Chaihuín	Chaihuín	0	---	0	0
Escuela Melipulli	Chamiza	0	---	0	0

Colegio Charles Darwin	Las Compuertas	0	---	0	0
Escuela Rural Semillero	Laguna Rolecha	0	---	0	0
Escuela Litoral Austral	Aysén	0	---	0	0

^a The data from two sampling sites/schools were not considered for analyses because the net deployment time was not recorded by the schools, and thus small floating plastics abundance (items h⁻¹) could not be calculated for those sites.

Table C5. Variables used for the statistical analysis of riverside litter, floating macrolitter, and small floating plastics. N = number of datasets used for analysis; NA = variable not analyzed for respective litter sampling.

Variable	Analysis of riverside litter (items m ⁻²)	Analysis of floating macrolitter (items h ⁻¹)	Analysis of small floating plastics (items h ⁻¹)
Zone of Chile	N = 52	N = 25	N = 47
Sampling year	N = 52	NA	N = 47
Distance to source of river	N = 52	N = 25	N = 47
River width	N = 52	N = 25	N = 47
Discharge of river	N = 42	N = 19	N = 39
Land use	N = 52	N = 25	N = 47
Population size	N = 52	N = 25	N = 47
Wastewater treatment effluents	N = 52	N = 25	N = 47
Dams within the river	NA	N = 25	N = 47

Table C6. Description of the variables used for the analyses of riverside litter, floating macrolitter, and small floating plastics, as well as the references used to determine or measure the values of the variables, and selected references where the factor linked to the respective variable has been shown or suggested to influence riverine litter in any way. NA = not available.

Variable	Description of variable	References to determine or measure the values of the variables ^a	References where respective factor was shown or suggested to influence riverine litter ^b
Zone of Chile	The five zones in which Chile was subdivided for this study	Bravo et al. (2009)	NA
Sampling year	The year of sampling (2013 or 2017)	This study	NA
Distance to source of river	The distance in km from each sampling site to the source of the river, measured along the river path (each river source was established according to the criteria indicated below Table C2)	Google Earth Pro 7.3.2	Kapp and Yeatman (2018)

River width	The width of the river at each sampling site in m, based on satellite images corresponding to the closest date to the respective sampling (as the widths of Chilean rivers may be highly variable and the schoolchildren may have moved around the sampling site conducting the different activities, river width was measured as the average of three measurements at the sampling coordinates, separated from each other by 100 m along the river course)	Google Earth Pro 7.3.2	Kiessling et al. (2019)
Discharge of river	Average discharge of river in $\text{m}^3 \text{s}^{-1}$ for the month the sampling took place in, based on streamflow data from the General Water Directorate of Chile (“Dirección General de Aguas, DGA”) (the DGA’s database is the most accurate and complete in Chile, but it still has some missing data, especially for smaller rivers; due to this limitation, not all monthly averages correspond to the exact month of the sampling or contain exactly 30 (or 31) data points, but we intended to cover most of the sampling’s month as possible or include the closest possible data to the sampling date, in order to obtain an average around or near the sampling date; in addition, streamflow data could not be obtained for some sampling sites, as the DGA does not have any streamflow measuring stations in those rivers and therefore no data are available)	Dirección General de Aguas (DGA)	Castro-Jiménez et al. (2019) van Emmerik et al. (2019)
Land use	The type of land use, classified following Cowger et al. (2019) categories (Developed land, Agriculture land, Open land), and evaluated by satellite images of the respective year of sampling within a 4 km^2 square immediately upstream of the sampling site (i.e., up to 2 km upstream and 1 km to each side of the river), establishing land use according to which type of use covered the majority of the square	Cowger et al. (2019) Google Earth Pro 7.3.2	Yonkos et al. (2014) Baldwin et al. (2016) Cowger et al. (2019a)
Population size	Two variables were included, based on the official Chilean population census conducted in 2017: a) Population of the largest human settlement within 10 km upstream of each sampling site, and b) accumulated population of all human settlements within 50 km upstream of each sampling site; in both cases, only settlements within 5 km of the river course were considered, and population values were classified into five categories: <10,000 inhabitants, 10,000-50,000 inhabitants, 50,000-100,000 inhabitants, 100,000-500,000 inhabitants, >500,000 inhabitants	Instituto Nacional de Estadísticas (INE) ^{a, b} Google Earth Pro 7.3.2	Yonkos et al. (2014) Mani et al. (2016) Baldwin et al. (2016) Scheurer and Bigalke (2018)
Wastewater treatment effluents	Two variables were included, based on data from the Superintendencia of Sanitary Services of Chile (“Superintendencia de Servicios Sanitarios, SISS”): a) Presence or absence of wastewater treatment effluents within 50 km upstream of each sampling site, and b) number of wastewater treatment effluents within 50 km upstream of each sampling site	Superintendencia de Servicios Sanitarios (SISS) Google Earth Pro 7.3.2	Williams and Simmons (1999) Morritt et al. (2014) Mani et al. (2016) Cowger et al. (2019b)
Dams within the river	Presence or absence of dams within 50 km upstream of each sampling site, based on satellite images corresponding to the respective year of sampling	Google Earth Pro 7.3.2	Zhang et al. (2015) Watkins et al. (2019)

