Citizen science for assessing riverside macrolitter pollution - Communication and quality mechanisms for scientifically valid data

DISSERTATION

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Abstract

Since the start of industrial plastic production in the 1950s, global annual production has risen from 1.5 million tons to 413.8 million tons in 2023. At present, no ecosystem remains unaffected by plastic pollution. The most thoroughly studied is marine litter pollution, with a substantial share of plastic litter entering the oceans via rivers. While earlier studies primarily identified large river systems as the main sources, more recent studies show that smaller rivers also contribute significantly to marine litter pollution.

Consequently, spatially and temporally comprehensive monitoring is required to obtain information on the quantity, composition, and potential sources of litter input. Citizen science has proven to be an effective approach for collecting large-scale datasets while simultaneously raising public awareness of the plastic pollution problem.

In this thesis, the results of the Plastic Pirates, one of the largest citizien science programs on riverine plastic pollution, are analysed and lessons learned for generating scientifically valid data are shared. Since 2016, the program has worked with school classes and engaged more than 23.000 schoolchildren. Together with their teachers, schoolchildren visit a river of their choice and collect various data on litter pollution along the chosen river segment.

This thesis is based on the results of the Plastic Pirates program, obtained between 2016 and 2022 and is organized in three subsections. Each subsection represents a peer reviewed publication. The first publication emphasizes the importance of continuous communication with the participants before, during and after data collection to generate extensive and reliable datasets and defines four key phases of communication. The second publication demonstrates that clear research questions, supportive educational material, field data-quality measures (photos, standardized methods and self-evaluation), and transparent reporting of excluded datasets are essential for ensuring scientific acceptance of citizen science data.

Building on the outcomes of these two publications, the third publication analyses macrolitter quantities along the riversides of five major river systems in Germany over a period of seven years. On average, 0.28 litter items per m^{-2} were recorded, with no clear trend observed over the years. Litter was found at 92 % of all surveyed riversides, consisting mainly of plastics and cigarette butts. River visitors were identified by the schoolchildren as the main source of litter.

These findings demonstrate that citizen science with schoolchildren can serve as an effective tool for researching riverine litter pollution, provided that both a robust

communication strategy and clear data quality standards are in place. In the long term, citizen science could thus represent a valuable supplementary monitoring measure at both local and global scales.

Zusammenfassung

Seit Beginn der industriellen Plastikproduktion in den 1950er-Jahren ist die jährlich produzierte Menge von 1,5 Millionen Tonnen auf 413,8 Millionen Tonnen im Jahr 2023 stark angestiegen. Gegenwärtig existiert kein Ökosystem, das nicht von der Plastikmüllverschmutzung betroffen ist. Am besten erforscht ist bisher die Verschmutzung der Ozeane, wobei ein Großteil des Plastikmülls über Flüsse eingetragen wird. Während frühere Studien vor allem große Flusssysteme als Hauptquellen identifizierten, zeigen neuere Untersuchungen, dass auch kleinere Fließgewässer erheblich zur Verschmutzung der Meere beitragen.

Daher ist ein räumlich und zeitlich umfassendes Monitoring erforderlich, um Informationen über Menge, Zusammensetzung und potenzielle Eintragsquellen zu gewinnen. Citizen Science hat sich hierbei als wirkungsvolle Methode etabliert, um großflächige Datensätze zu erheben und gleichzeitig das Bewusstsein für das Problem der Plastikmüllverschmutzung zu schärfen.

Das Programm Plastik Piraten arbeitet seit 2016 mit über 23.000 Schulkindern zusammen. Gemeinsam mit ihren Lehrkräften begeben sich die Schüler*innen an einen Fluss ihrer Wahl und erheben dort verschiedene Daten zur Müllbelastung am Flussufer. Die gesammelten Daten werden anschließend von Wissenschaftlerinnen und Wissenschaftlern ausgewertet und international veröffentlicht.

Die Ergebnisse dieser Dissertation basieren auf Datensätzen, die zwischen den Jahren 2016 und 2022 erhoben wurden. Die Ergebnisse der ersten Publikation zeigen, dass eine umfassende Kommunikation mit den Teinehmenden vor, während und nach der Datererhung unerlässich ist, um wissenschaftich nutzbare Daten zu generieren. Die Ergebnisse der zweiten Publikation zeigen, dass klare Forschungsfragen, unterstützendes Lehrmaterial, Maßnahmen zur Sicherung der Datenqualität am Fluss (Fotos, standardisierte Methoden und Selbsteinschätzung) sowie eine transparente Dokumentation der ausgeschlossenen Datensätze entscheidend für die wissenschaftliche Akzeptanz von Citizen Science Daten sind. Durch die Umsetzung dieser beiden Publikationen konnte die dritte Publikation dieser Dissertation realisiert werden, in der Makromüllmengen an deutschen Flussufern über einen Zeitraum von sieben Jahren analysiert wurden. Im Mittel wurden 0,28 Müllteile pro Quadratmeter erfasst, wobei sich über die Jahre hinweg kein eindeutiger Trend abzeichnete. An 92 % aller untersuchten Flussufer fanden die Schülerinnen und Schüler Müll, überwiegend Plastik und Zigarettenkippen. Als Hauptquelle identifizierten sie Besucher*innen der Flüsse.

Diese Ergebnisse verdeutlichen, dass Citizen Science mit Schulklassen ein geeignetes Instrument zur Erforschung der Müllverschmutzung an Flüssen sein kann, sofern sowohl eine wirksame Kommunikationsstrategie als auch klare Datenqualitätsstandards gewährleistet sind. Langfristig könnte Citizen Science somit als ergänzende Monitoringmaßnahme auf lokaler wie auch auf globaler Ebene sinnvoll eingesetzt werden.

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Chapter 1: Introduction

1.1 Ecological implications of plastic pollution

Plastics are now ubiquitous in the environment, found everywhere from the deepest parts of the ocean to the highest and most remote mountains (Napper and Thompson 2019; Bucci et al., 2020; Caruso et al., 2022). Studies have already documented their presence in deep sea ecosystems, sediments, soils, freshwater bodies, sea ice, oceans, and on mountaintops (Obbard et al., 2014; Smith et al., 2018; Napper et al., 2020; Zhu et al., 2024). Alarmingly, plastics have also been detected in human blood, the placenta and the brain (Ragusa et al., 2021; Leslie et al., 2022; Nihart et al., 2025).

Synthetic polymers, commonly known as plastics, are fossil-based materials characterized by their lightweight, robust, flexible, and durable properties (Andrady 2011). These qualities have made plastic an essential and widely used raw material in modern society (van Emmerik and Schwarz 2020). Originally, plastic was produced for durable products, but is now predominantly used for single-use purposes (Jambeck et al., 2015; Law et al., 2017; Geyer et al., 2017).

However, most plastics are non-biodegradable and persist in the environment for decades, causing long-term ecological harm (Barnes et al., 2009; Kühn and van Franeker 2020). Since the 1950s, global plastic production has increased from 1.5 million tonnes to 413.8 million tonnes annually by 2023 (UNEP 2016; Lebreton et al., 2017; Plastics Europe 2024). Over the decades, plastics have become increasingly integral to the global economy, permeating various sectors such as construction, agriculture, and medicine, among others (Geyer et al., 2017). Packaging accounts for 39.9 % of production, followed by construction (19.8 %), the automotive industry (9.9 %), and electric devices (6.2 %) (Plastics Europe 2024). However, approximately 79 % of plastic litter ends up in landfills or is improperly discarded in the environment (Geyer et al., 2017; Hahladakis et al., 2018; Râpă et al., 2024).

Plastic can accumulate in various compartments of the aquatic environment, including freshwater systems (van Emmerik and Schwarz 2020; Nava et al., 2023), coastal areas (Browne et al., 2011; Biermann et al., 2020), floating garbage patches in ocean gyres (Pattiaratchi et al., 2022), and the deep sea (Chiba et al., 2018). Once released into the environment, macroplastics break down into smaller fragments depending on plastic's characteristic and exposure to environmental factors such as ultraviolet radiation and mechanical forces (Weinstein et al., 2016; van Emmerik and Schwarz 2020).

Plastic fragments are classified by size into microplastics (1–5 mm), mesoplastics (5–25 mm), and macroplastics (larger than 25 mm) (GESAMP 2019). However, there are ongoing recommendations to include additional properties, such as shape, color, and origin, in plastic categorisation (Hartmann et al., 2019). Their transport, accumulation patterns, remobilisation, and degradation rates vary significantly depending on their type and shape (Schwarz et al., 2019). These fragments pose serious threats to ecosystems, wildlife, and human health (Sussarellu et al., 2016; Galloway et al., 2017). Marine organisms and seabirds frequently mistake plastic for food, leading to ingestion, entanglement, suffering, and death (Gall and Thompson 2015; Hardesty et al., 2017).

Additionally, microplastics ingested by zooplankton can travel up the food web, ultimately reaching higher trophic levels (Cole et al., 2013). Plastics are also associated with endocrine disruption and carcinogenic effects in living organisms (Oehlmann et al., 2009; Teuten et al., 2009). Furthermore, additives and chemicals used in plastic production can leach into the environment and have already been detected in marine species and seabirds (Batel et al., 2016; Laing et al., 2016). This also suggests the transfer of persistent organic pollutants from plastic to organisms (Teuten et al., 2009; Rochman et al., 2013).

Plastics are durable and some particles, such as fibers, are lightweight, allowing them to travel long distances through air and water (Lamb et al., 2018). These plastics can act as vectors for pathogens, posing a global biosecurity threat (Parthasarathy et al., 2019). As plastics persist in the environment for decades, their impacts continue to escalate, emphasizing the urgent need for long-term studies and effective waste management (Borrelle et al., 2020).

1.2 Plastic pollution of freshwater systems

Despite substantial research into marine plastic pollution, freshwater environments as well as larger debris (> 5 mm) have long remained under-studied (Blettler et al., 2017; Serra-Gonçalves et al., 2019). While marine plastic pollution is already included in the European Marine Strategy Framework Directive (2008/56/EC, MSFD), freshwater plastic litter has not yet been recognized as an indicator of good environmental status under the European Water Framework Directive (2000/60/EC, WFD; Philip et al., 2024). This is despite rivers being major pathways for plastic transport to the ocean.

Estimates suggest that up to 2.8 million tons of plastic enter the global ocean annually via rivers, with 70 % originating from those in Asia and Africa (Lebreton et al., 2017; Schmidt et al., 2017). A study by Meijer et al. (2021) concluded that plastic emissions from small rivers have been heavily underestimated, revealing that more than 1,600 rivers account for 80 % of

total emissions. However, in recent years, research on the sources and sinks of plastic, the dynamics within river systems, the quantification of riverside litter and methods for effective monitoring has gained increasing scientific interest (Geyer et al., 2017; González-Fernández and Hanke 2017; Kiessling et al., 2019; van Emmerik et al., 2022).

Plastic litter generally enters river systems through both intentional or incidental activities (Rech et al., 2014; Kiessling et al., 2019; van Emmerik and Schwarz 2020, Figure 1.1). Understanding the retention and natural dynamics of plastics in river systems remains a challenge due to the numerous factors influencing these processes, such as hydro-meteorological conditions, which particularly determine how plastic enters the river system (Schrank et al., 2022; van Thi et al., 2024). Wind and heavy rainfall-induced surface runoff can contribute to the remobilisation of plastics from riversides into river systems (Lebreton et al., 2017; Bruge et al., 2018; Meijer et al., 2021; Roebroek et al., 2021; Tramoy et al., 2022). Some river systems exhibit clear point sources of plastic pollution, such as direct illegal dumping observed on riversides in Chile (Rech et al., 2014; Honorato-Zimmer et al., 2021). In major German rivers like the Weser, Elbe, Rhine, and Danube, river visitors were identified as main source of intentional or unintentional plastic pollution (Kiessling et al., 2019).

Once plastic litter is introduced into the river, its transport is affected by various factors, including flow velocity, water level, and discharge (van Emmerik et al., 2018). However, there is still limited knowledge regarding the influence of river geomorphology on plastic transport, as well as the behaviour of different plastic types based on their buoyancy characteristics (van Emmerik et al., 2018). A study by Castro-Jiménez et al. (2019) shows a significant fragmentation of larger litter items during the transport down the river course. Especially larger plastic items temporarily accumulated on riversides and in vegetated zones can be remobilised during high water levels or may accumulate again further downstream (Figure 1.1). Additionally, artificial barriers, such as hydraulic infrastructure like watergates and dams, can serve as temporary retention zones for riverine litter (Lebreton et al., 2017).

Riverside litter is a growing global issue, encompassing a diverse array of discarded materials, including single-use plastics and substances that may pose risks to both human health and the environment (Palmas et al., 2022). Although significant efforts have been made in recent years to quantify plastic debris in river systems, many scientific questions remain unanswered, and numerous challenges persist. To date, most research on plastic litter within river systems has focused on small-scale, localised studies that are not easily transferable or scalable, and especially riversides remain understudied (Philip et al., 2024). Developing simple, standardised collection methods for recording large-scale data across time and space is

becoming increasingly important. Gaining a thorough understanding of potential litter sources and the distribution of plastic litter in riverine environments is crucial for creating long-term solutions to plastic pollution.

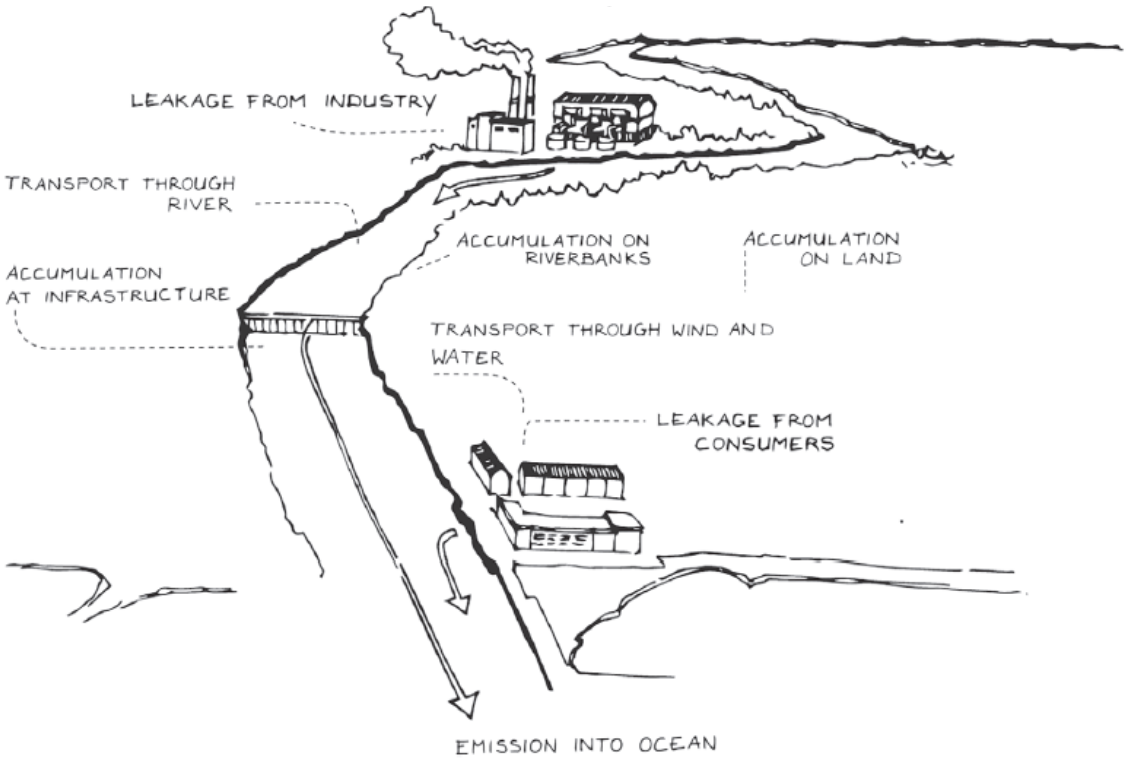

Figure 1.1: The transport of plastic litter from riversides towards the ocean, showing different sources and (temporary) sinks (van Emmerik and Schwarz 2020, Graphic by Cher van der Eng, used under Creative Commons license CC BY).

1.3 Citizen Science in plastic pollution research

Citizen science involves non-professional participants in scientific research, engaging them in activities such as developing research questions, collecting data or interpreting results (Dickinson et al., 2012). Citizen science has emerged as an effective approach to merge science and societal aspects related to plastic pollution (Hidalgo-Ruz and Thiel 2015; Zettler et al., 2017; Kawabe et al., 2022). The growing interest in plastic pollution and the increasing number of citizen science projects on this topic highlight the importance of involving the public in large-scale research efforts (Hidalgo-Ruz and Thiel 2013; Bergmann et al., 2017; Zettler et al., 2017; Kiessling et al., 2019).

Citizen science has been employed since at least two decades for the collection of data on marine litter pollution (Serra-Gonçalves et al., 2019). Examples include studies in Australia

(Edyvane et al., 2004) or Chile (Bravo et al., 2009; Hidalgo-Ruz and Thiel 2015). In recent years, the number of studies using citizen science to investigate the litter pollution of rivers has increased, although research specifically focusing on riversides remains limited (Philip et al., 2024). Most monitoring projects on riversides have concentrated on collecting scientific data on macrolitter, such as plastic bags, cigarette filters, and food packaging, as they are easy to identify for volunteers as compared to microplastic particles (Zettler et al., 2017; Kawabe et al., 2022). Notable examples include initiatives such as Científicos de la Basura (Litter Scientists) in Chile (Rech et al., 2014; Honorato-Zimmer et al., 2021), Plastic Spotter in the Netherlands (Tasseron et al., 2020) and the Plastic Pirates in Germany and other European countries (Kiessling et al., 2019; Kiessling et al., 2021; Kiessling et al., 2023; Uogintė et al., 2024).

To assess the extent of plastic pollution in the aquatic environment, extensive data collection with large geographical coverage is needed (Rambonnet et al., 2019). Citizen science provides a unique opportunity to collect large-scale temporal data, covering extensive geographic regions over relatively short periods of time, achieving scales that would be unattainable through traditional scientific approaches (Dickinson et al., 2010). In the field of plastic pollution, this approach has proven effective in establishing baseline information and monitoring the quantity and distribution of plastic litter (Silvertown 2009). Outcomes include identifying potential sources, assessing the effectiveness of legislation, and raising public awareness (Zettler et al., 2017).

However, citizen science projects offer more than just data collection, as they can enhance scientific literacy and provide participants with valuable insights into research processes (Bonney et al., 2016). By bridging research and environmental education, these projects enable participants to learn about ecological principles while contributing to meaningful scientific work (Dickinson et al., 2012; Hartley et al., 2015; Nelms et al., 2017; Wyles et al., 2017).

Many projects incorporate educational materials that provide background knowledge, explanations of theoretical frameworks, clear research objectives, and detailed observation protocols for the citizen scientists (Dickinson et al., 2012). Moreover, citizen science projects vary in the level of participant involvement (Bonney et al., 2009). In contributory projects, participants primarily collect data, with no involvement in research design or analysis. In collaborative or co-creative projects, however, participants engage in data analysis and may even contribute to formulating research questions (Bonney et al., 2009; Vries et al., 2019; Senabre Hidalgo et al., 2021). The level of interaction between professionals and participants

often depends on the research question and can significantly influence participants experiences and learning outcomes (Dickinson et al., 2012).

1.4 Success drivers and challenges in citizen science

Citizen science has made significant contributions to ecological research, particularly as it has emerged as a professional discipline in recent years (Bonney et al., 2009; Silvertown 2009; Theobald et al., 2015; Johnston et al., 2023). Researchers and participants can both benefit from citizen science projects, as participants gain hands-on experience in scientific research processes, while researchers can collect large datasets within a relatively short timeframe (Riesch et al., 2014).

Although research on citizen science exists, only few studies address the perspectives of researchers involved in these projects, and insights from coordinating scientists remain scarce (Cigliano et al., 2015; Golumbic et al., 2017; Rambonnet et al., 2019). However, as the number of citizen science projects on plastic pollution continues to grow, evaluating their challenges, best practices, and recommendations is becoming increasingly important (Rambonnet et al., 2019). Challenges between scientists and participants, such as communication before, during and after data collection, data quality and access, and participant recognition, pose significant obstacles while also representing core principles of citizen science (Bonney et al., 2009; Robinson et al., 2018). In particular, the importance of effective communication is often underestimated by project coordinators, despite studies highlighting the need for a dedicated team member responsible for communicating with participants and ensuring scientifically valuable data that drives community benefits and policy changes (Tweddle et al., 2012; Cigliano et al., 2015; Rambonnet et al., 2019). Successful citizen science initiatives depend on collaboration among multiple stakeholders, including public participants, project coordinators, NGOs, local governments, and research scientists. This is particularly crucial during the dissemination phase when results must be effectively communicated (Zettler et al., 2017; Rambonnet et al., 2019). Since citizen science projects engage a broad audience, findings should be shared in a target-group specific format, for example through non-scientific reports, website updates, and social media posts (Follett and Strezov 2015).

Citizen science data offer potential societal benefits and can provide unique scientific insights (van Etten et al., 2019). However, some studies have raised concerns about data quality compared to professionally collected data, especially when schoolchildren contribute to data collection (Gardiner et al., 2012; Kosmala et al., 2016). These concerns include data accuracy or errors due to misidentification, particularly in the absence of adequate verification measures

(Dickinson et al., 2010; Gardiner et al., 2012). Thus, non-standardised research methods and the lack of strong data validation mechanisms can make it difficult to integrate citizen science data into professional research (Zettler et al., 2017). This underscores the need for clear and simple sampling protocols, a well-structured submission design ensuring high standards of data completeness and accuracy, and a robust data verification process (Kelling et al., 2015). These factors are important to consider, as citizen science is part of the scientific process, aiming to produce and disseminate scientifically valuable knowledge (Golumbic et al., 2019). With the growing number of citizen science projects, particularly those focusing on macroplastics in aquatic environments, it is essential to evaluate past experiences, identify best practices, and develop recommendations to improve both ongoing and future initiatives (Rambonnet et al., 2019, Figure 1.2).