^a References used to determine or measure the values of the variables:

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Table C7. Overview of riverside litter, litter accumulations, potentially dangerous items, floating macrolitter and small floating plastics for each geographic zone and sampling year. NA = data not available because the respective sampling was not conducted that year.

	Riverside litter			Litter accumulations	Floating macrolitter		Small floating plastics	
	Percentage of sampling sites with litter (number of surveyed sites)	Percentage of sampling circles containing litter (number of surveyed circles)	Average litter abundance per m ² ± standard deviation (median, IQR)	Percentage of sampling sites with litter accumulations of any size (number of surveyed sites)	Percentage of sampling sites with macrolitter (number of surveyed sites)	Average macrolitter abundance per h ⁻¹ ± standard deviation (median, IQR)	Percentage of sampling sites with small plastics (number of surveyed sites)	Average small plastics abundance per h ⁻¹ ± standard deviation (median, IQR)
All zones, both years	100% (52)	91% (448)	1.81 ± 2.49 (0.99, 1.83)	98% (55)	NA	NA	43% (47)	5.79 ± 11.38 (0.00, 5.50)
All zones, 2013	100% (27)	95% (231)	1.94 ± 2.26 (1.27, 2.11)	100% (29)	NA	NA	31% (26)	2.09 ± 3.73 (0.00, 2.50)
All zones, 2017	100% (25)	87% (217)	1.66 ± 2.71 (0.71, 1.56)	96% (26)	76% (25)	10.13 ± 13.49 (7.00, 11.60)	57% (21)	10.37 ± 15.51 (2.00, 19.71)
Zone 1, 2013	100% (2)	100% (18)	0.95 ± 0.67 (0.72, 0.52)	100% (2)	NA	NA	0% (1)	0.00 (0.00)
Zone 1, 2017	100% (2)	100% (18)	4.27 ± 4.77 (2.12, 4.03)	100% (3)	100% (3)	24.67 ± 32.58 (10.00, 30.00)	100% (2)	18.50 ± 23.33 (18.50, 16.50)
Zone 2, 2013	100% (5)	98% (45)	1.10 ± 0.96 (0.80, 1.35)	100% (6)	NA	NA	100% (6)	6.17 ± 3.97 (6.50, 6.50)
Zone 2, 2017	100% (6)	94% (54)	2.20 ± 3.59 (0.78, 1.73)	100% (6)	83% (6)	6.83 ± 5.95 (7.00, 9.75)	60% (5)	19.46 ± 22.18 (19.71, 23.57)
Zone 3, 2013	100% (9)	99% (75)	2.70 ± 2.95 (1.59, 1.83)	100% (9)	NA	NA	13% (8)	0.88 ± 2.47 (0.00, 0.00)
Zone 3, 2017	100% (7)	94% (63)	1.09 ± 1.17 (0.85, 0.64)	83% (6)	100% (5)	11.83 ± 8.35 (8.00, 5.60)	75% (4)	5.38 ± 7.61 (2.50, 6.38)
Zone 4, 2013	100% (7)	84% (57)	2.21 ± 2.30 (1.67, 3.02)	100% (7)	NA	NA	14% (7)	1.47 ± 3.89 (0.00, 0.00)

Zone 4, 2017	100% (7)	71% (55)	1.42 ± 2.07 (0.57, 1.98)	100% (6)	50% (6)	7.61 ± 12.34 (0.63, 11.12)	33% (6)	6.51 ± 14.08 (0.00, 3.00)
Zone 5, 2013	100% (4)	100% (36)	1.49 ± 1.57 (0.99, 1.71)	100% (5)	NA	NA	0% (4)	0.00 ± 0.00 (0.00, 0.00)
Zone 5, 2017	100% (3)	81% (27)	0.67 ± 0.62 (0.57, 0.71)	100% (5)	60% (5)	6.71 ± 7.39 (6.00, 10.00)	50% (4)	5.75 ± 10.21 (1.00, 6.75)

Table C8. Percentage of sampling sites presenting litter accumulations of the respective size at Chilean riversides, in 2013 and 2017. N = number of sampling sites. Note that accumulations (of any size) were different between 2013 and 2017, given that definitions and classifications of litter accumulations were not the same between sampling years.

	2013 (N = 29)	2017 (N = 26)
Small accumulations	100%	96.2%
Medium accumulations	62.1%	80.8%
Large accumulations	24.1%	73.1%
Accumulations of any size	100%	96.2%

Table C9. Percentage of sampling sites across Chilean rivers in 2017 where respective source was identified by the participating schoolchildren as a likely origin of encountered litter (N = 29 sampling sites).

Recreational visitors	86.2%
Residents	65.5%
Illegal dumping	58.6%
River depositing litter	51.7%
Industry	13.8%
Ship/boat traffic	3.4%

Table C10. Results of Kendall rank correlation tests between abundances of riverside litter, floating macrolitter, and small floating plastics.

Comparison between variables	Number of valid pairs for comparisons	Kendall's tau	p-value
Riverside litter (items m ⁻²) with floating macrolitter (items h ⁻¹)	21	0.084	0.62
Riverside litter (items m ⁻²) with small floating plastics (items h ⁻¹)	40	0.114	0.36
Floating macrolitter (items h ⁻¹) with small floating plastics (items h ⁻¹)	20	0.076	0.68

Table C11. Comparison of overall average abundance of riverside litter in Chilean rivers with data from other rivers, lakes or areas. NA = data not available.

Study river, lake or area	Size class (cm)	Reporting unit	Litter abundance		References ^a
			Range	Average	
Several rivers in Chile	≥ 2.5	Items m ⁻²	0–21.8	1.81	This study
Several rivers in Germany	≥ 2.5	Items m ⁻²	0–0.57 (IQR)	0.54	Kiessling et al. (2019)
Five streams in Illinois and Indiana	> 1	Items m ⁻²	NA	0.29	McCormick and Hoellein (2016)
Thames river	All identifiable litter	Items m ⁻²	0–251	27.7	Bernardini et al. (2020)
Setúbal lake	> 2.5 (only plastics)	Items m ⁻²	NA	1.15	Blettler et al. (2017)
Paraná river	> 2.5 (only plastics)	Items m ⁻²	NA	2.27	Blettler et al. (2019)
Ems river	> 0.5	Items 100 m ⁻¹	0–256	16.4	Schöneich-Argent et al. (2020)
Weser river	> 0.5	Items 100 m ⁻¹	0–49	8.2	Schöneich-Argent et al. (2020)
Elbe river	> 0.5	Items 100 m ⁻¹	0–353	47	Schöneich-Argent et al. (2020)
Dutch Rhine–Meuse delta	> 0.5	Items km ⁻¹	NA	2060	van Emmerik et al. (2020)
Several streams in Iowa	Visible litter from canoes	Kg km ⁻¹	NA	188	Cowger et al. (2019)

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Table C12. Comparison of overall average abundance of floating macrolitter in Chilean rivers with data from other rivers, lakes or areas. NA = data not available.

Study river, lake or area	Size class (cm)	Reporting unit	Litter abundance		References ^a
			Range	Average	
Several rivers in Chile	Visible to the naked eye	Items h ⁻¹	0–62	10.13	This study
Several European and South East Asian rivers	> 1	Items h ⁻¹	10 ⁰ –10 ⁴	2.5 x 10 ² (Europe) 7.1 x 10 ³ (SE Asia)	van Calcar and van Emmerik (2019)
Five rivers in Indonesia	NA	Items h ⁻¹	3 x 10 ³ –20 x 10 ³	NA	van Emmerik et al. (2019)
Three rivers in Philippines	> 1	Items h ⁻¹	1 x 10 ⁴ –1 x 10 ⁵	NA	van Emmerik et al. (2020)
Rhone river	> 2.5	Items h ⁻¹	0–293	50	Castro-Jiménez et al. (2019)
Tiber river	> 2.5	Items h ⁻¹	10–130 (approx.)	85.4	Crosti et al. (2018)
Rhine river	> 5	Items h ⁻¹	10–75	NA	Vriend et al. (2020)
Several rivers in Germany	> 2.5	Items m ⁻¹ h ⁻¹	0–8.25	0.34	Kiessling et al. (2021)

^aReferences:

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Table C13. Comparison of overall average abundance of small floating plastics in Chilean rivers with data from other rivers, lakes or areas. A wide diversity of sampling methods, size classes and reporting units have been utilized in the different studies. To facilitate comparison, the studies are sorted by reporting unit. Given that items m⁻³ is a more common unit than items h⁻¹, the national average abundance obtained in this study is presented in both units, keeping in mind that the items m⁻³ value excludes two sampling sites from 2013 due to missing information needed to standardize per m⁻³. In the cases where the reporting unit can be converted to items m⁻³ for comparison, the converted value is shown in brackets.