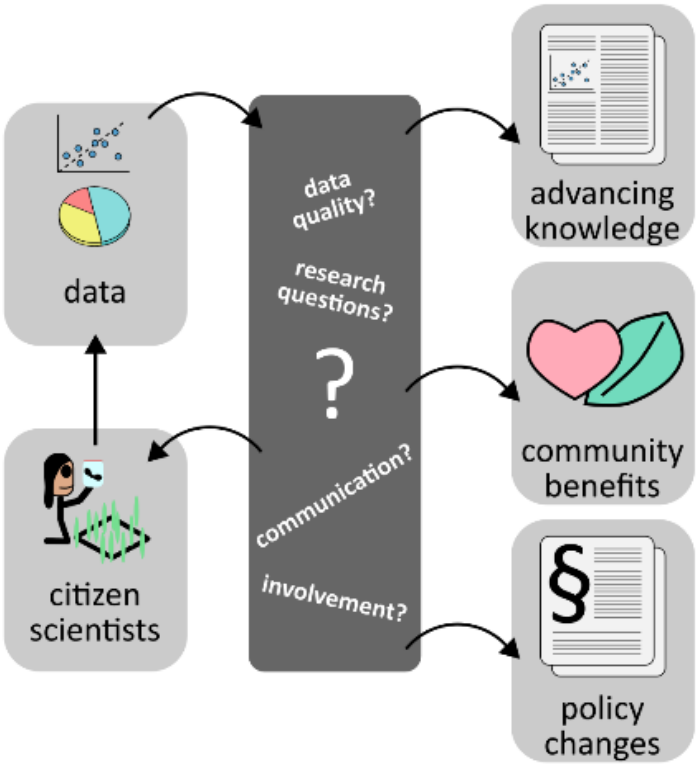

Figure 1.2: Citizen scientists can contribute to large-scale data collection, advancing scientific knowledge, benefiting communities, and influencing policy. However, effective communication between the program team and participants is essential for participant engagement and data quality (Graphic by Tim Kiessling, under Creative Commons license CC BY 4.0).

1.5 The Citizen science program Plastic Pirates

The Plastic Pirates are a citizen science program to investigate the plastic litter pollution in rivers and streams. The initiative involved school children all over Germany in gathering valuable large-scale scientific data. Its goals are to enhance scientific understanding of the sources and pathways of plastic pollution, foster environmental awareness, and empower diverse stakeholders, including schoolchildren and teachers. Moreover, the initiative seeks to improve scientific literacy among participants. The schoolchildren are free to select a river to study, collect samples, measure and analyse findings, and upload data on the program's website. Through this hands-on experience, participants can develop valuable insights into the litter pollution affecting their local rivers. Further, they may gain a deeper understanding of scientific processes while contributing meaningfully to research (Kruse et al., 2020; Wichmann et al., 2022).

The program was initiated by the Kiel Science Factory (https://www.forschungs-werkstatt.de/en/) in 2016, in cooperation with the Chilean citizen science program Científicos de la Basura (Litter scientists, https://cientificosdelabasura.ucn.cl/). It was developed as a follow-up program to "Following the Pathways of Plastic Litter", a Chilean-German citizen science program on beach litter pollution (Honorato-Zimmer et al., 2019).

At the end of the project, comprehensive booklets and teaching materials were developed through collaboration between scientists and teachers (see Figure 1.3). As the Plastic Pirates is a contributory citizen science program, the materials were designed to gather scientifically valuable data. They are tailored to match the complexity of sampling to the target group (schoolchildren aged 12 to 18) while minimising potential errors in data collection.

The booklets provide step-by-step guidance to schoolchildren, ensuring both clarity and accuracy throughout the sampling process. Each stage of data collection is carefully structured to contribute critically to the overall study, ensuring the reliability and usability of the data upon completion. The sampling methods cover different aspects of litter pollution, including the macrolitter pollution on the riverside per m^{-2}, the pollution by single-used plastics on the riverside, the microplastic pollution of the river surface as well as the examination of the riverside for potential litter sources by the schoolchildren.

After data collection, participants upload all data to a centralised website, making them accessible for further scientific analysis. Citizen science studies are increasingly used to collect data on environmental plastic pollution (Nelms et al., 2022). However, the success of these projects relies on well-designed communication strategies, easy-to-use sampling protocols, and

comprehensive data quality controls to achieve reliable scientific data (Rambonnet et al., 2019; Fraisl et al., 2022).



Figure 1.3: (A) Cover of the Plastic Pirates program booklet for schoolchildren, which provides background information on plastic pollution, sampling protocols, and data sheets to be completed during data collection (available on Zenodo: https://zenodo. org/records/7986321). (B) Guidance for schoolchildren on working as scientists, explaining the main steps of the scientific workflow. (C) Sampling instructions for assessing macrolitter pollution on the riverside per m^{-2}, presented in a clear and concise format alongside an illustration of the sampling setup (D). Additionally, short explanatory videos are available online (https://www.plastic-pirates.eu/en/video-group-a).

1.6 Research questions and thesis outline

This dissertation focuses on analysing the citizen science program Plastic Pirates and addresses the following research questions:

(1) What role does communication in citizen science initiatives play to engage participants and successfully collaborate to investigate aquatic river pollution by macrolitter?

(2) What strategies are effective in ensuring the quality of data collected through citizen science?

(3) What are the quantities, compositions, and sources of riverine macrolitter pollution in Germany over seven years, based on citizen science data contributed by school children?

The following three studies demonstrate how the citizen science program Plastic Pirates implemented communication strategies and data quality control mechanisms to generate reliable, large-scale data on the spatial and temporal variability of macrolitter pollution along German riversides.

Chapter 2 presents the study *Sharing Communication Insights of the Citizen Science Program Plastic Pirates – Best Practices from Seven Years of Engaging Schoolchildren and Teachers in Plastic Pollution Research* (Dittmann et al., 2023). This research examines the communication strategy of the Plastic Pirates throughout the program's duration, identifying four key phases essential for obtaining complete datasets. This study was published in Frontiers in Environmental Science.

Chapter 3 features the publication *How to Get Citizen Science Data Accepted by the Scientific Community? Insights from the Plastic Pirates* (Dittmann et al., 2022). This study demonstrates how data quality can be ensured to generate scientific reliable data for publication. This study was published in Proceedings of Science.

Chapter 4 focuses on the publication *Temporal variability of litter pollution of rivers in Germany – A long-term assessment by schoolchildren as citizen scientists* (Dittmann et al., 2024). This study represents the scientific analysis of data collected through the Plastic Pirates, examining the temporal variability of litter pollution along German riversides over seven years. It builds on the findings discussed in chapter 1 and 2. This article was published in Marine Pollution Bulletin.

Chapter 5 is a non-peer-reviewed article with the title *Die Plastikpiraten – Ein Citizen Science Projekt zur Erforschung der Müllverschmutzung von deutschen Flüssen* published in

German in Wasser & Abfall (Dittmann et al., 2021), a journal intended for engineers and the general public, an important peer group besides scientists.

Chapter 6 resents a discussion of the findings from the previous chapters.

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Chapter 2: Sharing communication insights of the citizen science program Plastic Pirates – best practices from 7 years of engaging schoolchildren and teachers in plastic pollution research

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2.1 Abstract

Engaging the general public in research processes through citizen science allows for innovative scientific studies and makes science accessible to the general public. Effective communication strategies are crucial for the success of such initiatives. The citizen science program Plastic Pirates investigated the plastic pollution of rivers and implemented a variety of communication strategies with participating schoolchildren, teachers, and youth groups (e.g., sport associations, scouts or educational vacation programs, representing approximately 6 % of participating groups). These were continuously revised and adapted since its start in 2016. Without time-efficient communication and strategies to keep track of conversations, it would not have been possible to achieve the scientific and educational goals of the program, i.e., to help teachers increase the environmental awareness and scientific literacy of their schoolchildren, and to produce peer-reviewed articles based on the collected citizen science data. Communication within the Plastic Pirates program was divided into four distinct phases: 1) recruiting and motivating participants, 2) coordination and guidance of participants, 3) data reception and revision, and 4) sharing updates and results. Some of the obstacles that had to be overcome to achieve successful communication were e.g., time constraints to obtaining scientific data from the participants, the time lag between the active involvement of the participants and the actual data analysis and publication of results, and limited personnel resources available for communication efforts. Our recommendations for other citizen science practitioners include regular and transparent communication with the participants regarding their contribution, the use of adequate and various communication channels, shifting the workload from the participants to the coordinating team of a citizen science initiative, as well as offering feedback on the research findings to the citizen scientists, thereby disseminating the results of the program.

2.2 Introduction

Citizen science initiatives represent a promising approach to involve the general public in research processes and thereby answer novel research questions (Bonney et al., 2009). Effective communication between the initiators (usually people with a formal scientific education) and participants (usually members of the general public without a formal scientific education, Eitzel et al., 2017) is crucial for the success of citizen science initiatives (Hecker et al., 2018; Rüfenacht et al., 2021; Wagenknecht et al., 2021): Respectful, appreciatory, and efficient communication contributes to an increase of the participants motivation (Rotman et al., 2012; Anderson et al., 2020), ensures high data quality (Balázs et al., 2021; Dittmann et al.,

2022), and facilitates participant feedback to the team coordinating the citizen science activity (Kieslinger et al., 2018; Rambonnet et al., 2019). Furthermore, it informs participants of results and outcomes of the initiative (de Vries et al., 2019; Probert et al., 2022). Communication can occur through various channels, in person or via digital communication (Rüfenacht et al., 2021). In this study we present the various communication strategies used in the Plastic Pirates program.

The Plastic Pirates are a citizen science program in which schoolchildren and youth groups collect data on litter pollution on riverbanks and in rivers within the European Union (https://www.plastic-pirates.eu/). The schoolchildren, youth groups and their teachers and youth group coordinators participate in the program by collecting litter data and samples during campaigns, which are 2-months long periods, taking place once or twice per year (according to the capacity of the coordinating team; Figure 2.1).

The participants work in groups on different aspects of local litter, each group employs a specific method to respond their corresponding research questions. One group investigates litter quantities and the main material composition of litter, while another explores the surroundings to infer the principal source of litter found (Kiessling et al., 2019). Another group focuses on identifying certain single-use plastics to evaluate whether a European legislation aiming at reducing single-use plastic pollution actually reduces the quantities of these items in the river environment (Kiessling et al., 2023). Finally, one group examines the litter floating at the water surface in the river by counting larger floating objects and sampling plastic particles smaller than 5 mm; (Kiessling et al., 2021).

The program's target audience are schoolchildren and youth groups as the Plastic Pirates have a strong educational focus, including aspects of environmental education, scientific literacy, youth empowerment, and getting active to reduce the environmental plastic pollution problem. The age of participants for which the program was designed was 12 and older, although some elementary schools participated every year as well.

Since the start of the project in 2016 more than 23,000 schoolchildren, teachers and other people participated in the program in eleven sampling campaigns (Table 1.1). During the lifetime of the project the size of the project team varied substantially, ranging from one person being responsible for communication and data analysis to a team of two persons being involved in communication before the sampling and four to five persons responsible for the communication after the sampling and analysing data (all of which did not work full time in the program).

The Plastic Pirates are one among many citizen science initiatives investigating anthropogenic, and especially plastic litter: notable large-scale and international examples include the International Coastal Cleanup (Ocean Conservancy, 2022), Marine Litter Watch (EEA, 2022), the Marine Debris Tracker (Jambeck and Johnsen, 2015), and International Pellet Watch (Ogata et al., 2009). Citizen scientists have contributed substantially to our knowledge about plastic pollution (Hidalgo-Ruz and Thiel, 2015; Zettler et al., 2017; Kawabe et al., 2022). This global problem has reached unparalleled dimensions (Eriksen et al., 2023) with severe impacts to the wellbeing of natural environments (MacLeod et al., 2021), and it is expected that the scale of the problem will further intensify (Borrelle et al., 2020).

While all environments are affected, rivers play an important role as a transport pathway of inland litter to the sea (Rech et al., 2015), and as a sensitive and polluted environment alike. This is no different for rivers in Germany, as the results of the Plastic Pirates have shown (Kiessling et al., 2019; Kiessling et al., 2021; Kiessling et al., 2023).

This article describes the different communication phases and communication channels (telephone helplines, emails, postal mailings, social media posts, etc.) of the Plastic Pirates in Germany and explains how they were employed to achieve the main goals of the program: (i) generating novel scientific insights on the litter pollution of rivers, (ii) improving the scientific literacy and environmental awareness of the participating schoolchildren, youth groups and teachers, and (iii) raising the general publics' awareness of the plastic pollution problem.

The communication strategies of the Plastic Pirates can be divided into four distinct phases: (1) recruiting and motivating participants, (2) coordination and guidance of participants, (3) data reception and revision, and (4) sharing updates and results (Figure 2.2). Phase (1) comprised communication efforts to recruit a sufficient number of interested school teachers and youth group leaders and motivate them to participate in the program. Phase (2) refers to the communication prior to data collection, with the aim of clarifying questions about the sampling methodology and organisational aspects of the program. Phase (3) relates to the communication after data collection, with the aim of ensuring that scientific data and associated metadata, photos, and samples were available to the coordinating team (i.e., the scientific team analysing and processing data), and to clarify questions regarding the quality of the citizen science data. Subsequently, phase (4) covers the communication of the results to the participants by providing feedback on the scientific insights to the participating schools as well as the general public.

These communication strategies have been adapted and refined since the start of the program in 2016 and were essential for the success of generating novel data and insights about

environmental litter pollution at riversides. Moreover, the communication strategies allowed the program to engage more than 23,000 schoolchildren in Germany.

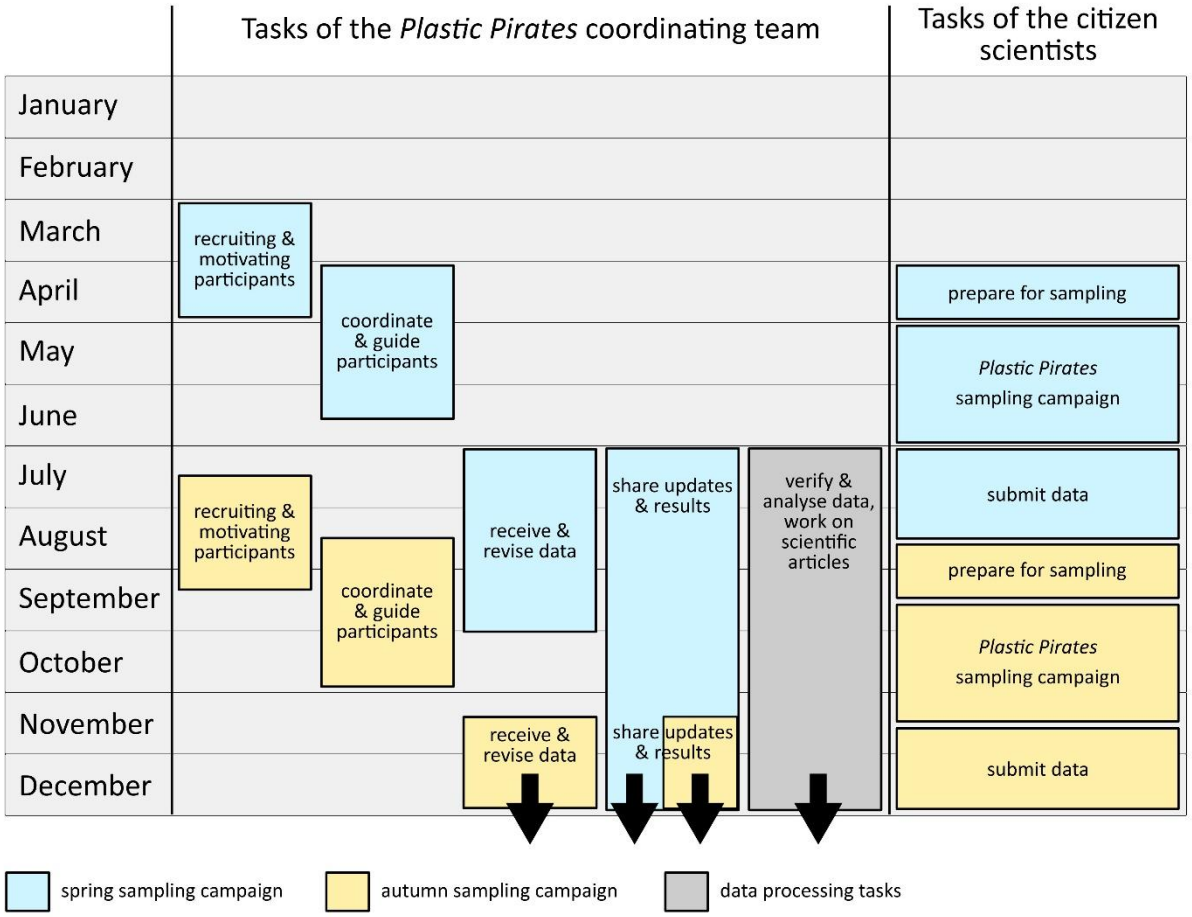

Figure 2.1: Tasks of the Plastic Pirates coordinating team and the citizen scientists in an exemplified year in which a spring and autumn sampling campaign were conducted. Data processing tasks, such as citizen science data verification, data analysis and advancing work on scientific articles were loosely connected to the actual sampling campaigns and happened throughout the program. The black arrows indicate that work resulting from these phases was carried over to the subsequent year. The overlap of phases and the resulting workload for the coordinating team illustrates a main challenge of the Plastic Pirates.

Table 1.1: Number of groups ordering educational material, the microplastic sampling net, and submitting datasets for the eleven different sampling campaigns of the Plastic Pirates. The last column shows the proportion of groups submitting a dataset compared to the number of groups ordering educational material. The sampling campaigns in the year 2020 correspond to the most severe COVID-19 restrictions in Germany.

Sampling campaign	Educational material ordered (number of packages)	Sampling net ordered (number of packages)	Datasets submitted to the website [1]	Number of participants	Proportion of groups following through with sampling
2016 (autumn)	858	200 [2]	173	2,999	20 %
2017 (spring)	784	200 [2]	190	3,883	24 %
2018 (spring)	428	133	107	1,960	25 %
2018 (autumn)	470	167	137	2,223	29 %
2019 (spring)	630	202	136	2,515	22 %
2020 (spring)	312	60	40	153	13 %
2020 (autumn)	368	144	82	1,520	22 %
2021 (spring)	300	170	102	1,707	34 %
2021 (autumn)	315	215	154	2,535	49 %
2022 (spring)	396	237	173	2,991	44 %
2022 (autumn)	226	144	97	1,585	43 %
Total	5,087	1,872	1,391	24,071	27 %
Average	462	170	126	2,188	

[1] A submitted dataset did not necessarily mean that it was considered in a resulting scientific article as it had to pass certain data verification steps (see Dittmann et al., 2022 for details): Kiessling et al., 2019 used 50 % and 83 % of available datasets, depending on the research question, Kiessling et al., 2021 used 43 % and 81 % of available datasets, and Kiessling et al., 2023a used 86 % of available datasets.

[2] This value is estimated as there is only a combined number of an order of 400 sampling nets available for 2016 and 2017. According to our recollection, approximately the same number of sampling nets was ordered in each of those years.

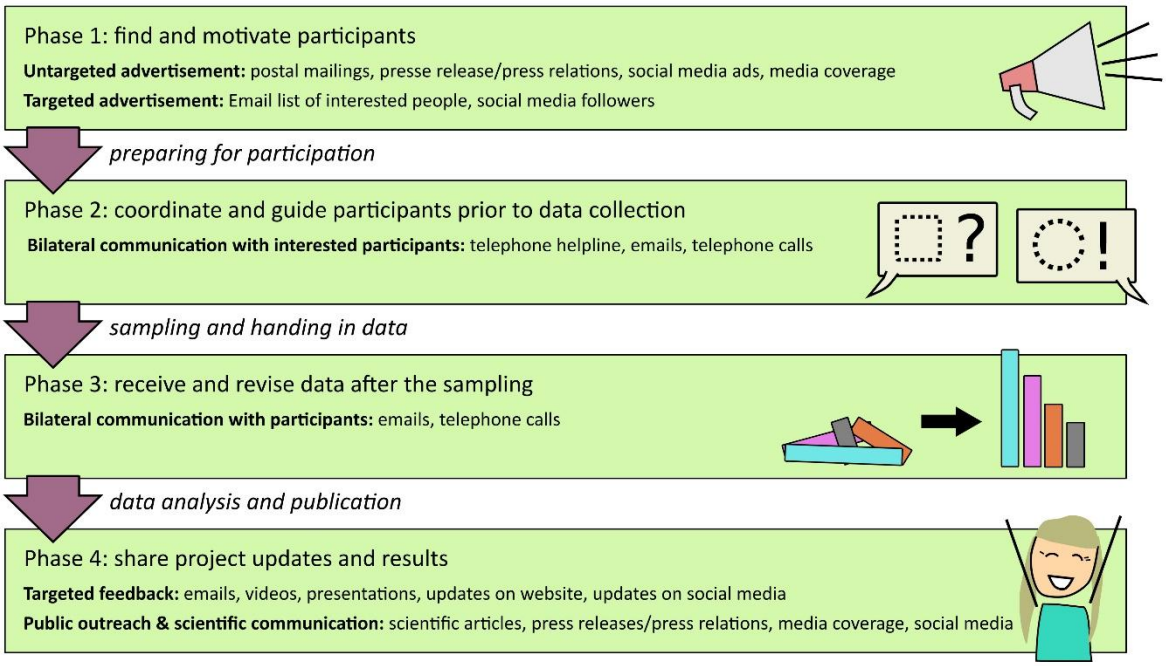

Figure 2.2: Communication tools used by the coordinating team of the citizen science program Plastic Pirates during the different communication phases with the participants.

2.3 Phase 1: communication to recruit and motivate a sufficient number of participants

This first communication phase was implemented in advance of each Plastic Pirates sampling campaign. The sampling campaigns were usually conducted twice a year over a period of 2 months. During these campaigns data collection was the main objective (primarily to ensure comparability of data).

To engage new participants, two main strategies were employed: (i) Addressing potentially interested school teachers, group leaders and the general public at large (broad communication), and (ii) a targeted outreach to people who previously showed interest in the Plastic Pirates (Figure 2.2). Regarding the broad approach, a postal mailing was sent to approximately 25,000 schools around 2 months prior to the beginning of a sampling campaign. At the same time, the information about a new sampling campaign was advertised via the program's website, relevant web portals and newsletters about citizen science initiatives.

Additionally, a professional communication agency was commissioned to do the press work for the program from 2016 to 2017. This led to more than 2,000 media reports throughout the lifetime of the program, including newspaper articles, online articles, radio features and contributions on national television channels (however, due to a lack of data of these media reports we were unable to evaluate the success of these measures in regards to recruiting

participants). A study by Giardullo et al. (2023) has shown that 85.3 % of citizen science projects surveyed in the EU, United Kingdom and Switzerland used social media as communication medium for their projects, indicating the importance of digital communication tools to reach large target groups (Giardullo et al., 2023).

For the targeted outreach effort an email distribution list with approximately 2,000 email addresses was used, consisting of former participants as well as individuals who had contacted us to express their interest in the program. Moreover, posts on Facebook and Instagram informed followers about each new sampling campaign.

As a further measure, a dedicated teacher training was offered twice a year through an established online teacher training service, serving the purposes of advertising the program as well as preparing participants for sampling. Each of these teacher trainings attracted approximately 100 teachers on average. In order to keep the barriers for participation as low as possible, there were no requirements for official registration. Instead, interested teachers and youth group leaders could access educational materials (a sampling booklet, Kiessling et al., 2022; and teaching materials, Knickmeier et al., 2022) on the Plastic Pirates website and order printed copies via an online form free of charge throughout the year. Subsequently they could make an informed decision on whether they would like to participate.

For each sampling period, up to 6,000 sampling booklets were sent out to interested teachers and other parties (with a decline during the pandemic). The educational material has been conceptualized through close cooperation between scientists and school teachers, and contained information that provided orientation on this field of research to participating teachers. The educational material contained solutions for assignments, an indication on time requirements and recommended group sizes for exercises, as well as detailed lists of materials needed for experiments (Knickmeier et al., 2022).

As a secondary step, informed and interested people would order a sampling net by providing the name, address and email of their institution, as well as the date they intended to sample with their school class or youth group. As the sampling net was costly, its shipment was restricted to participants who had acquainted themselves with the educational material. On average more than 450 people requested packages with educational material for each sampling period (containing up to 6,000 sampling booklets; Table 1.1), which translates to approximately 1.5 %–2 % of people addressed by the recruitment activities mentioned above.

Overall, the number of participants, materials ordered and datasets submitted varied with each sampling campaign. This was not only related to the success of communication strategies, but also influenced by external factors such as the COVID-19 pandemic (Table 1.1).

2.4 Phase 2: communication to coordinate and guide participants prior to data collection

The second communication phase overlapped with the first phase, but extended into the sampling period (Figure 2.1). Here, the focus of communication was on bilateral exchange with teachers and youth group leaders who were seriously considering participating in the program. This phase included clarifying questions about the methodology, sampling, and organisational aspects of the program. Typical questions concerned the necessary size of groups and age of participants, sampling dates and sampling sites, required materials, and the suitability of the chosen river for sampling. At times these questions were asked before ordering the sampling material. Sometimes, however, these questions arose once the participants had acquainted themselves with the sampling material. Questions concerning the specific scientific methodology were asked less frequently.

Inquiries to the coordinating team could be posed via a telephone helpline that was active for 4 hours a day prior to and during the sampling campaigns, as well as via email (Figure 2.2). Most people used the second option, illustrating that this was the preferred mode of communication for teachers and youth group leaders in Germany. The value of this individual communication with each participant can also be exemplified by a survey that was conducted among Plastic Pirates teachers with the purpose to find out which factors motivated them to involve their class in a citizen science activity (Kiessling et al., 2023b): out of the 623 teachers invited, 153 teachers handed in a complete survey (26 %, see the peak in March 2021 of invitational emails being sent in Figure 2.3).

To ensure that participants were able to conduct the sampling independently, i.e., without the presence of members of the coordinating team, the sampling booklet served as a hands-on guide for preparing of the field trip and for the actual sampling procedure (Kiessling et al., 2022). By dividing the sampling into five subgroups, the complexity of the individual samplings was reduced. Concise lists with the most important information (e.g., information boxes with a list of needed materials) further served to eliminate ambiguities.

2.5 Phase 3: communication to receive and revise data after sampling

Once a school or youth group had completed the actual data collection, the next phase of communication was immediately initiated by the coordinating team after their sampling event (Figure 2.1). This was the most critical, time-sensitive, and work intensive phase of communication as data and samples had to be secured and ambiguities about the data, such as missing metadata, had to be clarified as soon as possible (see also Dittmann et al., 2022 for

concerns regarding the citizen science data quality of the Plastic Pirates program). Therefore, the communication effort via email usually reached its peak directly after the sampling campaign (Figure 2.3), resulting in an extraordinary workload especially in years with two sampling campaigns (2018, 2021 and 2022, though not 2020 due to COVID-19). The coordinating team contacted school teachers and youth group leaders either after the intended sampling date (communicated by the participants while ordering the materials) or once a dataset was uploaded to the Plastic Pirates website.

This phase of communication had three main goals: (i) assistance in data submission, (ii) data screening and immediate clarifications, and (iii) data validation. For the first goal, participants uploaded their dataset making it publicly accessible on the website. The total amount of submitted and accessible datasets was an important public indicator for the success of a sampling campaign. Most issues here were caused by "unconfirmed datasets" as teachers and youth group leaders were required to publish their submitted dataset via an email link they received, a necessary extra step due to data protection regulations. Another issue was caused by missing data and material that was required when submitting a dataset to the website. We assume that the latter was mostly related to a lack of time among participants to organize and process meta-data, data about litter findings, and photos in the requested way. Therefore, in specific cases we offered teachers to submit their data and material via email, thereby shifting the workload of sorting data adequately, correcting sampling coordinates or resizing photos to fit the image size requirements away from the participants and towards the coordinating team.

The second goal was to screen the submitted data and photos for completeness and inconsistencies and to contact the teachers as quickly as possible to clarify these issues. Difficulties related for example to, for example, data sheets that were only partially filled out, photographs with unreadable labels or with a poor resolution, or coordinates that were not located close enough to a river to identify the actual site that was sampled. Due to the large number of participants and submitted datasets, it was challenging to screen the data in a timely manner. The sampling campaigns organized in spring were highly time sensitive due to the summer vacations and the transition to the next school year. In our experience, untimely communication resulted in data, photos and samples being lost, e.g., because images were deleted from smartphones, datasheets were discarded at the end of the academic year, the samples were lost during cleaning of the classrooms by uninstructed personnel, or teachers and schoolchildren (holding required information) became unavailable due to changes in class or school constellation.

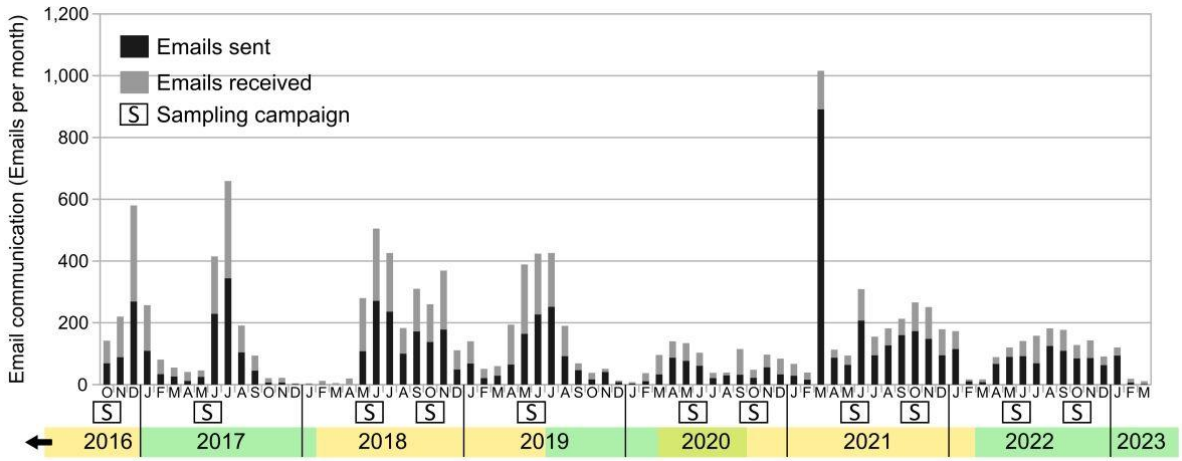

Figure 2.3: Numbers of emails sent and received per month by a centralized email address created for individual communication with participants, before, during and after the active data collection (i.e., sampling campaigns) of the Plastic Pirates (see Supplemental Material A1 original data). The purpose of the individual communication was to coordinate the shipment of the microplastic sampling net, answering questions regarding the sampling, and getting in contact to obtain missing data and samples and clarify questions regarding the citizen science data quality. The six different funding periods, partially overlapping, are highlighted as bars overlaying the indication for years. In total 12,767 emails were registered (7,237 emails sent, 5,530 emails received). This represents a little more than 1,000 h of work, assuming every email required 5 minutes of attention, and therefore approximately individualised invitations to participate in a survey (see main text of the manuscript).

The third goal, the data validation, was not as time sensitive in terms of communication, as all data and materials were either obtained from participants or deemed to be unobtainable after the first two steps. During this final step the citizen science data were verified, i.e., the submitted data sheets were compared to the photos showing the litter findings (see Dittmann et al., 2022 for details). This process sometimes led to open questions on the side of the scientists, such as whether empty sections of the data sheet indicated that there was no litter at this sampling station or whether this sampling station had not been established and investigated (Kiessling et al., 2019). Another example of clarifying communication during this phase was whether annotated floating litter was actually mobile, or whether it was immobile and had become entangled in the vegetation (Kiessling et al., 2021).

2.6 Phase 4: communication to share updates and results

The final phase of communication aimed to inform participants about the results and progress of the program. The major challenge of this phase was the time difference between data collection and the actual publication of scientific results, particularly the publication of a study investigating microplastics which required thorough visual analysis of each sample and the polymer characterization of each microplastic particle (Kiessling et al., 2021; Table 1.2). These long times between being involved in an activity and seeing actual results was difficult to convey to the participants, especially given the fast paced school environment. Due to this, the program was designed to offer closure to participants before the publication of scientific articles by employing different strategies: (i) The sampling booklet encouraged participants to compare their own results with data collected by other groups (Kiessling et al., 2022). This was done using the website, which automatically showed a summary of uploaded data of all groups and calculated means of litter findings (Supplemental Material A2). We chose this fast access to data summaries over data quality as the verified data would only be available much later in the process (see Phase 3). (ii) The educational material further contained an optional chapter on how to get involved in solving the plastic pollution crisis, in case teachers wanted to encourage interested schoolchildren to pursue the problem beyond the collection of data (Knickmeier et al., 2022). (iii) A certificate of participation was sent out to participating teachers (usually about 2 months after the end of a sampling campaign). During the first campaigns, the certificate was a printed document, during later campaigns, however, the certificates were sent via email, due to budget constraints. (iv) Program updates were posted on social media, providing participants with a behind-the-scenes look. This additional work (attending social media) illustrates the challenges faced by the coordinating team (e.g., meetings with project partners to prepare the sampling campaign, the time required for data reception and posterior analysis) and demonstrated why this was such a time-intensive process (Supplemental Material A3).

Once data were screened, we usually reported results in an abbreviated and summarized form on a dedicated section of the website (Supplemental Material A2). This took multiple months and was especially challenging in years with two sampling campaigns as this phase (Phase 4) overlapped with Phase 1 of the next sampling campaign (Figure 2.1). After full analysis, i.e. the publication of the respective scientific article, a summary of the article in German was sent to all participating teachers and youth group leaders and also disseminated via social media. This summary took different shapes, e.g. slides to be shown in class or short videos for schoolchildren to watch (Supplemental Material A3).

Table 1.2: Time between citizen science sampling campaigns and the actual peer-reviewed publication of the respective Plastic Pirates study making use of these data.

Plastic Pirates study	Citizen science data collection campaigns	Published (available online)	Time between data collection campaigns and publication (counting from last sampling campaign of which data were considered)
Investigation of riverside litter quantities, composition and sources (Kiessling et al., 2019).	Autumn of 2016 and spring 2017	November of 2018	Approximately 17 month
Investigation of microplastic quantities, polymer composition and sources (Kiessling et al., 2021).	Autumn of 2016 and spring of 2017	May of 2021	Approximately 4 month
Evaluation of the EU Single-Use Plastic Directive (Kiessling et al., 2023).	Multiple campaigns from spring of 2019 to autumn of 2021	April of 2023	Approximately 18 month

Apart from this targeted communication to participants, other stakeholders such as non-scientific groups (policymakers, environmental engineers, NGOs etc.) were also informed of the outcome, e.g., through non-scientific technical reports (Dittmann et al., 2021; Dittmann and Kiessling, 2021; Mederake et al., 2021) as well as press work which resulted in print, online and broadcast media coverage.

2.7 Discussion

Being a mostly contributory program (as opposed to co-designed citizen science initiatives, Senabre Hidalgo et al., 2021) the communication processes in the Plastic Pirates program were largely designed to ensure that (i) participants can effectively learn about the scientific process and the plastic pollution problem, and (ii) scientifically useful data about the litter pollution of rivers could be collected and submitted by participants.

The purpose of communication within citizen science initiatives varies depending on e.g., the desired outcomes, target audience, timescales, and the level of engagement of the participants in the initiative (Rüfenacht et al., 2021). For initiatives engaging their participants

in the design of research questions (Ballard and Belsky, 2010), in extensive training to perform data collection and the shipment of samples (Schneider et al., 2021), the analysis of data (Weigelhofer et al., 2018) or even the publication of results (Nicosia et al., 2014), individual communication naturally starts much earlier and ends much later in the lifetime of a citizen science initiative. Stronger, deeper interaction has been shown to lead to a stronger participant commitment (Rüfenacht et al., 2021).

For the Plastic Pirates program, a more co-creative approach would not have resulted in the large number of participants (who were geographically dispersed across Germany). Much of the coordinating team's resources were already allocated to communication and data quality assurance efforts (Figures 2.1, 2.3; Dittmann et al., 2022). Regarding the workload, the third phase of communication, the reception and revision of data, was the most complex within the Plastic Pirates program, but essential for the achievement of the program's main goals. Especially in years in which two sampling campaigns were conducted, the follow-up phases of one campaign (Phase 3) and the preparation phase of another (Phase 1) often overlapped (Figure 2.1).

Other citizen science initiatives overcome this demanding workload by relying on technology to involve participants or other interested parties in processes such as the verification of data (e.g., iNaturalist, di Cecco et al., 2021), see also the citizen science app SPOTTERON, which offers a platform for various citizen science initiatives, (Hummer and Niedermeyer, 2018). For the Plastic Pirates program the development of an app would have been too costly, and school classes in Germany are currently insufficiently digitized to allow for data collection via mobile devices in the field. Furthermore, subsequent communication between teachers or youth group leaders and the coordinating team for the purpose of clarifying questions would not have been resolved via an app as many issues could only be clarified bilaterally via email or telephone.

A further challenge was providing feedback to teachers and youth group leaders after participation, as the publication of the scientific articles took over 1 year after datasets were submitted (Table 1.2). In contributory initiatives timely feedback of results is important for participants to gain insights into the scientific findings, to which they had contributed (de Vries et al., 2019), which is why we chose to share insights into the scientific process via social media. Feedback can be a very important motivating factor for participants (Rotman et al., 2012). The only possibility for feedback for teachers and youth group leaders in the Plastic Pirates program was direct contact with the coordinating team. Here, a central platform with the purpose of building a community would have given participants a chance to reflect upon their participation

and interact with each other. The predecessor of the Plastic Pirates program, the project Following the Pathways of Plastic Litter, engaged classes in community building exercises through an online blog and through sharing experiences via video and texts. Still, there was a moderation and language barrier between the two participating countries (Chile and Germany), which was challenging to overcome and time-consuming for the coordination team (Kruse et al., 2020).

Similarly, short funding periods (Figure 2.3) and uncertainties about future funding made the communication with participants even more difficult, as we (the coordination team) could only offer ambiguous responses to the questions of teachers whether future participation was possible, had no certainty in planning these future campaigns, and submitted data were not fully analysed yet. It has to be emphasized that we see the motivation of the participants and the integration of their particular interests and knowledge, as well as their involvement beyond data collection within the research approach as an essential component of citizen science. Therefore, extensive educational materials were prepared that could be used mostly independently by participants (Kiessling et al., 2022; Knickmeier et al., 2022). Educational material or data collection protocols are an integral part of many citizen science initiatives and it is important that their format is adapted to the target audience (Balázs et al., 2021).

Overall, the success of communication strategies varied, which could be seen in the ranges of people ordering materials and participating in sampling excursions in different years, and was also influenced by external factors such as the COVID-19 pandemic (Table 1.1). Over the long duration of the program in Germany (more than 6 years to date), the communication strategies used within the Plastic Pirates were constantly adapted based on our experiences. This included, for example, keeping track of conversations with the help of a spreadsheet (annotating missing information alongside dates when participants were contacted), simplifying sampling protocols, and establishing the backend of the website in such a way that the coordinating team could easily access information about datasets (e.g., upload data, check for missing photos, ensure accuracy of metadata). These improvements along with frequent individual conversations with teachers and youth group leaders with the purpose of achieving the scientific goal of the initiative, illustrated the value of the citizen scientists' contributions and resulted in effective communication strategies within the Plastic Pirates program going forward.

2.8 Recommendations for citizen science communication strategies

Our experience with the Plastic Pirates program showed that quick and efficient individual communication with participants (usually teachers and youth group leaders), mostly via email, was key for obtaining and verifying citizen science data. We would have preferred to systematically involve participants in an evaluation of the program's communication strategies and include them in the more scientific processes of the Plastic Pirates program (such as verifying each other's datasets), and digitizing educational materials (or developing an app).

However, due to financial and time constraints, we focused on the key mission of the program, namely, offering participants a short-lived scientific experience beyond the typical classroom activities, and gathering novel insights into the problem of environmental plastic pollution. Because of this, we were able to convey scientific findings based on citizen science data in several peer-reviewed publications (Kiessling et al., 2019; Kiessling et al., 2021; Kiessling et al., 2023), share our lessons learned regarding data quality mechanisms of the program (Dittmann et al., 2022), involve more than 23,000 participants in Germany, who contributed more than 1,200 datasets of litter pollution, and extend the spatial scope of the program beyond Germany to other European countries (https://www.plastic pirates.eu/).

The main challenge to be overcome was balancing the limited personnel resources of the coordination team with the need for individual communication with participants after the field sampling for the purposes of receiving data and reviewing data quality. While successful citizen science communication strategies are tied to the goals of individual initiatives, we offer the following ten best practice tips based on the experiences of the Plastic Pirates, which might be especially valuable for similarly structured contributory citizen science initiatives:

(i) Communicate as flexible as possible and in a transparent and concise manner to ensure scientifically valuable data.

(ii) Make sure to have the extensive personnel resources needed for efficient communication.

(iii) Keep the barriers for participation as low as possible by offering material free of charge and shifting workload from participants to the coordinating team.

(iv) Ask for sampling dates in advance to anticipate data processing efforts at an early stage.

(v) Offer an alternative way to submit data, as for some participants the barrier to submit data via a dedicated web form can likely not be overcome, for the alternative use a communication medium the participants are familiar with.

(vi) Assist participants during work phases requiring technical skills or tasks that are repetitive.

(vii) Keep participants engaged and communicate with them beyond the data collection phase.

(viii) Acknowledge the value of the contributions of participants (in publications or social media posts) and celebrate achievements together, for example, upon reaching important milestones (see Supplemental Material A3).

(ix) Ensure that communication with teachers (e.g., in form of telephone helplines or webinars) is available outside of school
hours (in the afternoon or evening).

(x) Consider the realities in which schools operate, e.g., vacations, teaching schedules and formats, school curricula, available
personnel resources and time constraints.

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Chapter 3: How to get citizen science data accepted by the scientific community? Insights from the Plastic Pirates project

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3.1 Abstract

Data resulting from citizen science investigations are often questioned as most participants do not (yet) have a thorough scientific education. This is especially true for projects taking place in schools, and conducting citizen science in this context is further complicated by different motivations of participants and a busy school curriculum. Herein we present strategies to ensure quality of data generated by the citizen science project Plastic Pirates in which schoolchildren investigated litter pollution at and in rivers. We show how formulating concise research questions, offering accompanying educational material, employing data quality mechanisms in the field (photographs, standardized sampling methods and self-evaluation) as well as transparently detailing which datasets were excluded from analysis was vital to accomplish the acceptance of resulting citizen science data by the scientific community.

3.2 Introduction

The accumulation of plastics in the environment causes significant harm to wildlife, ecosystems, and the economy (Beaumont et al., 2019; Kühn and Franeker et al., 2020) and is a concern for human health (Rist et al., 2018). Most research has been conducted on plastics in the marine environment, and the occurrence and distribution of litter in other environments has been comparatively understudied (Blettler et al., 2017), even though it is estimated that approximately 80 % of litter originates from land-based sources (Andrady 2011).

Involving the general public in the research of this environmental problem has the potential to provide valuable data on these understudied environments as well as on ascale unobtainable with other means (Bonter and Cooper 2012; Bird et al., 2014). However, involving people without a formal scientific education in research processes causes concerns about the quality of the resulting data (Kosmala et al., 2016; Swanson et al., 2016). The dimensions of data quality are manifold and are defined differently depending on the focus of the research project (Sullivan et al., 2009).

Generally, data quality is characterised by many different aspects, such as sufficient quantity of data, completeness, being standards-based as well as by being free of errors (Pipino et al., 2002; Balázs et al., 2021). However, so far no “one-size-fits-all” approach exists with regard to data quality as the definition depends on the respective stakeholder (Balázs et al., 2021).

Meanwhile, there are various recommendations for ensuring data quality in citizen science, for example, having low thresholds for participation, using standardised data collection protocols to ensure comparability between datasets, training of participants previous to

samplings, dividing the data collection process into different tasks to reduce complexity and revising results and/or samples by project coordinators and getting in contact with participants for clarification (Delaney et al., 2008; Wiggins et al., 2011; Bonter and Cooper 2012; Bird et al., 2014; Kosmala et al., 2016; Dickinson et al., 2017).

Within the project Plastic Pirates different data quality mechanisms were successfully implemented in order to process and analyse the data collected by the participants.

The Plastic Pirates are investigating litter pollution at and in rivers, building on a previous project by Rech et al. (2015). Since the start of the citizen science project in 2016, more than 18,000 schoolchildren, together with teachers and youth group leaders, have examined rivers throughout three countries in more than 1200 sampling events (https://www.plastic-pirates.eu/ en/results/map). The objectives of the project are to increase the scientific literacy of young people by giving the participants insights into scientific ways of working, and to raise their environmental awareness. Further, resulting scientific data on litter pollution allows a wide-ranging recording of this environmental problem and the identification of potential litter sources.

To ensure high quality of these citizen science data we divided the data verification mechanisms of the Plastic Pirates into four steps: (1) planning and involvement of participants in study design, (2) motivation and training of the participants, (3) data collection and ongoing support, and (4) data validation and analysis.

3.3 Four steps of Plastic Pirates data verification

3.3.1 Planning and involvement of participants

Data quality considerations before the active involvement of the participants concerned mainly the development of research questions and accompanying adequate methods addressing the plastic pollution problem. Building on experiences made by Rech et al. (2015) also investigating river litter with schoolchildren offered the advantage of avoiding errors and thus enhance data quality. The research questions were concise and omitted methods that other groups of researchers might have employed (e.g. investigating microplastics smaller than 1 mm) to streamline the sampling and not overburden participants with tedious tasks (e.g., sorting through a fine microplastic net loaded with organic material, (Rech et al., 2015; Figure 3.1).