Study river, lake or area	Sampling method	Size class (mm)	Reporting unit	Small plastics abundance		References ^a
				Range	Average	
Several rivers in Chile	Neuston net	1.0–20.0	Items h ⁻¹	0–54	5.79	This study
Several rivers in Germany	Neuston net	1.0–24.99	Items h ⁻¹	0–220	6.86	Kiessling et al. (2021)
Several rivers in Chile	Neuston net	1.0–20.0	Items m ⁻³	0–0.67	0.08	This study
Yangtze estuary	Teflon pump	> 0.5	Items m ⁻³	500–10,200	4137.3	Zhao et al. (2014)
Yangtze river	Teflon pump	< 5.0	Items m ⁻³	1597–12,611	4703	Di and Wang (2018)
Saigon river	Plankton net	> 0.3	Items m ⁻³	10–223	NA	Lahens et al. (2018)
Tributaries of the Great Lakes	Neuston net	> 0.355	Items m ⁻³	0.05–32	4.2	Baldwin et al. (2016)
Snake and Lower Columbia rivers	Plankton net	0.1–5.0	Items m ⁻³	0–13.7	2.57	Kapp and Yeatman (2018)
Ottawa river	Neuston net	> 0.1	Items m ⁻³	NA	1.35	Vermaire et al. (2017)
Tamar estuary	Neuston net	> 0.3	Items m ⁻³	NA	0.028	Sadri and Thompson (2014)
Austrian Danube river	Stationary driftnets	0.5–20.0	Items 1000 m ⁻³	NA	316.8 [0.32]	Lechner et al. (2014)
Gallatin river	Bulk water	0.1–9.6	Items L ⁻¹	0–67.5 [0–67,500]	1.2 [1200]	Barrows et al. (2018)
Vaal and Orange rivers	Bulk water	> 0.025	Items L ⁻¹	NA	1.7 [1700]	Weideman et al. (2020)
Fall Creek and Six Mile Creek	Bulk water	> 0.335	Items L ⁻¹	1–25 (Approx.) [1,000–25,000]	NA	Watkins et al. (2019)
Vaal and Orange rivers	Neuston net	> 0.3	Items m ⁻²	NA	0.34	Weideman et al. (2020)
Yangtze river	Non-identified net	0.112–5.0	Items km ⁻²	3407.7 x 10 ³ –13,617.5 x 10 ³	NA	Zhang et al. (2015)
Laurentian Great Lakes	Neuston net	> 0.355	Items km ⁻²	NA–466 x 10 ³	43 x 10 ³	Eriksen et al. (2013)
Rhine river	Neuston net	0.3–5.0	Items km ⁻²	NA	892.7 x 10 ³	Mani et al. (2016)
Estuarine Rivers in the Chesapeake Bay	Neuston net	> 0.33	g km ⁻²	1–563	NA	Yonkos et al. (2014)

^a References:

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Figures

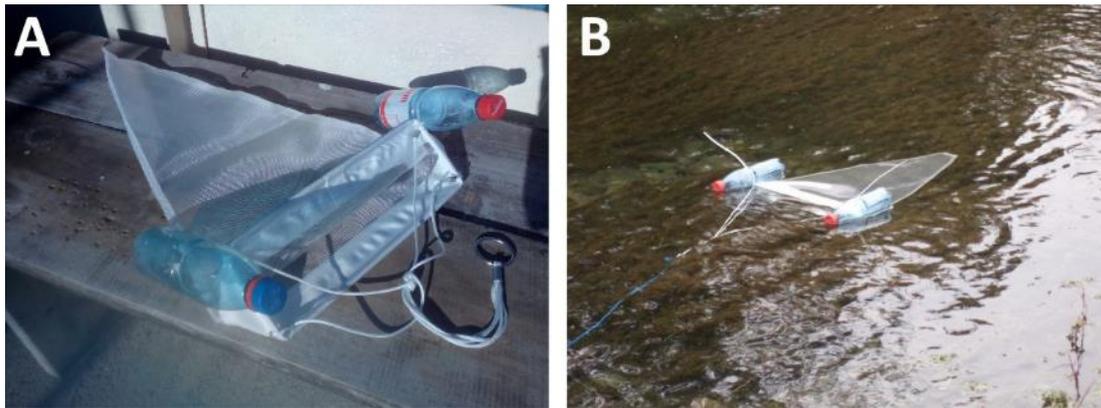


Figure C1. Neuston net utilized in 2017 to sample small litter floating at the surface of Chilean rivers, with empty reused plastic bottles attached to keep it afloat. (A) A net out of the water, prior to sampling. (B) A net floating at the surface of a river during a sampling, facing opposite to the flow direction.