Accompanying educational material (in the form of booklets) was important to engage the participants and offered them a wider perspective about the plastic pollution problem (the material was available free of charge https://www.plastic-pirates.eu/en/material/order). This

material as well as the sampling methods were co-created between a team of scientists and schoolteachers. Involving members directly working with the targeted citizen science group at this stage was important to reflect on the appropriateness of employed methods. Coulson and Woods also emphasize the importance of co-created booklets to assist participants in monitoring environmental pollution in their surroundings (Coulson and Woods 2021). For the Plastic Pirates a full co-creation approach involving school-children was not used because of time constraints and experiences of successful river and beach litter studies of the citizen science programs Científicos de la Basura (Litter Scientists, http://www.cientificosdelabasura.cl/en/) and Following the Pathways of Plastic Litter (Rech et al., 2015; Honorato-Zimmer et al., 2019; Kruse et al., 2020).

3.3.2 Motivation and training of the participants

The motivation and the goals of the participants are important aspects to consider planning a citizen science activity (Vohland et al., 2021). As a study by Land-Zastra et al. (2021) indicates, the level of engagement is strongly dependent on the individual motivation of the participants.

Contrary to most studies involving citizens, schoolchildren are usually not volunteers but compelled to participate by their teacher. To account for varying levels of enthusiasm, to motivate participants to get involved in tasks diverging from usual classroom assignments, and to address different personal capacities the field sampling offered a variety of activities (ranging from establishing transects to sorting through larger quantities of litter items, or inspecting potential litter sources and interviewing passersby, the latter being a more investigative approach; Figure 3.1). Regarding practical aspects, the project was developed to allow flexibility for already overtasked teachers trying to incorporate a citizen science project into a busy school curriculum: the only core activity was the field sampling (which could be conducted within a day) and other aspects were optional, e.g. working through exercises and experiments in the educational booklet and training before the sampling via a webinar offered by the project coordinators. The methods also allowed for some flexibility and could be employed at all kinds of rivers (large and small, urban and rural, with and without direct access to the river itself). Finding a balance between these practical considerations and ensuring high data quality were a main concern when developing the methods before the actual data collection phase (and are a main concern in other citizen science projects as well, see for example the review by Buytaert et al. (2014) for projects focusing on hydrology.

3.3.3 Data collection and ongoing support

For the actual field sampling, a participating course split up into several groups of about six to eight schoolchildren, each addressing their own research question, such as quantifying the riverside litter, sampling the river for microplastics or looking for sources of the litter. This reduction of complexity reduces possible mistakes during the sampling (Sheppard and Terveen 2011; Kosmala et al., 2016) and ensured that relevant data were obtained, even if one research question could not be addressed adequately (in one instance this happened due to very complex sampling instructions to assess accumulations of litter objects (Kiessling et al., 2019)). This was also recommended by Kosmala et al. (2016) particularly in cases where no training sessions with the participants were provided in advance.

For the quantification of riverside litter, three transects were established by the schoolchildren extending from the river shore up the riverbank. Sampling circles were located on each transect and only items within the circles were counted in order to record the level of pollution. Afterwards schoolchildren were asked to photograph their findings (so that they can be corroborated by the project coordinators). The instructions included a guide on how to take these pictures (placing the litter items on a uniformly-coloured background in such a way that items could be differentiated). For the investigation of microplastics a standardized net (mesh size of 1 mm) was used. Using standardized sampling instruments is a quality control measure commonly employed in citizen science projects, such as the Swiss Common Breeding Bird Survey which used a simplified territory mapping protocol (Dickinson et al., 2017; Figure 3.1). The net was sent free of charge in a package including assembly instructions, and a post- paid return stamp, to make the use of the net and shipment of sample as convenient as possible.
Overall, apart from the microplastic net, only easily obtainable materials were included in the sampling, such as buckets, gloves, sticks and ropes.

After the sampling, collected data as well as photos were uploaded via a centralised website, usually by the teachers. After a school class participated in the sampling, the coordinators at Kiel Science Factory revised whether all information and materials were available, i.e., data about the sampling itself (location and time), data about the litter findings, photos to corroborate the findings, and microplastic samples. Rapid communication and documentation of the conversations proved to be crucial to obtain missing data and clarify questions related to the respective data set, for example why annotated litter objects did not show up in photos. In total more than 11,000 emails were written and received over the project's lifetime, many of which were concerned with obtaining and verifying the materials submitted by the participants, which represented a significant workload for project coordinators.

This experience was also shared by Bonter and Cooper (2012) from the FeederWatch project, who therefore used a semi-automated system to detect potentially erroneous observations at an early stage. A further challenge during data revision was that we, as project coordinators, had no local knowledge about the sampling sites. Tools such as OpenStreetMap (https://www.openstreetmap.org) and Google Earth helped to double check certain parameters (such as the width of the investigated rivers at the sampling sites).

3.3.4 Data validation and analysis

Once all initial concerns had been resolved (or no further information was obtained) it was assessed whether a respective dataset could be considered for analysis following a decision-making flowchart. This flowchart shows step by step under which circumstances data were accepted or rejected and was published together with the scientific findings. Further, examples of photographs detailing individual cases of datasets accepted or rejected and a list of how many datasets had to be rejected (including the reason why) have been added to the study (Kiessling et al., 2019; Figure 3.1). The main reasons for rejecting a datapoint included missing samples and missing photographs to corroborate litter findings (Kiessling et al., 2019; Kiessling et al., 2021) highlighting the need for efficient communication between all parties involved.

Regarding microplastics, similar to a study by the Científicos de la Basura (Hidalgo-Ruz and Thiel 2013) a thorough analysis took place in the lab of the project coordinators. For the Plastic Pirates samples this included the extraction of potential microplastic particles from the samples by visual inspection with a dissecting microscope and infrared spectroscopy-analysis for each plastic particle in order to confirm whether the particle consisted of plastic or not (Kiessling et al., 2021).

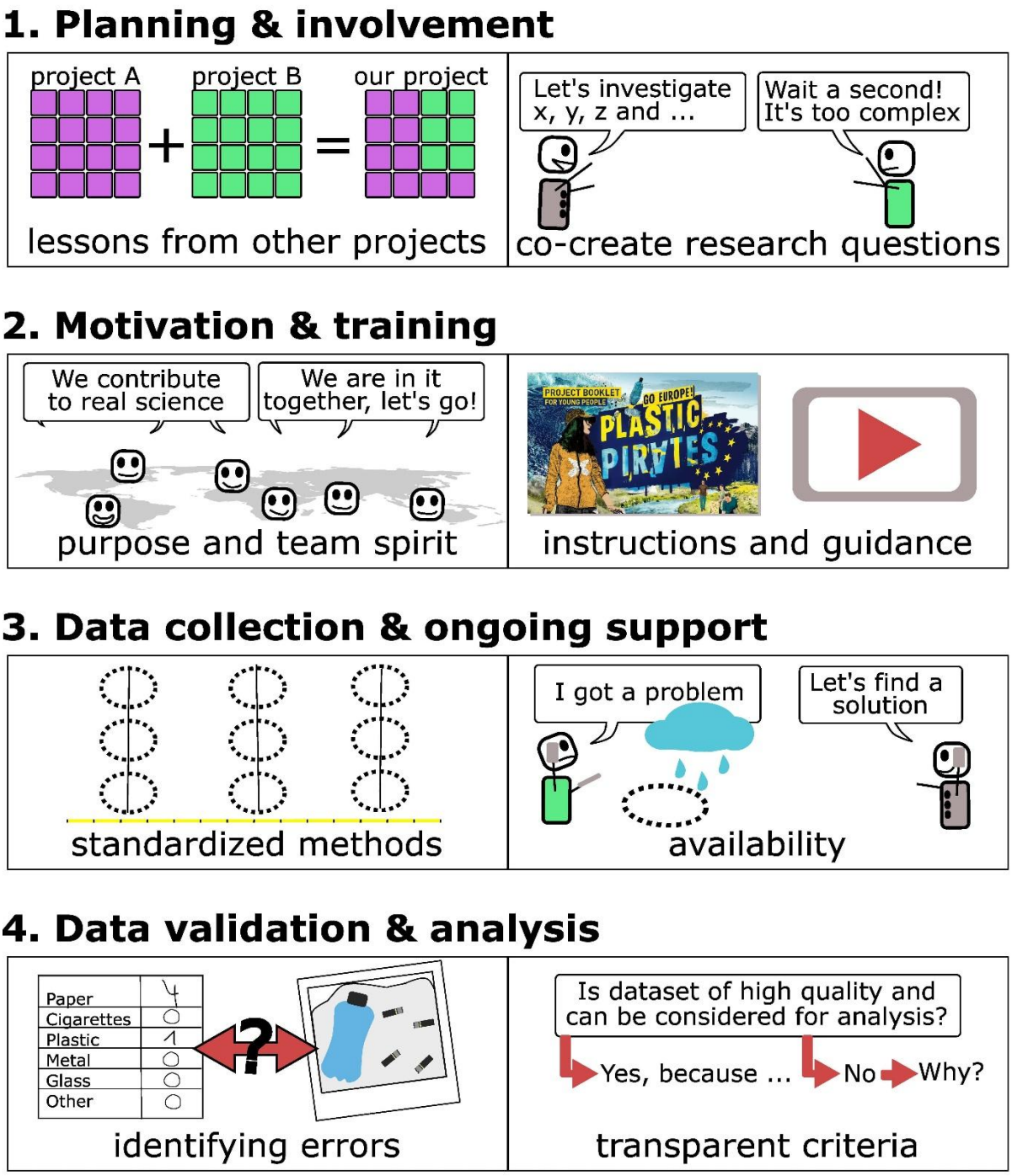

Figure 3.1: Mechanisms for high quality of citizen science data during different phases of a citizen science project, based on experiences from the Plastic Pirates.

3.4 Conclusion

In summary, high quality of the citizen science data originating from the Plastic Pirates project could only be ensured through comprehensive strategies applied before, during and after data collection. Questions related to data verification ("Which methods were employed to ensure data quality in the field?", "How were data treated for analysis?", "How many datasets

were considered for analysis", "Which problems caused the exclusion of datasets?") were an integral part of the Plastic Pirates throughout all project stages and key for the scientific success of the project. Developing functioning data quality assurance for citizen science projects is a long-term process involving multiple iterative steps where mistakes— when they happen—are continuously being corrected.

We therefore call for active collaboration between existing and future citizen science projects, explicitly also sharing mishaps (see e.g. Rech et al., 2015; Kiessling et al., 2019) in order to improve the data quality of citizen science studies and foster the acceptance of citizen science data within the scientific community.

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Chapter 4: Temporal variability of litter pollution of rivers in Germany – A long-term assessment by schoolchildren as citizen scientists

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4.1 Abstract

Understanding litter dynamics on riversides is challenging due to the need for extensive data. A seven-year citizen science study with schoolchildren showed no major changes in litter density, composition, and sources on German riversides. The study categorized 26,757 macrolitter items (> 2.5 cm in size), mainly consisting of plastic and cigarette butts, with a median litter density of 0.28 items m^{-2}. We found that wide rivers (> 51 m) had significantly higher median litter densities (0.42 items m^{-2}) than narrow rivers (< 10 m, 0.14 items m^{-2}), indicating greater litter accumulation in downstream areas. A zero-inflated binomial hurdle model showed that litter density variations were influenced by the interaction of the river system with sampling campaign and river width. Schoolchildren identified visitors as the most likely source of riverine litter. These findings highlight the value of citizen science in understanding long-term trends and show the urgent need for political measures.

4.2 Introduction

It is well known that rivers constitute an important source of macrolitter pollution of the ocean, but the river ecosystem itself is also directly affected, as large amounts of (plastic) macrolitter are retained in the rivers (van Emmerik and Schwarz, 2020; Al-Zawaidah et al., 2021; Meijer et al., 2021). Large rivers have already been reported to transport plastic litter such as the Yangtze (Zhao et al., 2014), the Danube (Lechner et al., 2014) and the Rhine rivers (Mani et al., 2015). Although it is well known that rivers are important conduits of plastic litter, there is still a lack of reliable data on its origin (van Emmerik et al., 2020). Most studies on riverine litter pollution focus on the river as a pathway for transporting buoyant floating litter items, which may be assessed by modelling the amount of litter entering the ocean (Lebreton et al., 2017; Al-Zawaidah et al., 2021).

However, anthropogenic litter on the riverside or near rivers has only been a focus of few scientific publications yet (Rech et al., 2015; Battulga et al., 2019; Schneider et al., 2021; Requiron and Bacosa, 2022), although it could be one of the main sources of litter that eventually ends up in the ocean (Kiessling et al., 2019; Honorato-Zimmer et al., 2021; Schneider et al., 2021). To substantially reduce the leakage of litter from land to sea, knowledge of the potential sources of litter on the riverside is essential (Al-Zawaidah et al., 2021). In general, the accumulation and deposition of litter items on the riverside can be influenced by various factors

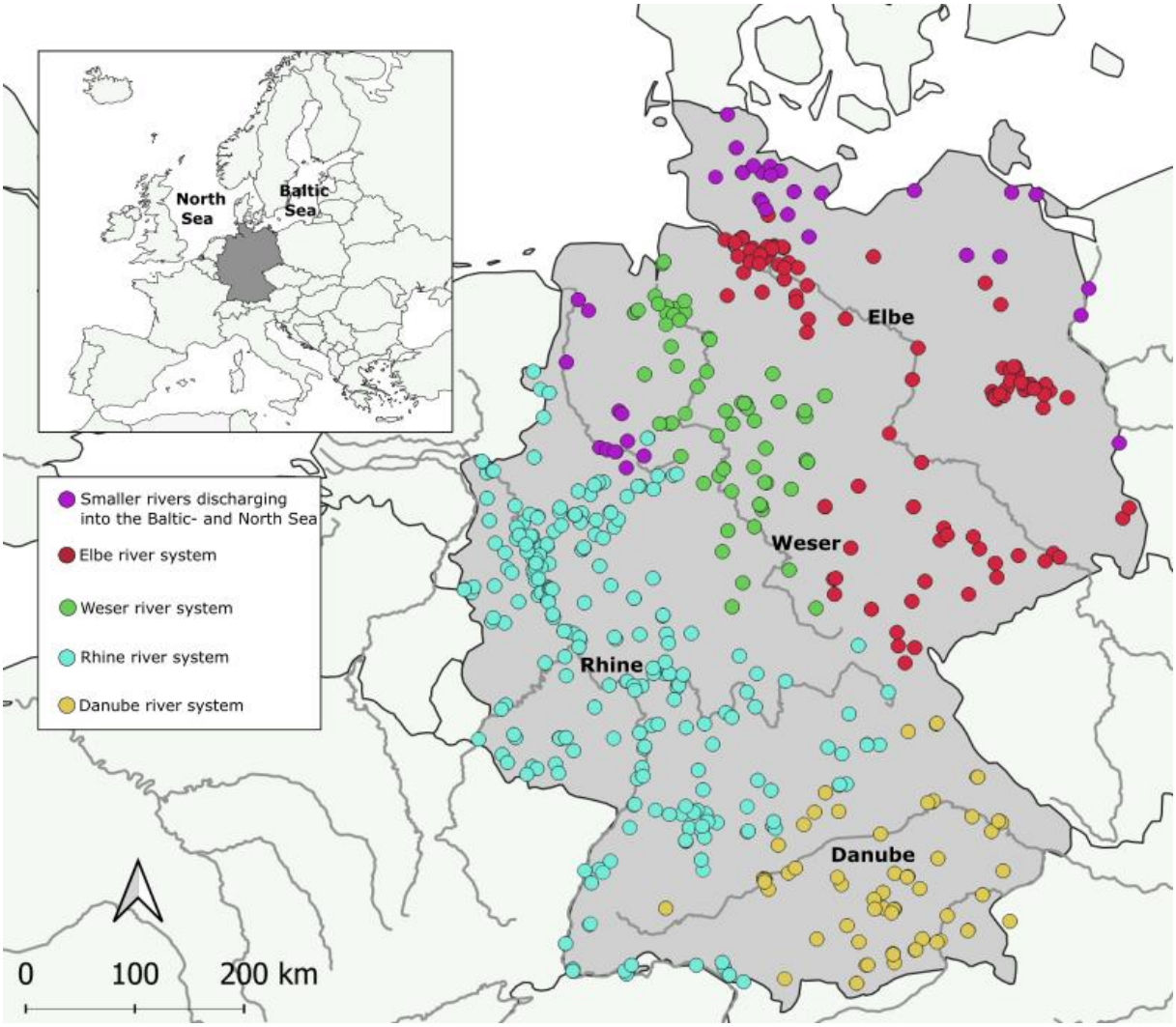

Figure 4.1: Map of Germany showing major river systems and sampling locations of the Plastic Pirates in Germany during the years 2016 to 2022. The colored dots showed the classification to the respective river system.

On the one hand, litter can end up on the riverside as a result of anthropogenic activities, such as illegal disposal or littering linked to recreational activities (Kiessling et al., 2019). On the other hand, natural processes, such as flood events, winds or currents, can also deposit litter on the riverside (Tramoy et al., 2022). Several studies have analysed litter pollution on the riverside (Rech et al., 2015; Kiessling et al., 2019; van Emmerik et al., 2020), the horizontal transportation of macrolitter at the water surface (González-Fernández et al., 2021; van Emmerik et al., 2022a), and the vertical transportation of litter in the water column of the river (Blettler et al., 2017; Vriend et al., 2020; Blondel and Buschman, 2022), whereas macrolitter accumulation and remobilization processes on the riverside were often neglected (but see Rech et al., 2015; Battulga et al., 2019; Schneider et al., 2021; Requiron and Bacosa, 2022). Factors causing variability in litter quantities include daytime (morning or evening, Requiron and Bacosa, 2022), season (spring or fall, Kiessling et al., 2019), river width (Kiessling et al., 2019), tidal dynamics, anthropogenic influences (population density, waste management

infrastructure, river bank modifications, Liro et al., 2020; Honorato-Zimmer et al., 2021), river sections (upstream, midstream, downstream, Requiron and Bacosa, 2022), flow velocities (van Emmerik et al., 2018; van Emmerik et al., 2020) as well as the natural dynamics of the river zone itself (vegetated or unvegetated areas, anthropogenic modifications of the river basin, Williams and Simmons, 1996; Hurley et al., 2020; Winton et al., 2020).

So far, most studies have focused on the collection of litter data in one river system and there are only few studies that consider data over several years (see e.g. Kiessling et al., 2019; Honorato-Zimmer et al., 2021; van Emmerik et al., 2022b), meaning that broad-scale and long-term data are still scarce (Al-Zawaidah et al., 2021). Broad-scale and long-term data are crucial as they provide information on the dynamics of litter along the river course, facilitate monitoring of inputs from possible sources and can identify trends over time. This is particularly important in order to generate data that can be used for policy-making decisions to reduce plastic litter generation and littering (Gallitelli et al., 2020).

Extensive samplings of the riverside are very costly and time-consuming (Moore et al., 2011; Lechner et al., 2014; Sadri and Thompson, 2014). As a result, citizen science approaches have become increasingly popular in recent years to obtain an extensive overview of litter quantities on and in the river (Kiessling et al., 2019; van Emmerik et al., 2020).

In general, citizen science is described as the participation of the general public in scientific research processes (Dickinson et al., 2010; Bonney et al., 2016). Through participation, citizens gain insights into authentic research processes, which can increase trust in scientific studies (Bonney et al., 2016). Furthermore, they are sensitised to environmental issues and can thus contribute to a change in personal behaviour (Thiel et al., 2014). From a scientific perspective, involving citizens opens up novel research questions by enabling data collection across broad spatial scales, although it requires significant dedication from all participants involved (Dittmann et al., 2023; Thiel et al., 2023).

In the present study, we analysed citizen science data collected by schoolchildren and their teachers on macrolitter items (> 2.5 cm in size) over a period of seven years (2016 to 2022, corresponding to eleven individual sampling periods) from five principal river systems and their tributaries in Germany (Figure 4.1). The aim of this study was to (1) investigate whether there are spatial and temporal variations of litter densities on riversides, (2) analyse whether litter composition and potential sources have changed over time, and (3) examine the influence of river width on the densities and composition of macrolitter on the riversides.

4.3 Materials and methods

4.3.1 Citizen science approach involving schoolchildren

The present study analysed data collected within the citizen science program Plastic Pirates. The program involved schoolchildren, their teachers and youth groups in Germany in the investigation of anthropogenic litter pollution of rivers (https://www.plastic-pirates.eu/de). To recruit participants, schools were contacted via postal mailing and e-mails. Social media advertisement and online teacher webinars further aimed at recruiting and motivating teachers to participate in the Plastic Pirates (see Dittmann et al., 2023, for communication aspects of the program).

In case a teacher or youth group leader was interested in participating in the program, the required educational (https://zenodo.org/records/7986353) and sampling materials (https://zenodo.org/records/7986321) were sent to the respective school free of charge. In order to guarantee standardised collection of data, a sampling booklet was developed in which the sampling procedure was explained in detail. The sampling booklet was designed collaboratively by scientists and teachers, in a way that school classes could participate independently in the sampling, i.e. without being accompanied by a scientist.

The program was conducted between the years 2016 to 2022, eleven national sampling campaigns in total, of which five took place during fall (mid-September to mid-November, for the sampling campaigns 2016, 2018, 2020, 2021, and 2022), and six during the spring (May and June, for the sampling campaigns 2017, 2018, 2019, 2020, 2021, 2022). Overall, > 23,000 schoolchildren contributed data to the present study, coming from all 16 German federal states.

In some cases, multiple classes from one school participated, resulting in a total of 568 groups that conducted the sampling on the riverside litter and submitted usable datasets and 812 groups that collected data on the evaluation of litter sources, and submitted usable datasets (Supplement B1). The participating school classes were free to choose the river and site for their sampling.

The sampling method is based on a study by Rech et al. (2015) and was adapted by the researchers of Kieler Forschungswerkstatt (Kiel Science Factory, https://www.forschungs-werkstatt.de/, see also Kiessling et al., 2019) and the Científicos de la Basura (Litter Scientists, http://www.cientificosdelabasura.cl/) in Chile.

To improve data quality, it was recommended to participating teachers to practise the sampling in advance with the schoolchildren in the classroom or in the schoolyard. Samplings were then conducted in small groups of approximately four to six schoolchildren to investigate different aspects of litter pollution in the riverine environment.