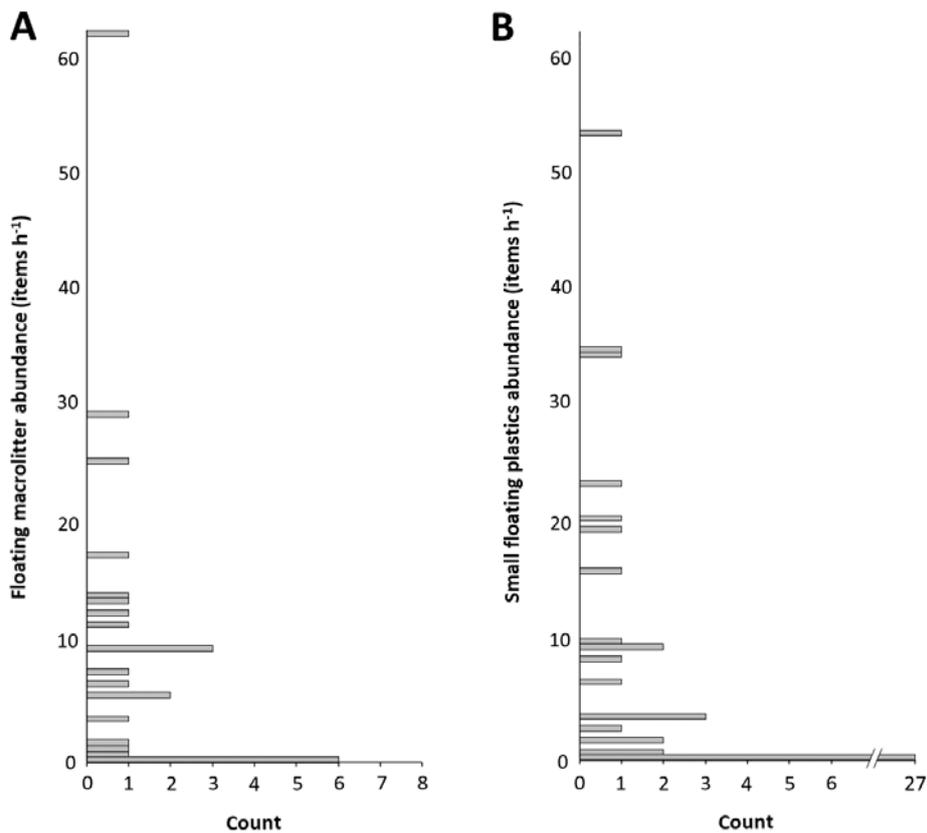


Figure C2. Frequency distributions of the abundances of floating macrolitter (items h⁻¹, A) and small floating plastics (items h⁻¹, B), which show the presence of zero values in the datasets and the skewness of the distributions.

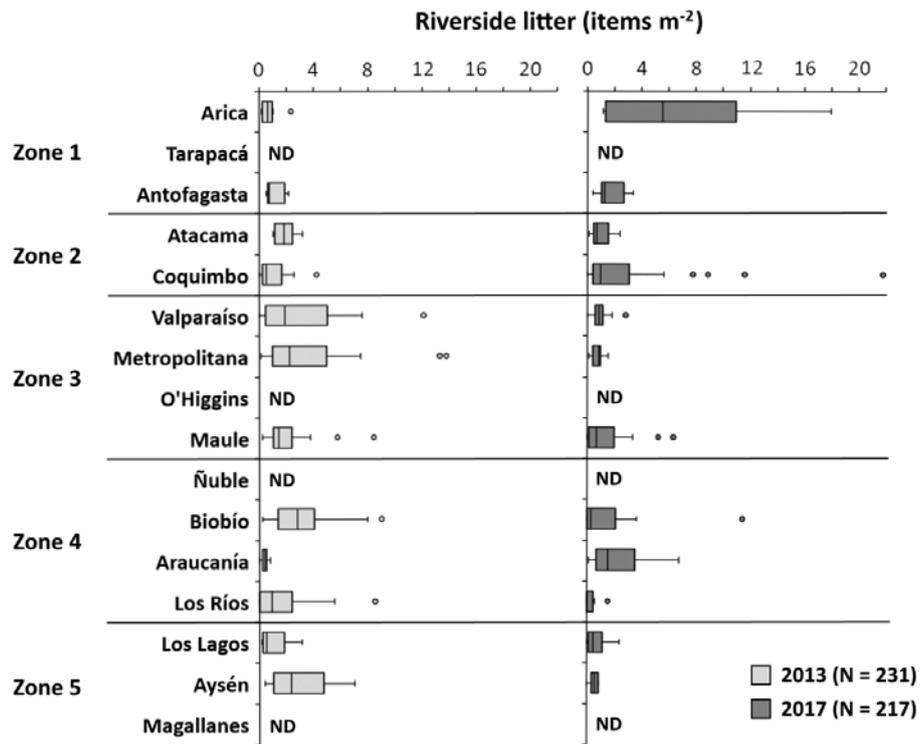


Figure C3. Litter abundance (items m⁻²) at Chilean riversides determined in 2013 and 2017, per administrative region. Each data point represents the average abundance at one sampling circle (N₂₀₁₃ = 231, N₂₀₁₇ = 217); the first and third quartiles (edges of the boxes) were calculated excluding the medians. ND = no data.

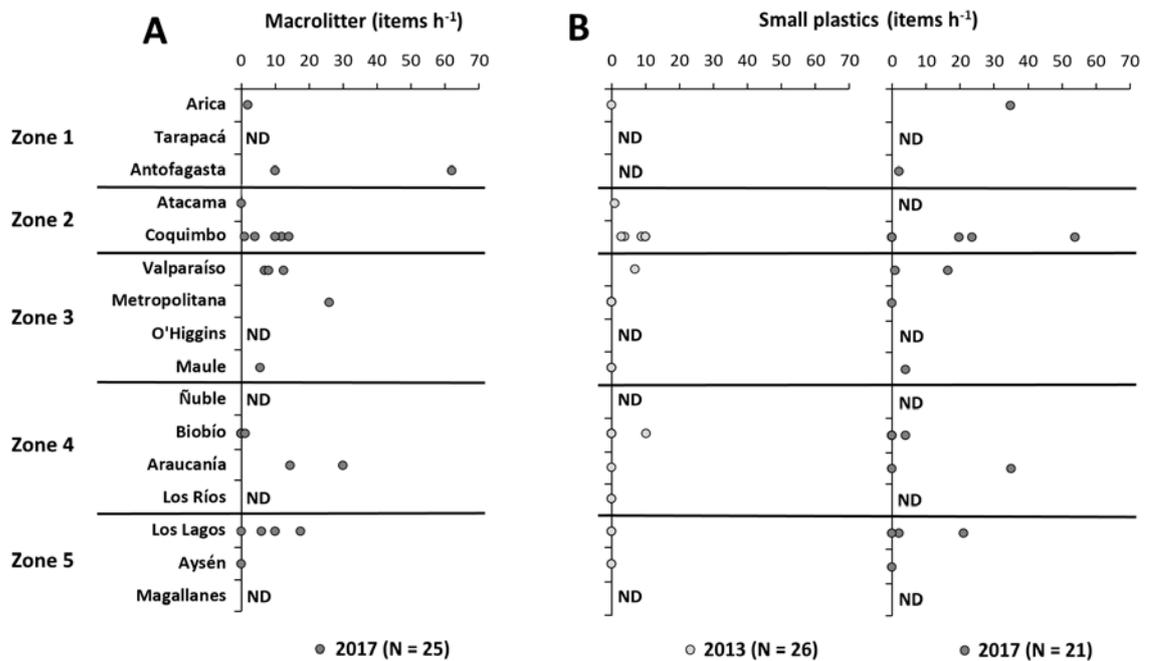


Figure C4. Abundances of (A) floating macrolitter in Chilean rivers in 2017, per administrative region (N = 25 sampling sites), and (B) small floating plastics in Chilean rivers in 2013 and 2017, per administrative region (N₂₀₁₃ = 26, N₂₀₁₇ = 21). Each data point represents the standardized abundance (items h⁻¹) at one sampling site. ND = no data.

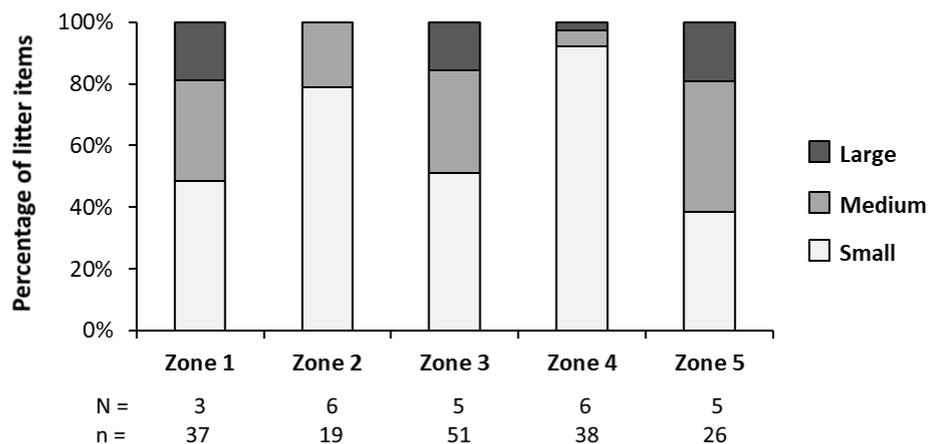


Figure C5. Size composition of floating macrolitter in Chilean rivers in 2017, per geographic zone. Schoolchildren were instructed to estimate the size of floating macrolitter by comparing the observed items to objects of known size (i.e., small: size of an apple; medium: size of a football; large: size of a bucket). N = number of sampling sites; n = number of macrolitter items registered.