4.3.2 Study area

Four major river systems that flow through Germany and smaller rivers that discharge directly into the North- and Baltic Sea were investigated by the participating schoolchildren. The Danube is the longest river in Germany, with a length of around 2850 km, flowing from southwest to southeast Germany. It is the second-longest river in Europe, and passes through nine other countries (Danube Commission, 2024). The Rhine is the second largest river in Germany, flowing from southwest to northwest over a length of around 1230 km before emptying into the North Sea via the Netherlands. The Elbe flows through both the eastern and western parts of Germany with a total length of 1094 km (FGG Elbe, 2019). The Weser is the shortest of the four main river systems with a total length of around 430 km, and flows through western Germany into the North Sea (NLWKN, 2022). All the rivers studied have catchment areas that include both densely populated and heavily industrialized regions (e.g., the Ruhr area in Germany, through which the Rhine flows or the port of Bremerhaven located along the Weser).

4.3.3 Sampling of riverside litter

To assess the density and composition of litter at riversides, the schoolchildren established three transects perpendicular to the river, using the method described by Kiessling et al. (2019): Three sampling stations were marked on each transect, one in each distinct predetermined zone: (Zone A) the river edge defined as having regular contact with the river itself and covering the first five meters of the riverside, (Zone B) the river bank (5–15 m from the water), and (Zone C) the river crest (> 15 m from the water), with irregular contact with the river, e.g. during flood events (Figure 4.2). The sampling stations consisted of circles with a radius of 1.5 m (~7.1 m^{-2}), which were marked on the ground with the help of a string, a stick and pebbles.

Subsequently, all macrolitter items were collected, classified and quantified. The classification was based on the respective types of litter: paper, cigarettes, plastic, metal, glass, food left-overs, and other litter items. This classification followed categories previously used in litter studies with schoolchildren (e.g. Rech et al., 2015; Hidalgo-Ruz et al., 2018; Kiessling et al., 2019). For the subsequent verification of the data (see below) by the program team (of the coordinating laboratory at the Kieler Forschungswerkstatt), the participants took photos of the litter items found. The photos were then uploaded together with the collected data to a

central online platform (https://www.plastic-pirates.eu/en). In the first two years of the project (2016 and 2017), the datasheets and photos were sent to the Kiel Science Factory by post.

4.3.4 Inference of litter source

The participants used different criteria to infer potential sources of the litter in the vicinity of the sampling site. The educational material encouraged the schoolchildren to discuss which of the following sources could contribute to pollution: residents (could be inferred for example by finding dumped garden waste), visitors (people who use the river area for recreation, inferred based on for e.g. leftovers from barbeque or cigarette butts), people dumping litter illegally, industry, ship and boat traffic (including small leisure craft and large river barges), and the river itself (washing up litter from upstream sources). Participants rated the sources on a scale of “Yes”, “Likely”, “Possibly”, “Unlikely”, and “No”, where a “Yes” would represent a positive answer to the question of whether the respective source contributed to the litter found.

Additionally, the schoolchildren were encouraged to take photographic evidence of possible litter sources in the surrounding area, e.g. of overflowing litter bins. For analysis, the first two statements (“Yes” and “Likely”) were merged to represent a positive response and the latter two statements (“Unlikely” and “No”) were merged to represent a negative response (the answer “Possibly” was not taken into consideration).

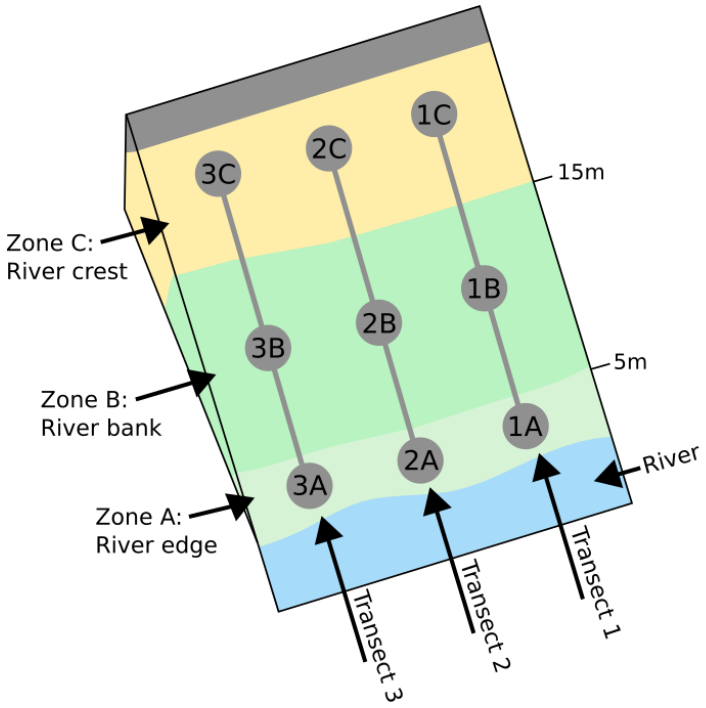

Figure 4.2: The sampling method for assessing the litter on the riverside involved three transects across three distinct zones, each varying by distance from the river (from Kiessling et al., 2019, used with permission from Elsevier).

4.3.5 Stepwise verification of the submitted citizen science data sets

For each individual group, all data were verified following the criteria established by Kiessling et al. (2019) and described in detail by Dittmann et al. (2022). In brief, the data relating to the litter findings of each sampling station were compared with photos the schoolchildren took. A minimum of one photo was required (unless no litter was found), otherwise the data set was not considered for analysis. Similarly, a data set was excluded when the comparison of photo and data showed that litter items were misidentified. Even though the sampling protocol focussed on the collection of macrolitter items (> 2.5 cm), it was not always possible to ensure that pieces of litter smaller than 2.5 cm were not collected by the schoolchildren.

A total of 1045 groups attempted the sampling of riverside litter between the years 2016 and 2022 and data from 568 groups (4875 data points) were accepted (~54 %) and used for analysis (310 groups did not submit any photo and their data were therefore rejected; Supplement B2). One dataset submitted by schoolchildren identified a total of 2645 litter items

at their sampling site on the river Tegeler Fließ, a tributary of the Elbe River. Due to the high number of litter items found, and because their photograph suggested that the litter consisted mainly of very small (< 2.5 cm) glass fragments, we have treated this data set as an outlier and excluded it from the analysis of riverside litter, as it would have skewed the interpretation of the results. For the inference of litter sources, data from 812 of 1339 submitted groups (~61 %) were accepted (Supplement B1). Reasons for the rejection of these data were for example the lack of important metadata of the sampling (such as sampling place and date), and illegible or incomplete data sheets (see Supplement B2).

Sampling sites were categorized by river system, meaning that the principal rivers and their tributaries were grouped. Rivers that did not fit in this scheme of categorization were grouped based on the sea into which they drain (following Kiessling et al., 2019; Figure 4.1). For analysis each sampling circle was treated as one data point, meaning one group could contribute up to nine data points (see Kiessling et al., 2019). Participants provided initial assessments of river width, which were subsequently remeasured by the program team using Google Earth 10.52.0.0. The respective river widths were divided into six different categories based on the classification of Kiessling et al. (2019), (see Table 2.1 and Supplement B3).

Table 2.1: Overview on the river width categories used for the analysis based on the study by Kiessling et al. (2019).

River width category	River width (in m)	Number of data points considered
very narrow	1-3	368
narrow	4-10	1,213
medium	11-25	1,037
medium wide	26-50	900
wide	51-100	469
very wide	> 100	888

4.3.6 Statistical analysis

Litter densities throughout the manuscript are expressed in median litter items m^{-2} and their interquartile range (IQR). Instead of using a nested design (treating individual sampling points contributed by a group as dependent on each other), we chose a zero-altered negative binomial (hurdle) model, which treated data points independently but allowed for the

consideration of reasonable outliers and the inclusion of various variables in the analyses (following Kiessling et al., 2019). We tested whether the following factors and the interaction of these could explain the differences in litter quantities at the riverside: (a) river system (four levels, Rhine, Weser, Elbe, Danube), (b) sampling campaign (eleven levels, 2016-fall, 2017-spring, 2018-spring, 2018-fall, 2019-spring, 2020-spring, 2020-fall, 2021-spring, 2021-fall, 2022-spring, 2022-fall), (c) river width category (six levels, 0–3 m, 4–10 m, 11–25 m, 26–50 m, 51–100 m, > 100 m) and (d) sampling season (two levels, spring, fall). The sampling zones were not considered in the analysis, as no significant effects on litter densities were expected, according to Kiessling et al. (2019).

Generally, a hurdle model consists of two parts: the likelihood of observing no (zero) litter is predicted by the binary part of the model, and the quantity of litter is predicted by a count model (Zeileis et al., 2008). Data from smaller rivers discharging into the Baltic- and North Sea were excluded from the model because they were not available for the spring and fall sampling campaign 2020, resulting in missing interactions between variables. The model with the lowest AIC (Akaike Information Criterion) was retained as it shows the model with the best fit. Pairwise post-hoc comparisons were conducted when significant differences were found (with a Tukey-HSD p-value adjustment). A Chi-Square test was used to determine whether the litter composition differs significantly depending on the river width.

For analyzing the inference of litter sources, a nonparametric Kruskal-Wallis test was conducted as variances were not homogeneous (Levene's test, $df = 9$, F-value = 74.916, p-value < 0.05). To check whether there was a statistically significant correlation between two variables, a Dunn's post-hoc test was used. The p-value was set at 0.05 for all tests. Statistical analyses and graphs were created using the open access statistical software R (R Core Team, 2023). The following R packages were used: pscl (Zeileis et al., 2008), lrtest (Zeileis and Hothorn, 2002), lsmeans (Lenth, 2016), tidyr (Wickham et al., 2024), dplyr (Wickham et al., 2022), car (Fox and Weisberg, 2019), ggplot2 (Wickham, 2016), dunn.test 1.3.6 (Dinno, 2024), and stats (R Core Team, 2023).

4.4 Results

The river systems of Rhine (~48 % of all groups), Elbe (~21 %), and Weser (~13 %) were the most frequently sampled by schoolchildren. The majority of groups went to rivers with a maximum width of 25 m (~54 % of all groups).

4.4.1 Spatial and temporal patterns of macrolitter on the riverside

A total of 26,757 litter items were quantified at riversides for an overall median of 0.28 items m^{-2} with an interquartile range (IQR) of 0–0.85 items m^{-2} and an overall average (±standard deviation) of 0.78 ±1.71 litter items m^{-2} (Table 2.2). The litter densities ranged from 0 items per sampling circle to a maximum of 233 items found (consisting mainly of plastic) in a circle (32.96 items m^{-2}) at the Radau in Lower Saxony (Weser river system, Figure 4.3A). Most of the groups (~92 %) identified at least one litter item at their sampling site, and approximately 65 % of all sampling circles contained litter (Table 2.2).

However, as there is no guarantee that the schoolchildren only collected litter items > 2.5 cm, the quantity of litter items found may be overestimated (see Figure 4.3A and B). The best-fitting binomial hurdle-model with the lowest AIC value considered the river system and the interaction with the sampling campaign and the river width as significant to predict litter densities (Table 4.3). In general, the number of litter items m^{-2} showed significant differences between the sampling campaigns. The highest overall median litter densities were found during the spring campaigns of 2018 and 2021 (median of 0.42 items m^{-2}), while the lowest median litter densities were found during the campaigns 2016, 2017 and fall campaign of 2018 (median of 0.14 items m^{-2}). There were also significant differences in the amount of litter between the two seasons (spring, fall), even though the median amount of litter found was the same for both seasons (0.28 litter items m^{-2}).



Figure 4.3 A: Schoolchildren from Bad Harzburg found a total of 233 pieces of litter in a circle (32.9 litter items m^{-2}) on the riverside of the river Radau (51°53'07.7"N 10°33'33.9"E), a tributary of the Weser river in Lower Saxony, probably from a balloon or packaging material. **B**: Schoolchildren from the Alemannenschule Wutöschingen found 89 pieces of litter in a circle

(12.6 pieces per m^{-2}) on the Wutach (47°39'43.3"N 8°21'52.2"E), a tributary of the Rhine river in Baden-Württemberg; most of the litter consisted of cigarette butts and glass shards.

Table 2.2: Overview of riverside litter for each sampling campaign. For years in which only one sampling campaign was conducted, the respective missing rows are labelled with na.

	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)**	**Mean litter density per m^{-2} and standard deviation**
All data	92.1 % (522 of 568)	65.3 % (3,184 of 4,875)	0.28, 0 – 0.85 (34,459)	0.78 ± 1.72
2016 - spring	na	na	na	na
2016 - fall	90.0 % (85 of 95)	60.0 % (500 of 832)	0.14, 0 – 0.57 (5,881)	0.56 ± 1.42
2017 - spring	93.0 % (77 of 84)	63.0 % (459 of 732)	0.14, 0 – 0.57 (5,174)	0.52 ± 0.89
2017 - fall	na	na	na	na
2018 - spring	92.9 % (26 of 28)	74.1 % (183 of 247)	0.42, 0 – 0.99 (1,746)	0.74 ± 1.01
2018 - fall	76.9 % (20 of 26)	57.3 % (122 of 213)	0.14, 0 – 0.42 (1,506)	0.60 ± 2.32
2019 - spring	89.7 % (52 of 58)	64.5 % (293 of 454)	0.28, 0 – 1.13 (3,209)	1.17 ± 2.97
2019 - fall	na	na	na	na
2020 - spring	100.0 % (8 of 9)	66.7 % (48 of 72)	0.35, 0 – 1.17 (509)	1.25 ± 2.34
2020 - fall	90.2 % (37 of 41)	67.7 % (243 of 359)	0.28, 0 – 0.85 (2,538)	0.78 ± 1.58
2021 - spring	97.6 % (41 of 42)	71.8 % (257 of 358)	0.42, 0.14 – 1.13 (2,531)	0.96 ± 1.52
2021 - fall	94.7 % (71 of 75)	71.1 % (452 of 636)	0.28, 0.11 – 0.85 (4,496)	0.71 ± 1.21
2022 - spring	93.9 % (62 of 66)	66.1 % (375 of 567)	0.28, 0 – 1.27 (4,008)	1.07 ± 1.93
2022 - fall	95.6 % (43 of 45)	62.2 % (252 of 405)	0.28, 0 – 0.85 (2,863)	0.81 ± 1.73

Table 2.3: Results of the zero-inflated negative binomial (hurdle) model. A * marks interactions between variables. The model with the lowest AIC was selected as the model best fitting the data and is marked in bold letters.

Model	Df	AIC	Likelihood ratio test
River system * sampling campaign	89	23,632.44	LogLik= -11727
River system + sampling campaign	29	23,704.25	LogLik= -11823, X^2= 191.806 (df=-60, $p < 0.05$)
River system	9	23,813.85	LogLik= -11898, X^2= 149.597 (df=-20, $p < 0.05$)
River system * season	17	23,785.15	LogLik= -11876, X^2= 44.695 (df= 8, $p < 0.05$)
River system + season	11	23,796.06	LogLik= -11887, X^2= 22.910 (df=-6, $p < 0.05$)
Season	5	23,814.04	LogLik= -11902, X^2= 29.979 (df=-6, $p < 0.05$)
River system * river width	49	23,534.69	LogLik= -11718, X^2= 367.351 (df=44, $p < 0.05$)
River system + river width	19	23,660.21	LogLik= -11811, X^2= 185.515 (df=-30, $p < 0.05$)
River width	13	23,671.18	LogLik= -11823, X^2= 22.970 (df=-6, $p < 0.05$)
River system * sampling campaign + river width	**99**	**23,447.80**	**LogLik= -11625, X^2= 395.378 (df=86, $p < 0.05$)**
Sampling campaign	23	23,716.43	LogLik= -11835, X^2= 420.632 (df=--76, $p < 0.05$)

Considering the litter densities (items m^{-2}) of the individual river systems across all sampling periods, significant differences were found (Table 2.3). While rivers belonging to the river system of the Rhine (*n* = 2330 sampling circles) and the river system of the Danube (*n* = 589) had median riverside litter densities of 0.28 items m^{-2} across all sampling campaigns, other rivers discharging into the river system of the Elbe (*n* = 1004) and into the Weser river system (*n* = 654) had lower litter densities at the riverside (median at 0.14 items m^{-2}, see Table 2.4). A Tukey-adjusted post-hoc test showed significant differences between the litter densities of the different sampling campaigns (Supplement B4), but not for litter densities of the different river systems. However, there is no obvious temporal or spatial trend in litter items m^{-2} across the sampling campaigns for the river systems analysed.

Table 2.4: Overview of riverside litter for each river system.

River system	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})	Mean litter density per m^{-2} and standard deviation
Rhine river system	94.8 % (255 of 269)	68.1 % (1586 of 2,330)	0.28, 0 - 0.85 (16,470)	0.82 ± 1.79
Weser river system	89.6 % (69 of 77)	60.2 % (394 of 654)	0.14, 0 - 0.71 (4,623)	0.68 ± 1.70
Elbe river system	87.3 % (103 of 118)	62.3 % (625 of 1,004)	0.14, 0 - 0.85 (7,097)	0.82 ± 1.77
Danube river system	94.2 % (65 of 69)	68.4 % (409 of 589)	0.28, 0 - 0.71 (4,227)	0.72 ± 1.36
Smaller rivers to Baltic- & North Sea	88.2 % (30 of 34)	58.8 % (170 of 289)	0.14, 0 - 0.71 (2,043)	0.64 ± 1.47

4.4.2 Composition of riverside litter and influence of river width on macrolitter abundances and composition

The majority of litter items found on the riversides consisted of plastic (~28 %), followed by cigarette butts (~21 %), glass (~19 %), paper (~10 %), and metal (~10 %; calculated across all sampling campaigns and all river systems, Figure 4.4). About 10 % of the litter was made up of other litter items and approximately 1 % consisted of food leftovers. Plastic litter was most frequently found on riversides of all river systems sampled, except on riversides of the rivers flowing into the Danube river system, where cigarette butts were most frequently found. The litter densities on the riverside further differed significantly according to the width of the river. A Tukey-adjusted post-hoc test showed that narrow rivers (≤ 10 m width) had significantly less litter (0.14, IQR: 0–0.57 items m^{-2}) than wide rivers (≥ 51 m width) at their riversides (0.42, IQR: 0–0.99 items m^{-2}) calculated across all sampling campaigns (see Figure 4.5 and Supplement B5). The composition of the litter varied significantly depending on the width of the river (Chi-Square test, df =30, X^2 =1560.4, p – value < 0.05). Plastic was found more frequently on riversides of smaller rivers (width ≤ 25 m), while cigarette butts and glass were found in relatively similar proportions on riversides of wider rivers (≥ 25 m) (Supplement B6).

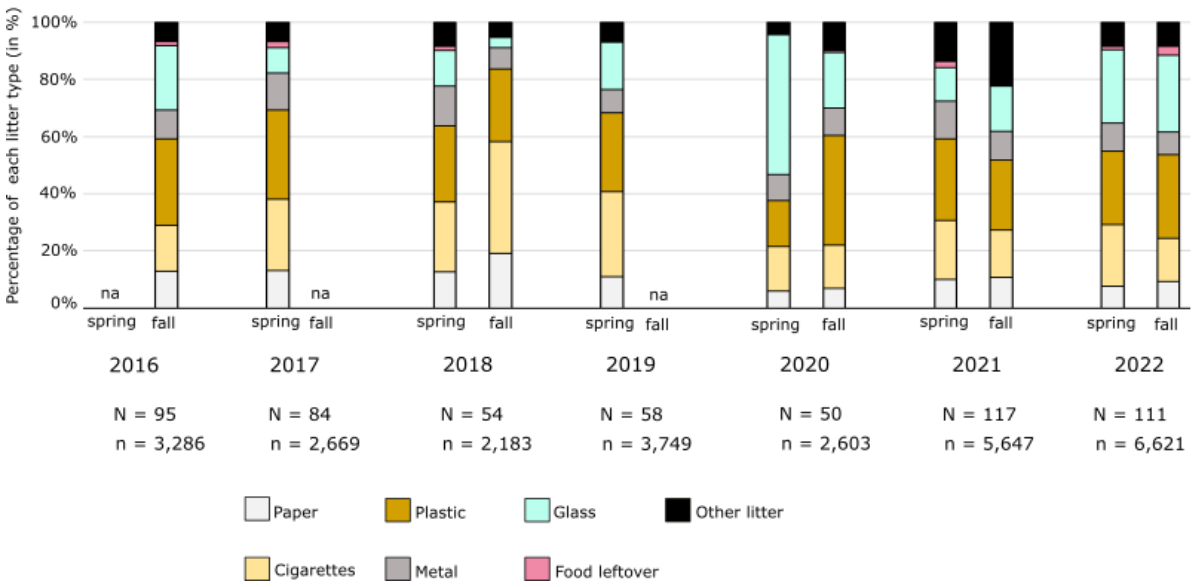

Figure 4.4: Composition of riverside litter according to the sampling campaign and season. N = number of sites, n = number of litter items.

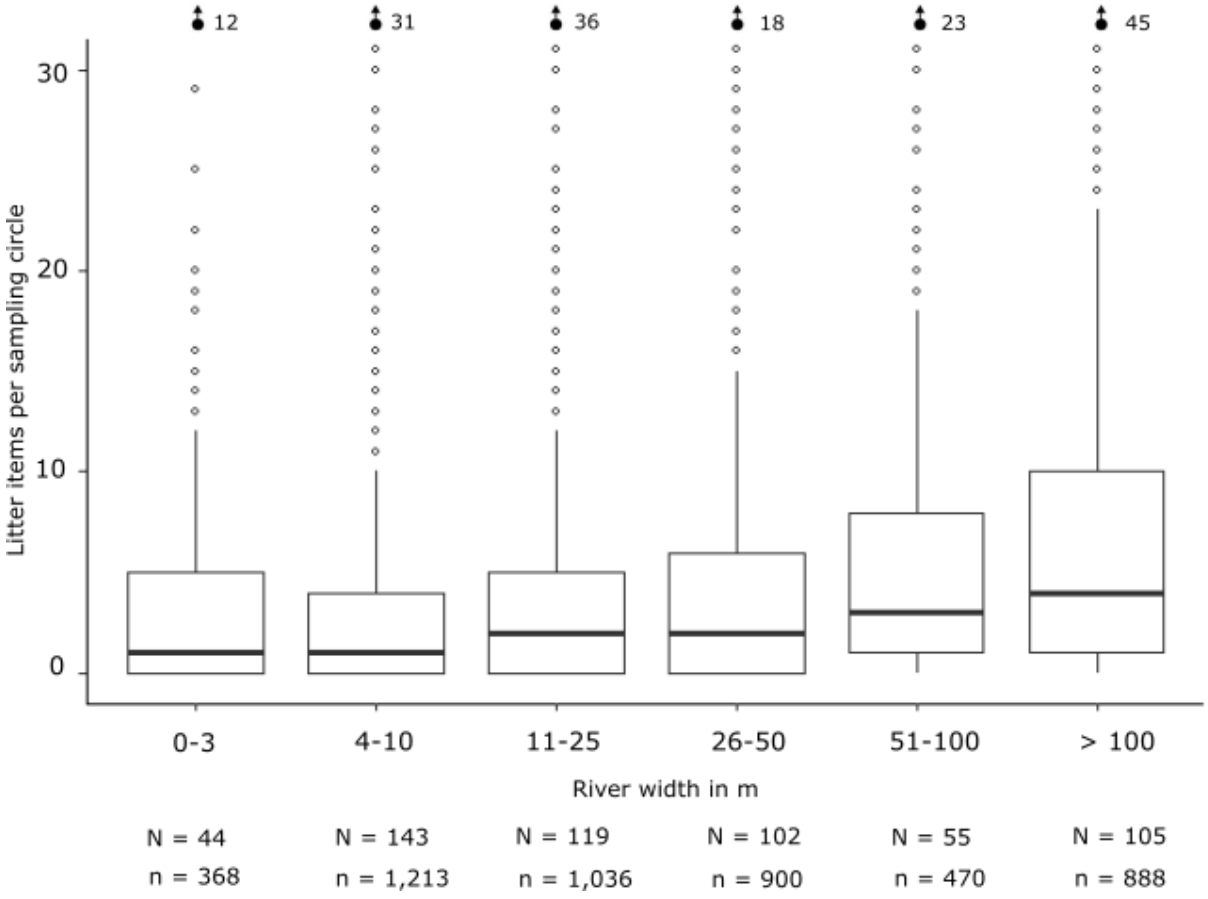

Figure 4.5: Median litter densities per sampling circle per river widths category considered for all sampling campaigns. Outliers are represented by dots, the number of outliers exceeding the

scale of the boxplot are shown next to the black arrows. N = number of sites considered for the analysis, n = number of sampling circles considered.