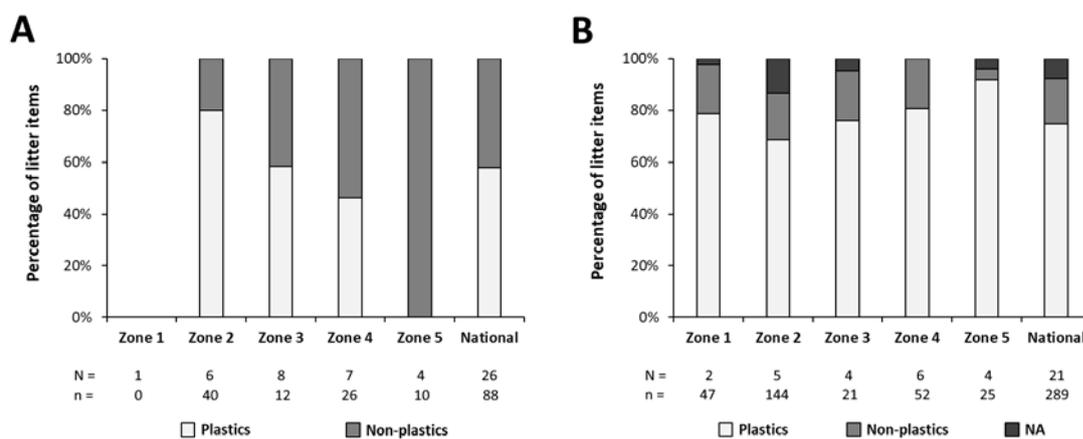


Figure C6. Percentage of small plastic items in the net samples collected at the surface of rivers, per geographic zone, in 2013 (A) and 2017 (B). For 2013, visually analyzed litter items were grouped as plastics (including the original categories “plastics” and “polystyrene”, whose values were corrected by multiplying them by the proportion of 2017 small floating items that were confirmed as plastics by FTIR) and non-plastics (categories “cigarette butts”, “glass”, “metals” and “other”). For 2017, the litter items analyzed by FTIR spectroscopy were grouped as plastics (i.e., all confirmed plastic polymers), non-plastics (i.e., all items confirmed as not corresponding to a plastic polymer, plus likely plastic polymers that could not be confirmed as such), and NA (i.e., items that could not be correctly analyzed by FTIR due to their loss or destruction during manipulation). N = number of sampling sites; n = number of small floating litter items registered.

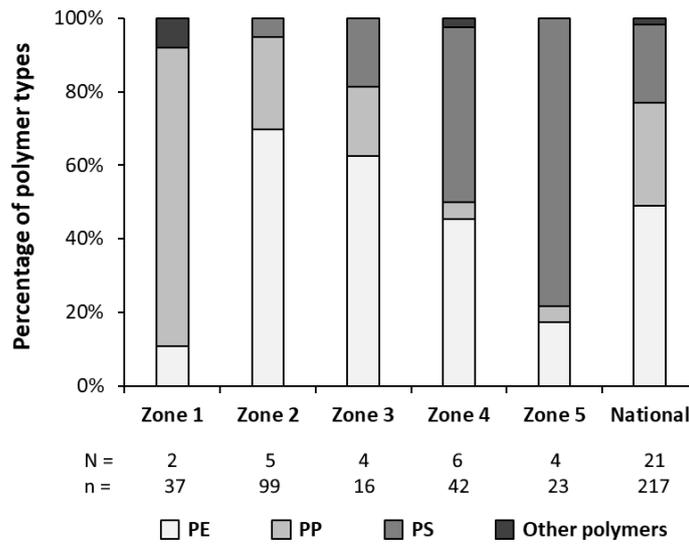


Figure C7. Polymer composition of small floating plastics in Chilean rivers in 2017, per geographic zone. PE = polyethylene; PP = polypropylene; PS = polystyrene; N = number of sampling sites; n = number of small plastic items found. Other polymers correspond to two ethylene vinyl alcohol items (zone 1), one polyester item (zone 1), and one styrene copolymer item (zone 4).