4.4.3 Inference of litter sources

There were significant differences between the litter sources inferred by the schoolchildren across all sampling campaigns and river systems (Kruskal-Wallis rank sum test, df =9, X^2 =1623.6, *p*-value < 0.05, Fig. 4.6). However, overall groups on all riversides considered visitors using the river for recreation as the most likely source of local litter pollution (~92 % of all groups, calculated across all sampling campaigns and riversides), followed by local residents (~49 % of all groups), litter deposited by the river itself (~43 % of all groups), and litter dumped illegally on the riverside (~31 % of all groups). Less frequently mentioned by the schoolchildren were sources of litter from shipping traffic, agricultural litter and fishing waste. This pattern has been evident throughout all sampling campaigns (Supplement B7).

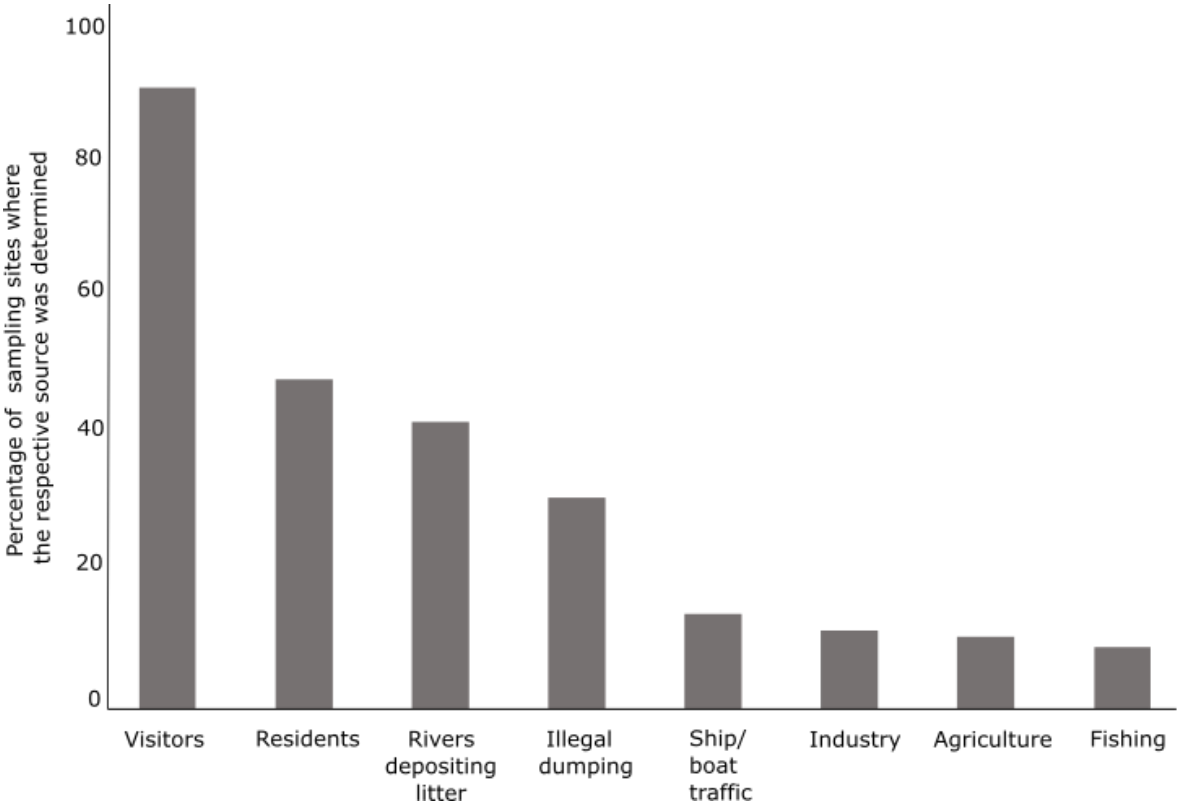

Figure 4.6: Number of sampling sites (in %) where the potential litter source was determined calculated over all sampling campaigns. The schoolchildren were able to indicate more than one possible litter source as probable (N = 812 data sets considered). The sources "agriculture" and "fishing" were only recorded since fall 2020.

4.5 Discussion

4.5.1 Citizen scientists contributing to litter research

The collection of data on the litter pollution of rivers and beaches by citizen scientists has increased in recent years (Rech et al., 2015; Hidalgo-Ruz et al., 2018; Kiessling et al., 2019; van Emmerik et al., 2020; Ballerini et al., 2022; de Veer et al., 2023). A study by Zettler et al. (2017) has shown that the quality of data taken by citizen scientists is comparable to that of data collected by professional scientists. In order to ensure rigorous data quality, the participants (in this case teachers and schoolchildren) need to be well prepared for sampling. Because of this, a continuous communication between the program team and teachers before, during and after sampling is essential to minimise potential errors (de Vries et al., 2019; Dittmann et al., 2023; Thiel et al., 2023). However, the quality of data collected by citizen scientists is often critically scrutinised, making verification procedures necessary to ensure high data quality (Kosmala et al., 2016; Swanson et al., 2016; Kiessling et al., 2019).

In order to be able to use the collected data, a comprehensive verification of the data was performed. About 42 % of the data were rejected, mostly due to missing photos. This is similar to the rate of rejection that Kiessling et al. (2019) presented in their study based on data from the Plastic Pirates campaigns of 2016 and 2017. The reasons for this were, based on communication with the teachers, mainly related to organisational issues, for example problems with uploading photos to the program's website or the time lag between receiving the data and the request for missing information by the program team due to the large number of participating groups (Kiessling et al., 2019; Dittmann et al., 2022).

Overall, data verification was conducted according to the scheme outlined by Kiessling et al. (2019). Data were rejected as soon as there were larger discrepancies between the submitted data table and the respective photos or when photos were missing (see method section of this manuscript and supplemental material of Kiessling et al., 2019).

4.5.2 Spatial and temporal patterns of macrolitter on the riverside

This study compared litter densities among subsequent sampling campaigns, and river systems over a seven-year period by using a collaborative citizen science approach. Overall, there were no significant differences in litter densities across river systems but across the sampling campaigns, however with no clear trend over the program's lifetime. This is consistent with the results of river litter studies considering different years and a very similar sampling protocol (Honorato-Zimmer et al., 2021), which also found no major differences in litter

densities between the two sampling periods. Similarly, other studies showed that there was variation in litter densities but no clear trend: A study by Schmidt et al. (2017), which used a data set from many different rivers over time, found that there was no temporal trend in densities of floating litter (large and small). Nelms et al. (2020) highlighted a number of reasons for the lack of temporal variation in litter densities recorded on UK coastlines over a 25-year period, e.g. that the amount of litter has changed only slightly over the time period studied and may represent a "real-world" situation, and that the detection of an overall trend is difficult due to the local dynamics (such as the transportation of litter by wind and currents) prevailing at each study site. This leads to the conclusion that despite the enactment of legislation addressing plastic litter (Burgess et al., 2021; Beghetto et al., 2023), no significant decrease in litter densities has been observed over the years. Our results suggest a similar pattern for litter found on riversides. This may be because existing single-use products can still be sold even though production was forbidden, so a decreasing trend might only become evident in the next few years.

Another possible reason for the lack of a clear trend in litter densities is that the litter covered by the legislation represents only a fraction of the litter found in the environment (Kiessling et al., 2023). Significant variability was also found in litter densities between seasons. Although the median litter densities were equal for both seasons, the hurdle model showed significant differences, and the posthoc test revealed slightly higher mean litter densities for the spring campaigns. The spring campaign samplings generally cover time periods where more recreational visitors would be expected at riversides (May through July), though in autumn it could be the case that litter accumulated during summer season would still be present. Litter items found during spring campaigns could also have a wider distribution or contain more outliers, which could increase the mean value but does not affect the median values.

Other factors such as weather conditions, local currents, on-site litter management and cleaning intervals, and the topography could vary from place to place, making it difficult to identify variabilities in litter densities (Nelms et al., 2020). This information was not collected by the participants in the present study, as it would have exceeded the time frame and acceptable complexity of data collection that is suitable for schoolchildren. In addition, the study design allowed flexibility for teachers and schoolchildren to determine sampling sites and dates themselves. This made it challenging to compare data over time, as sampling sites were rarely sampled twice. The freedom in choosing sampling sites led to a widely dispersed distribution of data all over Germany. As Schneider et al. (2021) have noted in their study, this approach

led to a large number of valuable snapshots of litter pollution on the riversides of large and small rivers but has limitations regarding comparability.

Another factor limiting the comparability of litter densities on riversides with the results from other studies relates to the fact that existing methods for assessing macrolitter vary widely (e.g. in terms of sampling duration or number of assessed sampling sites, van Emmerik et al., 2020; Vriend et al., 2020; Al-Zawaidah et al., 2021). However, several studies have recorded the densities of litter on riversides within Europe (Schöneich-Argent et al., 2019; van Emmerik et al., 2020; Cesarini and Scalici, 2022; Kiessling et al., 2023) and outside Europe (Rech et al., 2015; Honorato-Zimmer et al., 2021), considering a similar methodology and therefore allowing for direct comparisons. For example, the study by Honorato-Zimmer et al. (2021) investigated the macrolitter pollution of riversides in Chile and showed a higher overall median litter pollution of 0.99 litter items m^{-2} compared to our results (overall median of 0.28 litter items m^{-2}). The reason for this could be the different levels of waste management and reduction in the respective countries (see also Honorato-Zimmer et al., 2019).

In our study, the Rhine and Danube river systems had higher median litter densities than other river systems that flow into the Elbe, Weser, and smaller rivers discharging into the Baltic- and North Sea. These results are not consistent with a study by Schöneich-Argent et al. (2020), which showed a higher litter pollution level for riversides at the Elbe river system compared to those of the Weser river system (Schöneich- Argent et al., 2020). Once again, these findings demonstrate the difficulty of identifying a clear trend in litter pollution, even at spatial scale.

In future studies, participating schools could be encouraged to focus on predefined river systems in order to collect spatially condensed data and thus obtain a higher spatial resolution. In addition, the analysis of hydro-meteorological data, e.g. on extreme weather events with high surface runoff and floods, which occurred immediately before the sampling and could lead to leakage, mobilisation, and transport of macrolitter, would provide further useful information on litter density and distribution patterns (Roebroek et al., 2021; Tramoy et al., 2022; van Emmerik et al., 2022c). In addition, it would be interesting to assess anthropogenic factors and the surrounding infrastructure (e.g. the presence of dams, weirs or locks and the type of land use, Palmas et al., 2022) or discharges from settlements and urban areas into the river via stormwater and drainage systems (Tramoy et al., 2022; Wei et al., 2023) in order to predict the spatial distribution of riverine litter more precisely.

4.5.3 Transport dynamics of macrolitter in rivers of different width

For the development of effective litter reduction measures, a comprehensive knowledge of the transport dynamics of macrolitter in rivers is crucial (Roebroek et al., 2021). Here we found significantly higher litter densities in the wider (usually lower) sections of rivers across all sampling campaigns, while densities in the narrower (upper) sections were comparably low. This could suggest that litter from upstream sources has been repeatedly mobilised from the riverside and accumulated in the wider downstream river sections. This assumption is not consistent with the most frequently occurring litter items per river width category found in this study—namely, glass shards and cigarette butts—which aligns with the findings by the schoolchildren, suggesting that most litter on the riverside originated from river visitors. Those non- or short term-buoyant litter items are mainly deposited directly on the riverside due to direct dumping and are rarely transported along the course of the river (Bravo et al., 2009; Rech et al., 2014). However, seasonal effects appear to influence how far litter is transported within rivers, with longer travel distances occurring especially during spring and fall due to heavy rainfall events, stronger winds, and wave action (Castro-Jiménez et al., 2019; Schöneich-Argent et al., 2020). This seasonal pattern was also confirmed in a study by Rieger et al. (2024), which found a significantly higher level of riverine induced pollution on beaches along the coasts of NW Europe (including the North Sea) during the winter and spring months.

This illustrates that rivers can temporarily act as reservoirs for litter, but that this litter can be remobilised and transported into coastal areas. Although the schoolchildren considered the deposition by the river itself as low, this factor might be responsible for substantial transport of macrolitter during runoff events, as schoolchildren rarely sampled on the riverside when the water level was high (e.g., during/after storms).

Several studies had already highlighted the discharge of litter from rivers into the oceans (Galgani et al., 2000; Lebreton et al., 2017; González-Fernández et al., 2021), but there is still no clear evidence that a large proportion of riverine litter is transported into the North or Baltic Sea (Thiel et al., 2011; Schöneich-Argent et al., 2020; Schernewski et al., 2024). A study by Thiel et al. (2011) suggested that most of the litter in the North Sea comes from shipping, which may obscure the input of riverine litter. Schöneich-Argent et al. (2020) also found that large proportions of litter are retained in rivers, with only litter discharged near river mouths reaching the North Sea. Similar findings were reported by Schernewski et al. (2024) for the Warnow river system, which discharges into the Baltic Sea, showing that large proportions of macrolitter are retained within a few kilometers of their entry points. However, the input of plastic litter from rivers into the oceans depends on many factors, such as runoff dynamics and river

characteristics (van Emmerik and Schwarz, 2020). In general, it could be hypothesized that small rivers and tributaries often have weirs that prevent macrolitter from reaching the ocean. Larger rivers, such as the Rhine, Danube, Elbe, or Weser, have fewer weirs in their wider downstream sections, allowing greater quantities of litter to be transported and ultimately discharged into the ocean.

Blettler et al. (2017) purposefully sampled during summer months, as this period attracts a higher number of tourists and visitors. It could therefore be assumed that wider rivers easily accessible to tourists are visited more frequently during spring and summer months, which in turn leads to higher densities of litter during this time, as in line with the presented study (as well as with Kiessling et al., 2019). Many riversides accessible to recreational visitors in Germany typically have litter management infrastructure in place and are regularly cleaned during spring and summer months, which in turn can lead to a biased representation of the litter quantities on the riverside. These patterns suggest increased litter input in spring and summer, and remobilization in winter due to run-off events (van Emmerik et al., 2023; Vriend et al., 2023), complicating the identification of a clear annual trend. This aligns with our findings, which show only slight seasonal differences in litter quantities.

4.5.4 Litter composition and potential sources

The results of this study were consistent with those of other studies on the composition of litter on riversides, where plastic items and cigarette butts dominated (Castro-Jiménez et al., 2019; van Emmerik et al., 2020; Ballerini et al., 2022; Ergas et al., 2024). Large proportions of cigarette butts, glass, domestic macrolitter and food packaging indicate that individual households or visitors are responsible for the majority of the litter, which would be consistent with the schoolchildren's findings, as their assumptions showed that river visitors are responsible for the majority of the litter found on riversides. This is consistent with the results of other studies (Rech et al., 2015; McCormick and Hoellein, 2016) and agrees with the findings by Kiessling et al. (2019), suggesting that the source of litter has not changed over the years.

However, it is critical to note that our data may reflect a biased reality, as teachers were more likely to visit riversides that are easily accessible with schoolchildren, making them more likely to be frequented by river visitors as well (Williams and Simmons, 1999). Other possible sources for which the riverside was examined by the schoolchildren, such as litter items from ship traffic, fishing, industry or agriculture were considered as less likely by the schoolchildren.

These results underscore the necessity of mitigation measures, particularly on heavily frequented riversides. Consequent political action has been largely absent; for instance, plastic litter pollution is still not addressed in transnational directives of the European Union, such as the Water Framework Directive (WFD 2000/60, Gallitelli et al., 2020). A global strategy that includes both practical and measurable interventions to reduce plastic pollution is still lacking and there is an urgent need for comprehensive political action (Lau et al., 2020), specifically including legislation to reduce the production of (single-use) plastics.

4.6 Conclusions and outlook

Our study identified > 25,000 macrolitter items, predominantly plastic and cigarette butts, with a median litter density of 0.28 items m^{-2}. The amount of litter has not decreased or increased substantially over the past seven years. A relationship between higher levels of litter and wider rivers suggests that the accumulation of litter is occurring in downstream sections of rivers. Our findings also indicate that most macrolitter on riversides originated from visitors. The fact that macrolitter remains prevalent on nearly all sampled riversides (~92 %) and that this trend has not decreased over the years underlines the importance of further efforts, particularly at the political level. The involvement of citizen scientists in collecting data on litter pollution along rivers offers an opportunity to gather broad-scale data while making the problem of anthropogenic and especially plastic litter pollution tangible for citizens and schoolchildren.

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Chapter 5: Die Plastikpiraten – Ein Citizen Science-Projekt zur Erforschung der Müllverschmutzung von deutschen Flüssen

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5.1 Zusammenfassung

Die „Plastikpiraten“ sind ein Citizen Science-Projekt zur Erforschung der Müllverschmutzung deutscher Fließgewässer. Bundesweit werden Jugendliche in den wissenschaftlichen Forschungsprozess integriert, indem sie an Flüssen Daten zur Müllverschmutzung erheben. Diese werden anschließend von Wissenschaftlerinnen und Wissenschaftlern ausgewertet und in Fachzeitschriften publiziert.

5.1.1 Kompakt

- Citizen Science
- Müllverschmutzung an Flüssen
- Scientific Literacy

5.2 Hintergrund und Ziele des Projektes

Seit Mitte des letzten Jahrhunderts ist die weltweite Plastikproduktion stark angestiegen (Andrady 2011). Während im Jahre 1950 die Kunststoffproduktion jährlich 1.5 Millionen Tonnen weltweit umfasste, ist sie bis zum Jahre 2016 auf 322 Millionen Tonnen gestiegen – mit weiter steigender Tendenz für die kommenden Jahre (Geyer et al., 2017). Als Kunststoffe werden synthetische oder halbsynthetische Polymere definiert, deren Ausgangsmaterial häufig Rohöl ist. Sie zeichnen sich durch Eigenschaften wie Stabilität, geringes Gewicht, Bruchfestigkeit und chemische Beständigkeit aus (Li et al., 2016). Aufgrund dieser vielfältigen Charakteristika werden Kunststoffe für die Herstellung diverser Produkte genutzt und haben bereits eine Vielzahl an technischen Innovationen und Fortschritten ermöglicht (Andrady und Neal 2009). Dabei stellt die Beständigkeit von Kunststoffen eines der größten Probleme dieses Materials dar: Einmal in die Umwelt eingetragen, verbleiben Kunststoffe dort häufig über Jahrhunderte. Seit Jahren in der öffentlichen Aufmerksamkeit stehen dabei besonders Kunststoffeinträge in den Ozean.

Kunststoffe werden über vielfältige Pfade in den Ozean eingetragen. Nach Andrady 2011 haben 80 % des in die marine Umwelt eingetragenen Kunststoffs ihren Ursprung an Land und werden u. a. über Flüsse, die Atmosphäre oder direkt vom Strand durch Winde, Starkniederschläge oder Wellen in den Ozean eingetragen. Zu einem geringeren Anteil entsteht der Müll direkt auf dem Ozean, beispielweise durch Aquakulturen, die Schifffahrt oder Fischerei (Lebreton et al., 2017). Globale Modelle schätzen, dass jährlich bis zu 2,4 Millionen Tonnen Plastikmüll über Flüsse in den Ozean eingetragen werden (Lebreton et al., 2017). Die

Donau trägt jährlich beispielsweise bis zu 1500 Tonnen an Plastik in das Schwarze Meer ein, der Rhein bis zu 31 Tonnen in die Nordsee (Lebreton et al., 2017). Während erste Studien annahmen, dass große Flüsse aus Asien und Afrika bis zu 67 % des totalen Müllanteils ausmachen, wurde in aktuelleren Studien nachgewiesen, dass kleinere Flüsse ebenfalls relativ große Mengen an Plastikmüll in den Ozean transportieren können (Lebreton et al., 2017). Aufgrund dessen ist eine umfassende Betrachtung von möglichst vielen Flusssystemen notwendig, um Aufschlüsse über die Abundanz und Zusammensetzung des Mülls in Flüssen und an Flussufern zu erhalten.

Im Rahmen des Projekts „Plastikpiraten – das Meer beginnt hier“, gefördert vom Bundesministerium für Bildung und Forschung (BMBF), erheben Jugendliche Daten zur Müllverschmutzung an deutschen Flüssen. Das Projekt wurde 2016 im Rahmen des BMBF-Wissenschaftsjahrs „Meere und Ozeane“ ins Leben gerufen und wird aktuell im Rahmen der EU-Trio-Ratspräsidentschaft von Deutschland, Portugal und Slowenien unter dem Titel „Plastic Pirates – Go Europe!“ durchgeführt. Koordiniert wird das Projekt in Deutschland durch die Kieler Forschungswerkstatt (das Schülerlabor der Christian-Albrechts-Universität zu Kiel und des Leibniz-Instituts für die Pädagogik der Naturwissenschaften und Mathematik) und das Ecologic Institut. Seit Beginn des Projektes im Frühjahr 2016 haben über 15.000 Jugendliche, gemeinsam mit Lehrkräften und Jugendgruppenleitungen, an über 900 Standorten Flüsse und Bäche in ganz Deutschland auf ihre Verschmutzung durch Müll, insbesondere Plastik, untersucht (Abbildung 5.1). Das Ziel des Projektes besteht zum einen in der weiträumigen, wissenschaftlichen Erfassung der Müllverschmutzung an Fließgewässern sowie der Identifizierung von möglichen Müll-Hotspots. Neben den wissenschaftlichen Erkenntnissen geht es jedoch auch um die Förderung einer *Scientific Literacy*, d.h. die Förderung des wissenschaftlichen Verständnisses sowie die Steigerung des Interesses von Jugendlichen an den Naturwissenschaften. Auf Grundlage eines Citizen-Science-Ansatzes werden den Teilnehmenden Einblicke in wissenschaftliche Denk- und Arbeitsweisen ermöglicht, wie z. B. das Erstellen von wissenschaftlichen Fragestellungen und das Erheben und Auswerten von wissenschaftlichen Daten (Dickinson et al., 2010). Citizen Science, auch bekannt als Bürgerwissenschaften, bietet die Chance, innerhalb kurzer Zeit umfangreiche, räumlich verteilte Datenmengen zu erheben, welche unter herkömmlichen Forschungsansätzen lediglich mit erheblichem Zeit- und Ressourcenaufwand erhoben werden könnten. Damit ergibt sich durch Citizen Science die Möglichkeit der transparenten Gestaltung von Forschungsabläufen, was wiederum zur Stärkung des Vertrauens in wissenschaftliche Studien führt (Aivelo und Huovelin 2020). Einige der bestehenden Citizen Science-Projekte richten sich im Rahmen von

Schul- oder außerschulischen Lehr-/Lernangeboten an Jugendliche und ermöglichen eine handlungsorientierte Vermittlung von Fachwissen und Einblicke in transdisziplinarische Forschungsabläufe (Kruse et al., 2020). Nicht zuletzt werden die Jugendlichen hinsichtlich des Themas Nachhaltigkeit und ihres eigenen Konsumverhaltens sensibilisiert, wodurch eine langfristige Veränderung des eigenen Handelns initiiert werden könnte.

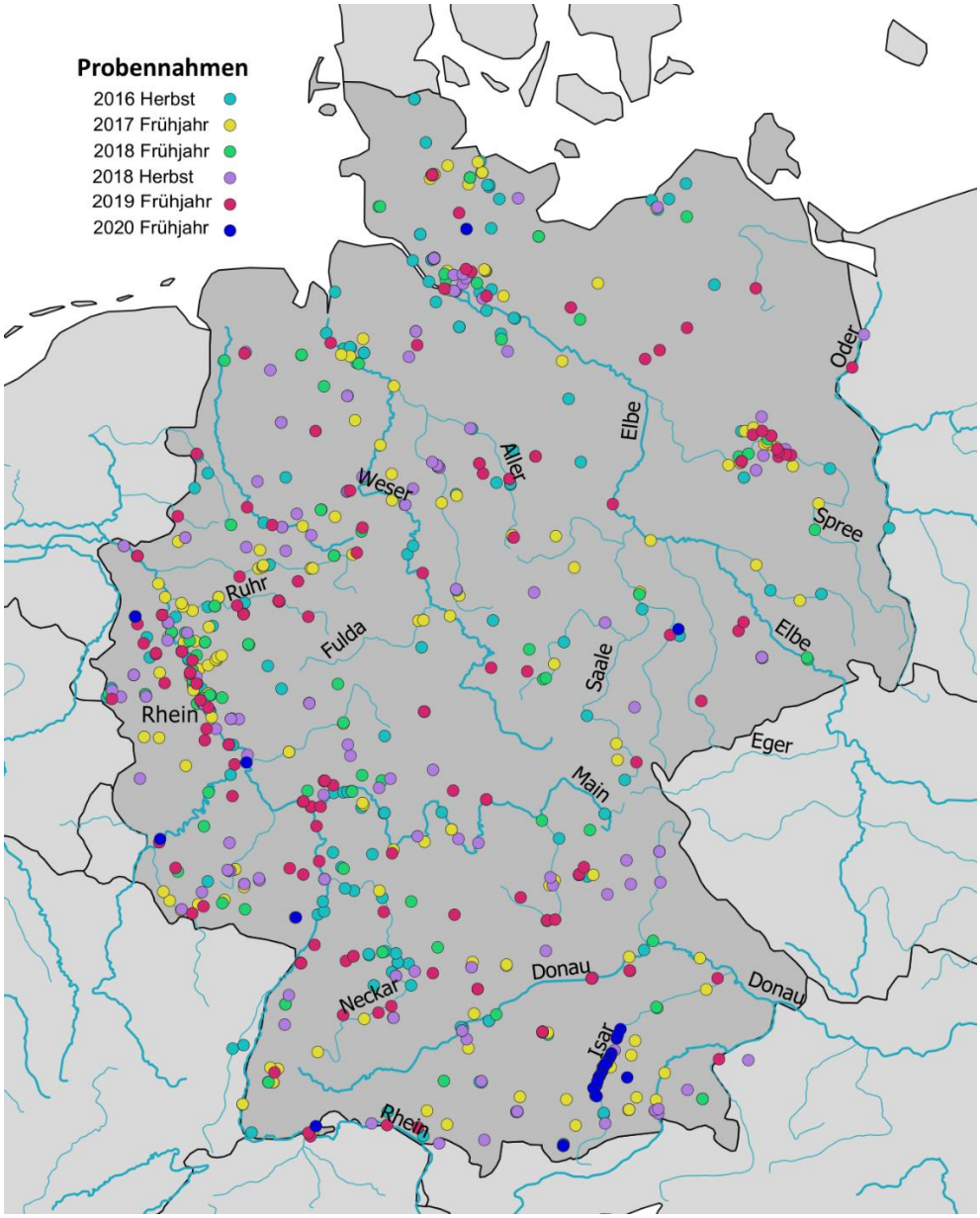

Abbildung 5.1: Beprobungsstandorte der Jahre 2016 bis 2020. Quelle: Kieler Forschungswerkstatt

5.3 Methodik

Um die wissenschaftliche Vergleichbarkeit der erhobenen Daten gewährleisten zu können, ist ein standardisiertes Vorgehen während der Datenerhebung von großer Wichtigkeit (Kosmala et al., 2016). Entsprechend wurden im Rahmen des Projektes Aktionsmaterialien für Lehrerkräfte und Schülerinnen und Schüler erstellt, in denen die Durchführung und Auswertung der jeweiligen Probennahmen detailliert angeleitet werden. Ergänzend hierzu werden Webinare und Workshops für Lehrkräfte angeboten, in denen das Vorgehen der Probennahme von Wissenschaftlerinnen und Wissenschaftlern erklärt wird. Insgesamt bestehen in dem Projekt vier verschiedene Gruppen der Datenerhebung, die von den teilnehmenden Jugendlichen zur Erfassung der Müllverschmutzung durchgeführt werden. Durch die Aufteilung der Datenerhebung in Kleingruppen wird die Komplexität der Probennahme je Gruppe geringgehalten, wodurch mögliche Fehler während der Datenerhebung reduziert werden (Kosmala et al., 2016). Alle Ergebnisse werden fotografisch festgehalten und anhand der Fotos später durch die Kieler Forschungswerkstatt verifiziert.

5.3.1 Müll am Flussufer (Gruppe 1)

Um Aufschlüsse über die Abundanz und Zusammensetzung des Mülls je Quadratmeter Flussufer zu erhalten, wird eine Transekt-Kartierung entlang des jeweiligen Flussufers durchgeführt. Auf einer Strecke von 50 m werden von den Jugendlichen zufällig drei Transekte mit jeweils drei Beprobungen untersucht. Das Flussufer wird hierfür in drei Zonen unterteilt. Diese umfassen den Flussrand (regelmäßiger Kontakt zum Fluss), die Flussböschung (unregelmäßiger Kontakt zum Fluss) sowie die Flusskrone (kein Kontakt zum Fluss). Die Transekte umfassen jeweils alle drei Uferzonen, sodass in jeder Uferzone eine Beprobung von den Jugendlichen durchgeführt wird. Hierfür werden kreisförmige Segmente erstellt (a ~ 7 m^2), in welchen der vorgefundene, sichtbare Müll klassifiziert und quantifiziert wird.

5.3.2 Müllvielfalt am Flussufe (Gruppe 2)

Des Weiteren analysieren die Jugendlichen, wie sich der Müll im Detail entlang des Flussufers zusammensetzt und zu welchem Anteil Einwegplastikartikel in dem gefundenen Müll zu finden sind. 2021 wird innerhalb der Europäischen Union ein Verbot für bestimmte Einweg-Plastikartikel eingeführt, basierend auf Funden von Einwegplastikartikeln an Stränden. Um Aufschlüsse darüber zu erhalten, ob diese Artikel auch an Flussufern zu finden sind und

wie viel Einwegplastik sich dort insgesamt befindet, begeben sich die Jugendlichen auf die Suche nach diesen Plastikobjekten. Zum Sortieren des Mülls werden von den Jugendlichen im Vorfeld Müllsortierstationen errichtet. Zum Sammeln des Mülls wird von den Jugendlichen das gesamte Flussufer abgesucht, bis zu einer Entfernung von maximal 20 m vom Fluss. Anschließend wird die abgesuchte Fläche entlang des Flusses vermessen. Der kategorisierte Müll wird im letzten Schritt quantifiziert, gewogen und der jeweilige prozentuale Anteil berechnet.

5.3.3 Treibender Müll (Gruppe 3)

Während in den zwei vorherigen Gruppen die Jugendlichen die Müllverschmutzung am Flussufer untersuchten, fokussieren sich die Teilnehmenden dieser Gruppe auf die Makro- und Mikroplastikverschmutzung im Fluss. Mithilfe eines speziell angefertigten Probennahme-Netzes (Maschenweite = 1 mm), wird der Fluss auf Mikroplastikverschmutzung an der Wasseroberfläche beprobt. Das Netz wird von den Jugendlichen von einem erhöhten Standort aus für eine Stunde in den Fluss eingelassen. Nach Ablauf der Zeit wird das Netz eingeholt und das Probenmaterial vollständig aus dem Netz entfernt (Abbildung 5.2). Die gesamte Probe wird für die Identifizierung der gefangenen Partikel mittels FTIR-Spektroskopie in das Labor der Kieler Forschungswerkstatt gesendet.

Um die Mikroplastikverschmutzung in der Auswertung einordnen zu können, wird von den Jugendlichen ebenfalls die Fließgeschwindigkeit des Flusses gemessen. Hierfür wird auf einer Distanz von 20 Metern ein Gegenstand (z. B. ein Stöckchen) in den Fluss geworfen und die benötigte Zeit zum Zurücklegen der Strecke gemessen.

Des Weiteren erfassen die Jugendlichen die Menge an Makromüll, der auf der Flussoberfläche treibt, indem für eine Dauer von 60 Minuten der vorbeitreibende Müll fotografiert und von den Jugendlichen identifiziert und quantifiziert wird.



Abbildung 5.2: Jugendliche des Ferienprogrammes der Förde Volkshochschule Kiel bei der Leerung des Probennahme-Netzes. Quelle: Kieler Forschungswerkstatt.

5.3.4 Reporterteam (Gruppe 4)

Um potentielle Müllquellen in der unmittelbaren Umgebung des Flusses zu identifizieren, suchen Jugendliche des Reporterteams nach Hinweisen wie beispielsweise überfüllte Mülltonnen, eingeleitete Abwässer oder Picknick-Reste. Ebenfalls diskutieren die Teilnehmenden über mögliche Ereignisse, wie größere Veranstaltungen oder Extremwetterereignisse, die zu der Verschmutzung vor Ort beigetragen haben könnten, interviewen Personen vor Ort und veröffentlichen nach Möglichkeit einen Bericht der Probennahme auf der Webseite Ihrer Schule.

5.4 Ergebnisse

Ein Großteil der teilnehmenden Jugendlichen erforschte den Rhein mit seinen Nebenflüssen, gefolgt von den Flusssystemen Elbe, Weser und Donau. Es wurden jedoch auch kleinere Fließgewässer wie die Ems, Peene oder Oder von den Jugendlichen beprobt. Die erhobenen Daten werden auf einer gemeinsamen Projektwebsite gesammelt und auf einer Karte dargestellt (Plastic Pirates-Go Europe! 2021). Zur Auswertung des Mülls am Flussufer wurden 513 Standorte von den Jugendlichen beprobt. Insgesamt identifizierten die Plastikpiraten

11.712 Müllteile auf 32.097 Quadratmetern Uferfläche. Im Schnitt also 0,36 Müllteile pro Quadratmeter. Zwischen den Flusssystemen gibt es allerdings Unterschiede: an Elbe und Rhein wurde mehr Müll gefunden, an der Donau und Weser hingegen weniger. Der gesammelte Müll wurde nach Material ausgewertet, dabei kamen Plastikartikel und Zigarettenkippen am häufigsten vor (Abbildung 5.3).

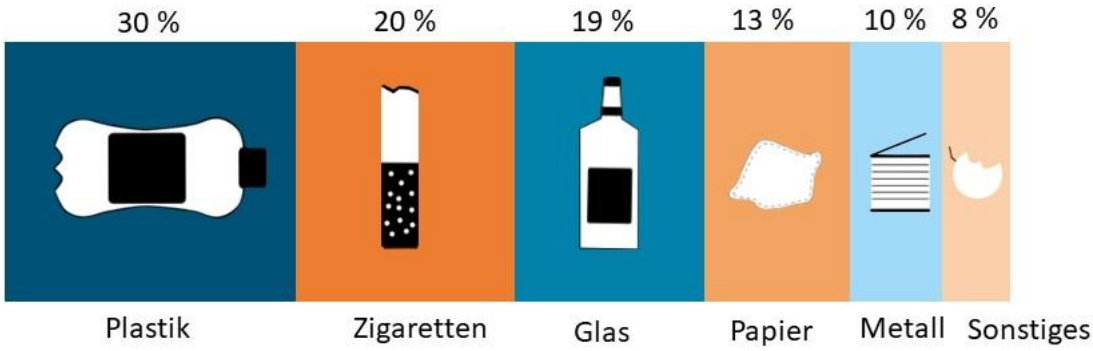

Abbildung 5.3: Zusammensetzung des Mülls, welcher am Flussufer während der Jahre 2016 bis 2020 von den Jugendlichen gefunden wurde. Quelle: Kieler Forschungswerkstatt.

Um genauere Informationen zur Müllzusammensetzung sowie zum Anteil des Einwegplastiks am Flussufer zu generieren, wurden von den Jugendlichen 130 Standorte untersucht und 26.974 Müllteile entlang des Flussufers gesammelt und identifiziert. Hiervon bestanden 16 % aus Einwegplastik, wie Süßigkeiten-Verpackungen oder Plastiktüten. Plastikflaschen, Becher und Einwegbesteck machten ca. 5 % des insgesamt gefundenen Einwegmülls am Fluss aus. Häufiger wurden Zigarettenkippen (33 % des insgesamt gefundenen Mülls), und Glasscherben (21 %) gefunden. Auch Papier (13 %) und Kronkorken (9 %) waren bei zahlreichen Funden dabei.

Um zu identifizieren, wie viele große Müllteile auf der Flussoberfläche treiben, wurden Daten von 520 Standorten analysiert. Insgesamt wurden 1.354 Teile gesichtet, welche normalerweise nicht in saubere Fließgewässer gehören. Unter Berücksichtigung der vorgegebenen Beobachtungszeit trieben im Durchschnitt etwa 3 Müllteile in der Stunde vorbei. Zur Ermittlung der Menge an Mikroplastik (Partikel größer 1 mm wurden berücksichtigt) haben 494 Gruppen die Probennahme durchgeführt. Nach erster Analyse durch die Schulklassen und Jugendgruppen meldeten 32 % der Gruppen Mikroplastik in ihren Proben. Es gab jedoch auch Gruppen, deren Proben hunderte Mikroplastikpartikel enthielten, wie z. B. eine Probe aus der Rur (auch Eifel-Rur), einem 164 km langer Nebenfluss der Maas, oder eine Probe aus der Nähe von Schkopau (Abbildung 5.4), mit über 200 Plastikpartikeln.

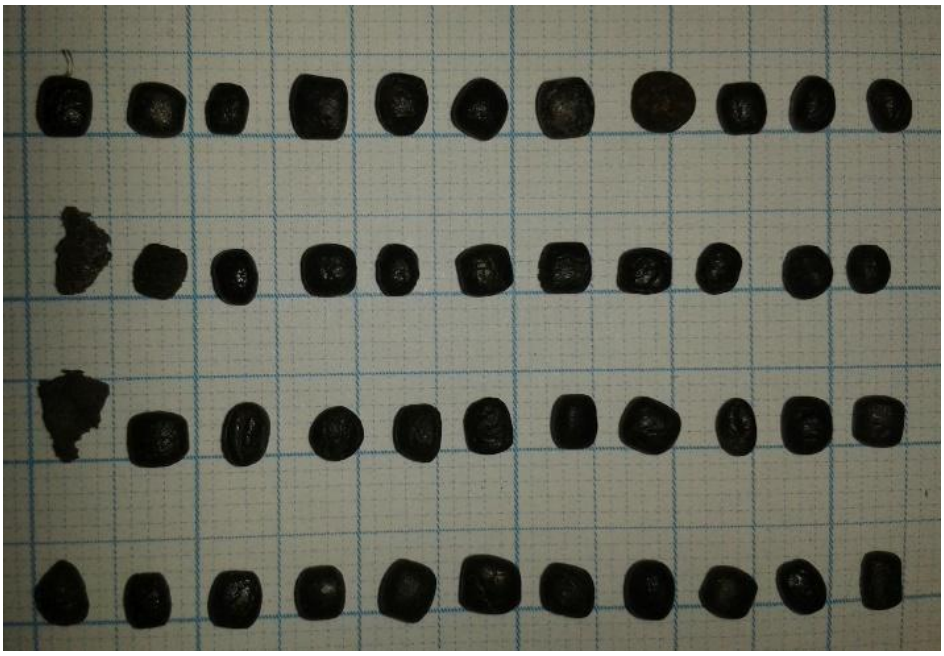

Abbildung 5.4: Mikroplastik aus der Laucha (Flusssystem Elbe). Quelle: Kieler Forschungswerkstatt

Laut den Teilnehmenden verursachen Flussbesucherinnen und Flussbesucher den meisten Müll. Diese wurden an 88 % der 490 Standorte, für die eine Bewertung von Müllquellen durchgeführt wurde, als wahrscheinliche Quelle identifiziert. Diese Bewertung basiert auf der großen Anzahl von vorgefundenen Lebensmittelverpackungen, Zigarettenkippen und Überresten vom Picknicken und Grillen (z. B. Plastikbesteck, Plastiktüten, zurückgelassene Grills und Grillkohle). Anwohnerinnen und Anwohner wurden an 41 % der Standorte als wahrscheinliche Müllquelle identifiziert, gefolgt von Müll, der in den Fluss gelangt ist und dann wieder angeschwemmt wurde (30 %), illegal abgeladenem Müll (28 %) und durch Schiffs- und Bootsverkehr entstandener Müll (13 %). Industriequellen wurden von 9 % der Gruppen als potentielle Müllquelle identifiziert. Da diese Einschätzung oft subjektiv ist, wurden von den Kindern und Jugendlichen Fotos gemacht, damit die Quelle der Verschmutzung auf Plausibilität überprüft werden kann.

5.5 Diskussion und Fazit

Im Rahmen des Projekts Plastikpiraten konnten bereits umfassende Erkenntnisse über die bundesweite Abundanz und Zusammensetzung der Müllverschmutzung von Fließgewässern gewonnen werden. So zeigt sich, dass in Deutschland besonders die Flussufer der Elbe und des Rheins verschmutzt sind. Der größte Anteil an gefundenem Müll besteht aus Zigarettenkippen und Plastik. Kleine Mikroplastikpartikel konnten von den Jugendlichen in

32 % ihrer Proben identifiziert werden. Hierbei sollte bedacht werden, dass für die Probennahme lediglich großes Mikroplastik berücksichtigt wurde, also Partikel, die größer als 1 mm sind. Viele der in der Umwelt eingetragenen Mikroplastikpartikel sind jedoch deutlich kleiner und konnten somit nicht durch das Probennahme-Netz erfasst werden. Des Weiteren gibt es Plastiktypen, die aufgrund ihrer spezifischen Dichteeigenschaften im Wasser sinken und somit ebenfalls nicht von dem Probennahme-Netz erfasst werden konnten. Mit Blick auf den gefundenen Müll am Flussufer konnten Flussbesucherinnen und Besucher als Hauptmüllquelle von den Jugendlichen ausgemacht werden. Erste Ergebnisse der Plastikpiraten konnten bereits in einer wissenschaftlichen Fachzeitschrift publiziert werden und wurden somit für die Wissenschaftsgemeinschaft zugänglich gemacht (Kiessling et al., 2019).

Auf Grundlage der Ergebnisse lassen sich bereits Vorschläge ableiten, wie die Müllverschmutzung an Flüssen reduziert werden kann. Ein erster Schritt könnte die Implementierung einer entsprechenden Infrastruktur vor Ort sein, wie das Aufstellen von Abfallbehältern oder Aschenbechern an hochfrequentierten Flussufern (Kiessling et al., 2019). Darüber hinaus könnte das von der Europäischen Kommission eingeführte Verbot bestimmter Einwegplastikprodukte ab dem Sommer 2021 dazu beitragen, die Menge des Einwegsmülls in der Umwelt und somit auch am Flussufer zu reduzieren. Eine Mehrwegförderung von Seiten der Politik ist jedoch zentral, damit Einwegplastikprodukte nicht durch Einweg-Produkte aus anderen Materialien ersetzt werden (European Commission).

Citizen Science bringt nicht nur Vorteile, sondern ebenso Herausforderungen mit sich. So ist die Sicherstellung der Qualität der Daten von enormer Relevanz, damit diese in der Forschungsgemeinschaft akzeptiert werden. Der Grund hierfür liegt in den meisten Fällen in dem geringen Vertrauen in die Qualität der Daten, da diese durch nicht ausgebildete Personen erhoben wurden. Wissenschaftliche Studien belegen jedoch, dass die Fehlerquote von Daten, die durch Citizen Science erhoben wurden, eine ähnliche ist, wie die von professionell-wissenschaftlich erhobenen Daten (Zettler et al., 2017). Im Rahmen der Plastikpiraten-Beprobungen wird die Datenerhebung auf mehrere Kleingruppen aufgeteilt, um die Komplexität der Datenerhebung zu minimieren und somit mögliche Fehler zu reduzieren. Des Weiteren wird während der Datenauswertung viel Aufwand in die Verifizierung der Daten gesteckt, damit eine Fehlerbelastung der Daten weitestgehend ausgeschlossen werden kann. Dies geschieht für die größeren Müllteile über Fotos, bei kleinen Partikeln erfolgt die Bestätigung auf Grundlage von spektroskopischen Analysen mithilfe eines Fourier-Transform-Infrarotspektrometers (FTIR-Spektrometer).