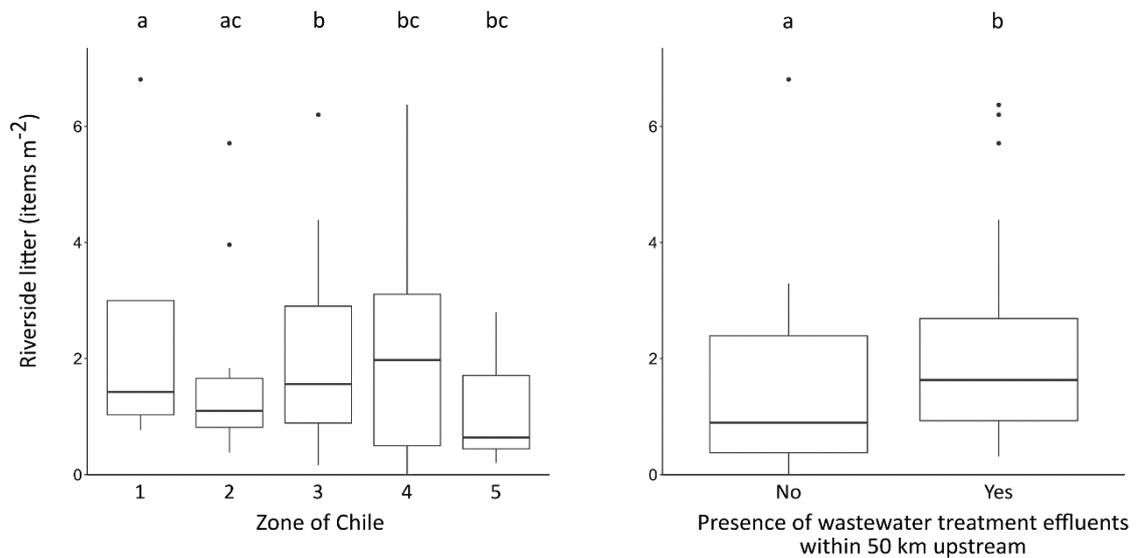


Figure C8. Significant variables for the model for riverside litter abundance (items m^{-2}). Significance letters are shown above the boxplots.

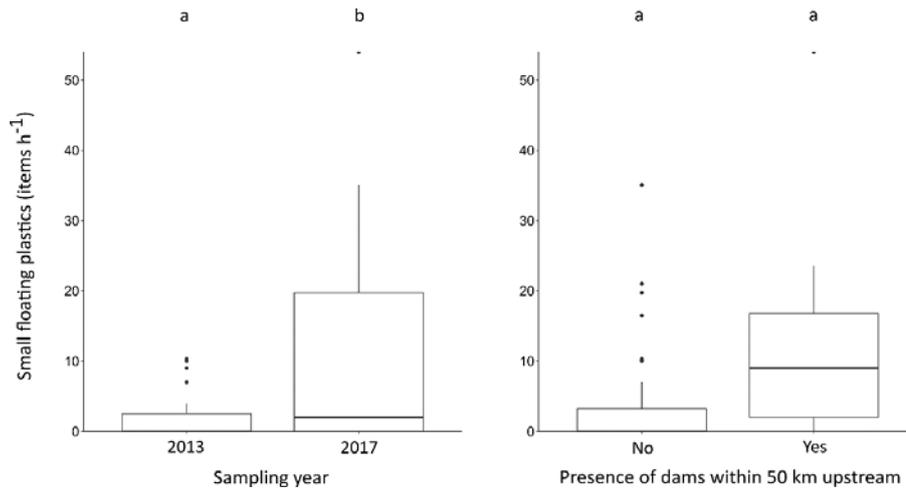


Figure C9. Significant variables for the model for small floating plastics (items h⁻¹). Significance letters are shown above the boxplots.

Formulas

Formula C1. Formula to calculate small plastics load (items m⁻³) at the surface of a river when sampling with a neuston net, proposed and used by Moore et al. (2011):

$$Plastics\ load\ [items\ m^{-3}] = \frac{plastics\ in\ net}{fv\ [m\ s^{-1}] * noa\ [m^2] * dt\ [s]}$$

where “fv” is flow velocity, “noa” is the net opening area, and “dt” is the net deployment time.

Formula C2. Formula to calculate small floating plastics abundance per unit of time (items h⁻¹):

$$Small\ floating\ plastics\ abundance\ [items\ h^{-1}] = \frac{plastics\ in\ net}{net\ deployment\ time\ [min]} * 60$$

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. <https://doi.org/10.5894/rgci194>.

Declaration of ethical conduct

I hereby declare that the work presented in this dissertation, apart from the advice given by my supervisors, is my own in both format and content. Chapters II, III were published in peer-reviewed scientific journals, while chapter IV was submitted to a peer-reviewed journal. Chapter V was published in German in a journal addressing teachers. This is my first dissertation and the contents have not been used in any prior attempts to obtain a PhD. The dissertation complies with the standards for good scientific practice as proposed by the German Research Foundation. I have not been deprived of an academic degree.

Kiel, 20.07.2021



Tim Kießling