Die im Rahmen des Plastikpiraten-Projektes erfassten Datenmengen hätten mittels herkömmlicher Forschungsansätze nicht in diesem Umfang erhoben werden können. Als besonders herausfordernd erwies sich hierbei, ein Forschungsprojekt derart zu strukturieren, dass es wissenschaftlich korrekt und dennoch für Jugendliche durchführbar ist. Mithilfe von didaktisch aufgearbeiteten Lehr- und Lernmaterialien sowie dem Durchführen von Lehrerworkshops und Webinaren ist es jedoch möglich, Wissenschaft und Bildung zu verbinden. Das Team der Plastikpiraten steht im engen Kontakt mit den teilnehmenden Lerngruppen, um bei aufkommenden Fragen oder Unsicherheiten jederzeit für die Teilnehmenden erreichbar zu sein. Bei unvollständig hochgeladenen Datensätzen wird die Ursache bei den Gruppen persönlich erfragt, um möglichst viele komplette Datensätze zu erhalten und um bestehende Unklarheiten im Upload der Daten zu klären. Auch wenn der stetige Kontakt zu den Teilnehmenden ein hohes Maß an personellen Ressourcen benötigt, ist dieser für den Erfolg des Projektes maßgeblich.

Für zukünftige Beprobungen wird die Ausweitung auf weitere EU-Länder im Rahmen der EU-Trio-Ratspräsidentschaft angestrebt, um das Problem der Müllverschmutzung von Flüssen über nationale Grenzen hinaus zu erforschen. Wissenschaftlich sehr spannend wäre es z. B., wenn Flüsse von der Quelle bis zur Mündung von Jugendlichen aus verschiedenen Ländern untersucht werden.

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Chapter 6: Discussion

This dissertation examined the success factors for generating scientifically reliable citizen science data on riverine litter pollution, using the citizen science program Plastic Pirates as a case study. After nearly a decade of implementation as a large-scale citizen science program in Europe, the initiative has generated extensive insights into riverine litter pollution and the usage of citizen-generated data (Kiessling et al., 2019; Kiessling et al., 2021; Kiessling et al., 2023; Dittmann et al., 2022; Dittmann et al., 2023; Dittmann et al., 2024; Uogintė et al., 2024). Moreover, it has involved over 23,000 schoolchildren, contributing to environmental education, as well as the development of best practices for translating citizen-generated data into scientific outputs.

In recent years, awareness has grown about the importance of comprehensive engagement and clear communication with participants throughout the sampling process in order to generate complete, high-quality datasets. Despite this progress, concerns about data quality persist among researchers, especially when schoolchildren are involved in data collection (Gardiner et al., 2012; Kosmala et al., 2016). Consequently, robust verification measures are considered essential to improve both data reliability and the scientific credibility of findings (Hidalgo-Ruz und Thiel 2013; Dittmann et al., 2022).

To address these challenges well-structured communication and participant support strategies are required, along with comprehensive data verification measures, as demonstrated in the first two publications of this dissertation (Dittmann et al., 2022; Dittmann et al., 2023). The first publication outlines both challenges and recommendations for citizen science practitioners, offering guidance on how to structure an effective communication strategy to engage participants and ensure the collection of complete datasets for scientific analysis (Dittmann et al., 2023).

The primary goal of the Plastic Pirates was to generate high-quality data suitable to rigorously respond to relevant scientific questions about riverine plastic pollution. To achieve this, a four-step framework for data accuracy was developed, based on practical experience gained during the program, as described in the second publication of this dissertation (Dittmann et al., 2022). While the implementation of citizen science initiatives has been largely successful across a broad range of thematic areas, maintaining consistently high data quality remains an ongoing challenge. As a result, different programs on plastic pollution have adopted various strategies to address this issue: Plastique à la loupe (Philip et al., 2024) encouraged participants

to report uncertainties but lacked a systematic revision process. The Mass Experiment (Syberg et al., 2020) and Científicos de la Basura (Honorato-Zimmer et al., 2021) both checked submissions for completeness and followed up with participants as needed. In terms of data verification, Plastique à la loupe had only limited verification procedures for macrolitter, while The Mass Experiment relied on large sample sizes to compensate potential non-systematic errors, with no formal verification in place. Científicos de la Basura initially relied on data accuracy through close supervision by local scientists. However, the approach to data quality assurance was later adapted due to the widespread availability of smartphones and the ability to take photographs. In the adapted verification approach, schoolchildren took pictures of each sampling station, which were then reviewed and compared with the recorded data by a professional scientist (de Veer et al., 2023).

These variations in data verification highlight a persistent gap: the frequent absence of standardised protocols for macrolitter verification, underscoring the need for consistent methodologies across citizen science initiatives. Moreover, Honorato-Zimmer et al. (2021) and Philip et al. (2024) emphasize the considerable coordination efforts required to support participants and maintain data quality, an enduring challenge in large-scale citizen science programs that is often underestimated (Honorato-Zimmer et al., 2021; Philip et al., 2024).

The implementation of comprehensive communication (Dittmann et al., 2023) and data quality mechanisms (Dittmann et al., 2022) within the Plastic Pirates enabled the third publication of this dissertation, a study on spatially and temporally large-scale macrolitter data on riversides across Germany (Dittmann et al., 2024). A total of 26,757 litter items (> 2.5 cm), primarily plastic and cigarette butts, were identified. Wide rivers (> 51 m) contributed significantly more litter, suggesting downstream accumulation. Litter density varied with river system, sampling campaign, and river width. Schoolchildren reported visitors as the most likely source of riverine litter pollution.

These results demonstrate that citizen science data can be successfully used for large-scale monitoring of litter pollution in aquatic environments, when effective communication and data quality requirements are implemented (Figure 6.1). In comparison, data collected through traditional scientific methods often lack the spatial and temporal coverage offered by citizen science, highlighting a major advantage of participatory monitoring (van Calcar and van Emmerik 2019; van Emmerik et al., 2020).

Although these success factors were essential to the scientific success of the Plastic Pirates, several other contributing factors have not yet been mentioned. Theobald et al. (2015)

emphasize that programs operating over large spatial and temporal scales are more likely to contribute to peer-reviewed publications (Figure 6.1). This applies to the Plastic Pirates, which, due to its long program duration, allowed for continuous adjustment of success factors to ensure scientifically sound data. Furthermore, untargeted outreach and independently conducted samplings by the school classes across rivers in Germany ensured broad spatial coverage and resulted in widely dispersed data.

Freitag und Pfeffer (2013) highlight the importance of expert collaboration (Figure 6.1). Although the Plastic Pirates are a contributory program with the focus on collecting large-scale data, the sampling protocol was co-developed by teachers and scientists from Germany and Chile (Rech et al., 2014) to ensure it is both accessible to schoolchildren and meets scientific standards for assessing litter pollution.

According to Scheliga et al. (2018) the scientific success of a citizen science program also depends on its ability to engage participants. Since the target group of the Plastic Pirates includes schools, particularly teachers and schoolchildren, significant resources were dedicated to the layout and design of the teacher's booklet and the sampling booklets for schoolchildren. To ensure a professional appearance, external graphic designers were hired for the layout work, which required considerable time and financial resources. Furthermore, all materials were offered free of charge to the schools to enable participation by everyone.

However, there are also several external factors influencing the scientific success of citizen science programs. Shortcomings include limited funding, personnel changes, and the COVID-19 pandemic significantly impacted the program success and the scientific outcomes of the Plastic Pirates. In particular, school closures during lockdowns resulted in very few data points being collected. Short funding periods of less than one year hindered early participant recruitment and the planning of large-scale data analyses.

These findings show that generating scientifically reliable citizen science data requires not only comprehensive communication and verification but also adequate time and financial resources as well as a broad spectrum of different expertise. While citizen science is often promoted as a cost-effective alternative to traditional research, this perception may underestimate the effort required for rigorous scientific outcomes. A study by Davis et al. (2023) analysed 895 citizen science programs initiated between 1890 and 2018, assessing that 75 % did not produce peer-reviewed publications, with just five programs accounting for nearly half of publications. Thus, while the number of citizen science programs grows, few succeed in

publishing their findings in peer-reviewed journals, likely due to limited resources and the absence of standardised data quality control.

However, the success factors presented here primarily focus on generating scientific data for peer-reviewed publications. In general, the success of a program often depends on its specific goals and may extend beyond the collection of scientifically valuable data to include aims such as education or community building (Freitag und Pfeffer 2013). In the future, the Plastic Pirates could shift their emphasis from producing scientific data to raising awareness, promoting education, or enhancing scientific literacy among the participating schoolchildren (Figure 6.1). In such cases, the criteria for success would differ from those aligned with the program's scientific objectives. Currently, there is no evidence regarding the programs impact on translating schoolchildrens behavior into eco-friendly actions, as this has not yet been the primary focus of scientific evaluation. A study by Kruse et al. (2020) evaluated whether participation in a citizen science program could empower schoolchildren to take action on environmental issues. The study focused on a predecessor program of the Plastic Pirates, in which schoolchildren collected data on coastal litter pollution in Germany and Chile. The findings indicated that participation in the program did not alter the schoolchildrens perceived inability to act. Similar results were reported by Wichmann et al. (2022) and Oturai et al. (2022) who examined whether schoolchildrens pro-environmental behavior changed following their participation in the Científicos de la Basura and the Mass Experiment. Their findings suggest that participation in citizen science programs alone is insufficient to foster pro-environmental behavior and must be complemented by additional educational actions and age-sensitive designs. Although the Plastic Pirates teaching materials include a chapter encouraging schoolchildren to take action after sampling (see teaching materials, p. 54 to 64), there is still no clear evidence whether participation in the program affects schoolchildrens environmental behavior. This represents a significant gap in research that could be addressed in future funding periods. The programs focus could then shift from a large-scale assessment of litter pollution to a more targeted approach engaging fewer schools in the sampling process, fostering closer collaboration between participating schools, scientists, and local actors, and placing greater emphasis on action-oriented outcomes rather than data collection alone (Figure 6.1).

Furthermore, Freitag und Pfeffer (2013) emphasised that presenting collected data to policymakers and other influencers should be considered as a key success factor in citizen science, as it highlights the importance of such programs and can help ensure long-term participants engagement. Given that citizen science has been recognized as a major contributor to the democratisation of science in the EU´s research and innovation agenda (European

Commission, 2020), there is a need to strengthen the dialogue between different actors (Göbel et al., 2019). Although the Plastic Pirates have been running since 2016, this aspect has only recently started to be integrated to a very limited extent. Since the program was scaled up to other EU member states in 2021, the program has gained increased recognition at the political level by the European Commission. However, the integration of collected data into official frameworks, such as the Water Framework Directive, has not yet been achieved and should be pursued in the future (Schönberg et al., 2025). Building on this, a meaningful democratisation of science requires more inclusive and diversified approaches, aiming to reach groups that have so far been underrepresented and to enable their active participation in scientific processes. In the case of the Plastic Pirates, participation has predominantly come from schoolchildren attending secondary schools, which may be partly attributed to the complexity of the sampling procedures. Simplifying the methodological materials, through the use of easy language and additional illustration, as well as offering more intensive guidance and support, could facilitate the inclusion of schoolchildren from a broader range of educational backgrounds.

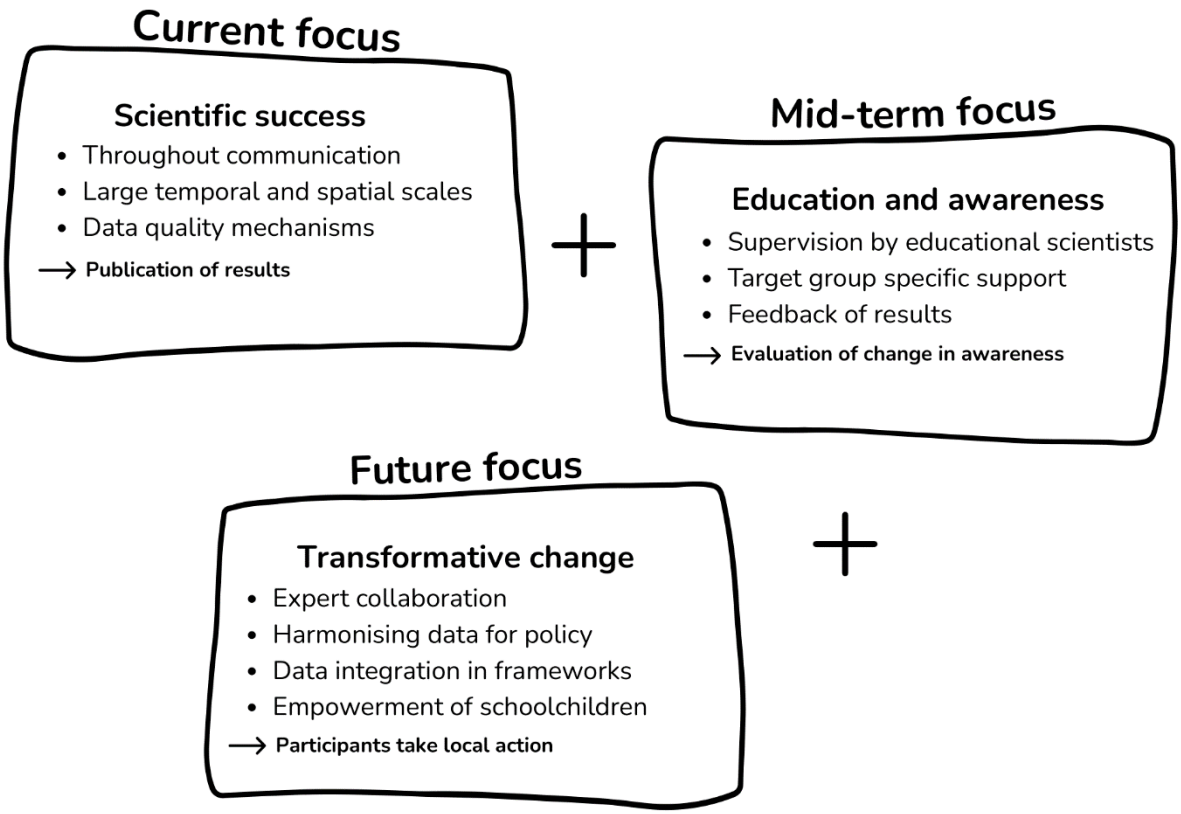

Figure 6.1: Success factors of citizen science initiatives are highly dependent on their specific objectives and vary according to the intended outcomes. Currently, the focus of the Plastic Pirates program is on generating scientific data for publication. However, a shift toward

education and awareness as a mid-term focus could reveal new potential objectives for the program, such as fostering transformative behavioral change among participants, ultimately leading to local action as a future focus. This shift would require the development and application of revised success factors.

In conclusion, this dissertation has demonstrated that, alongside other contributing factors, comprehensive communication and standardised methods for ensuring data completeness and reliability are essential success factors for opening the full potential of citizen science in addressing plastic pollution. In the long term, citizen science can meaningfully contribute to prevention and mitigation of plastic litter pollution, not only at the local level but also on a global scale, including policy development. This is particularly relevant in the context of the United Nations Sustainable Development Goals (SDGs), notably SDG 14: Life Below Water, which addresses the challenges affecting the oceans, including marine litter pollution. Achieving this target by 2030 demands timely, comprehensive, and high-quality data, something traditional monitoring approaches, such as official surveys, often struggle to provide. At present, SDG monitoring predominantly relies on traditional data sources, which are often hindered by high implementation costs and outdatedness (Fritz et al., 2019). Citizen science presents a valuable and scalable complement to these methods, helping to fill data gaps and enhance monitoring efforts globally (Wuebben et al., 2020; Fraisl et al., 2023; Fraisl et al., 2025). Ensuring the integrity of such data is therefore not merely a methodological concern but a strategic requirement for global environmental governance.

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Supplementary material

Supplementary material A for Chapter 2

A1. Amount of emails sent and received from a centralised *Plastic Pirates* email address with the purpose of individual communication with citizen science participants.

Month and Year	Sent	Received	Total
October 2016	69	73	142
November 2016	89	131	220
December 2016	269	311	580
January 2017	109	148	257
February 2017	34	47	81
March 2017	26	29	55
April 2017	12	29	41
May 2017	25	21	46
June 2017	229	186	415
July 2017	344	315	659
August 2017	104	87	191
September 2017	45	49	94
October 2017	7	14	21
November 2017	7	15	22
December 2017	2	2	4
January 2018	1	3	4
February 2018	1	11	12
March 2018	0	5	5
April 2018	0	20	20
May 2018	108	172	280
June 2018	271	234	505
July 2018	236	190	426
August 2018	100	83	183
September 2018	172	138	310
October 2018	138	122	260
November 2018	178	191	369
December 2018	49	62	111
January 2019	68	72	140
February 2019	21	30	51
March 2019	29	31	60
April 2019	65	129	194
May 2019	164	225	389
June 2019	227	197	424
July 2019	252	174	426
August 2019	92	98	190
September 2019	47	22	69
October 2019	17	21	38
November 2019	41	10	51
December 2019	8	5	13
January 2020	3	5	8

February 2020	11	26	37
March 2020	33	63	96
April 2020	87	53	140
May 2020	77	57	134
June 2020	61	42	103
July 2020	21	17	38
August 2020	30	9	39
September 2020	32	83	115
October 2020	22	26	48
November 2020	56	41	97
December 2020	33	51	84
January 2021	29	38	67
February 2021	16	23	39
March 2021	891	125	1,016
April 2021	87	26	113
May 2021	64	30	94
June 2021	207	102	309
July 2021	95	60	155
August 2021	127	55	182
September 2021	160	53	213
October 2021	173	93	266
November 2021	148	103	251
December 2021	95	84	179
January 2022	115	58	173
February 2022	11	6	17
March 2022	8	9	17
April 2022	67	22	89
May 2022	90	30	120
June 2022	92	49	141
July 2022	69	89	158
August 2022	125	57	182
September 2022	109	68	177
October 2022	85	43	128
November 2022	86	57	143
December 2022	63	28	91
January 2023	94	26	120
February 2023	7	12	19
March 2023	2	9	11
Total	**7,237**	**5,530**	**12,767**

A2. Excerpts from the program website of the Plastic Pirates

Excerpts from the website of the Plastic Pirates (https://www.plastic-pirates.eu/). It contained a result section with summarised data prepared by the coordinating team after a sampling campaign, and also the data submitted by individual groups to allow participants to compare their own litter findings.



Main page of the Plastic Pirates website.

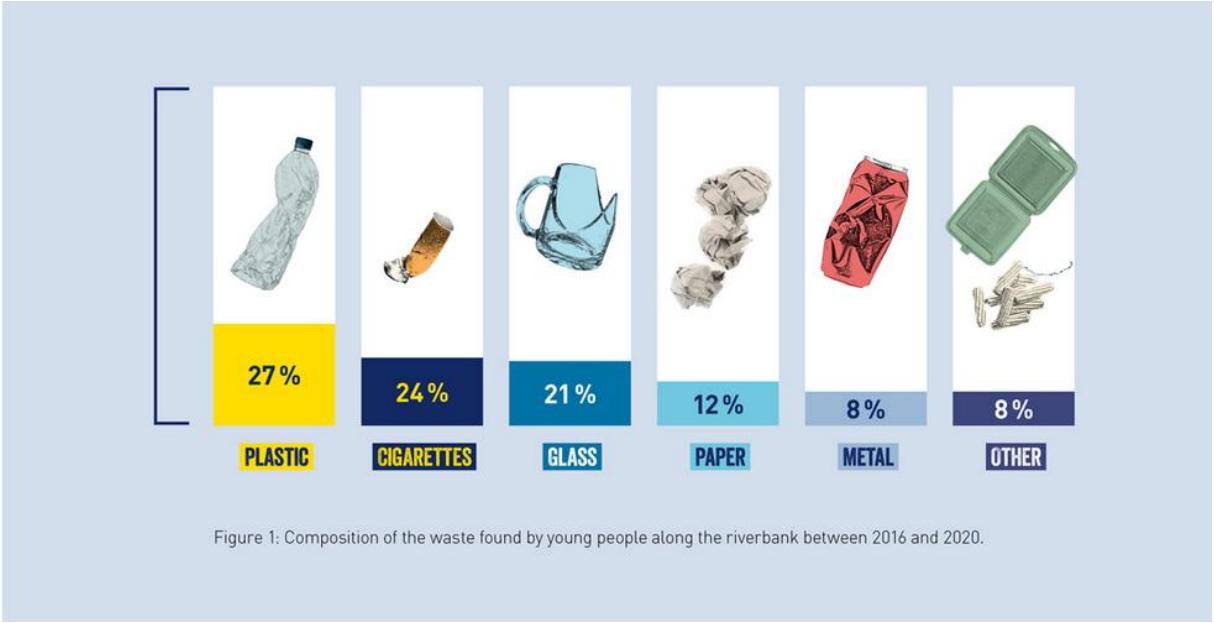


Figure 1: Composition of the waste found by young people along the riverbank between 2016 and 2020.

Data summary of materials found at the riverside.



12 October 2020
Schwentine
Kiel
Location coordinates: 54.32706249569002 10.188572715036422

Group A	
All riverside zones (average waste per m²)	6.4
Foreshore (average waste per m²)	-
Backshore (average waste per m²)	-
Riverbank crown (average waste per m²)	-
Group B	
Total number of waste items found (including single-use plastic)	1590
Share of single-use plastic (in percent of the total number of all waste items found).	32
Weight of all waste including plastic (in kg)	17

Data page of an individual group showing a group photo, sampling metadata and data about litter results.

A3. Example of social media activity of the *Plastic Pirates*.

It illustrated scientific findings, meetings of the coordinating team, and videos to inform participants and the general public about developments of the Plastic Pirates and the results presented in the scientific articles.



Facebook post about discovery of microplastic hotspots (meaning sampling spots that contained much plastic particles below the size of 5 mm).



Instagram post showing the *Plastic Pirates* team from Kiel Science Factory, Ecologic Institute, and the University Católica del Norte during a team meeting in Kiel, Germany.



Thumbnail of a Plastic Pirates video on YouTube, sharing the scientific findings of a study on microplastics with the participants. Available at https://www.youtube.com/watch?v=p6OC0gVHy28 (accessed on the 30th of May 2023).



Instagram post to acknowledge the contribution of the schoolchildren and youth groups after the end of a sampling campaign.

Supplementary material B for Chapter 3

B1. Overview of the verification of riverside litter data and inference of litter source per group

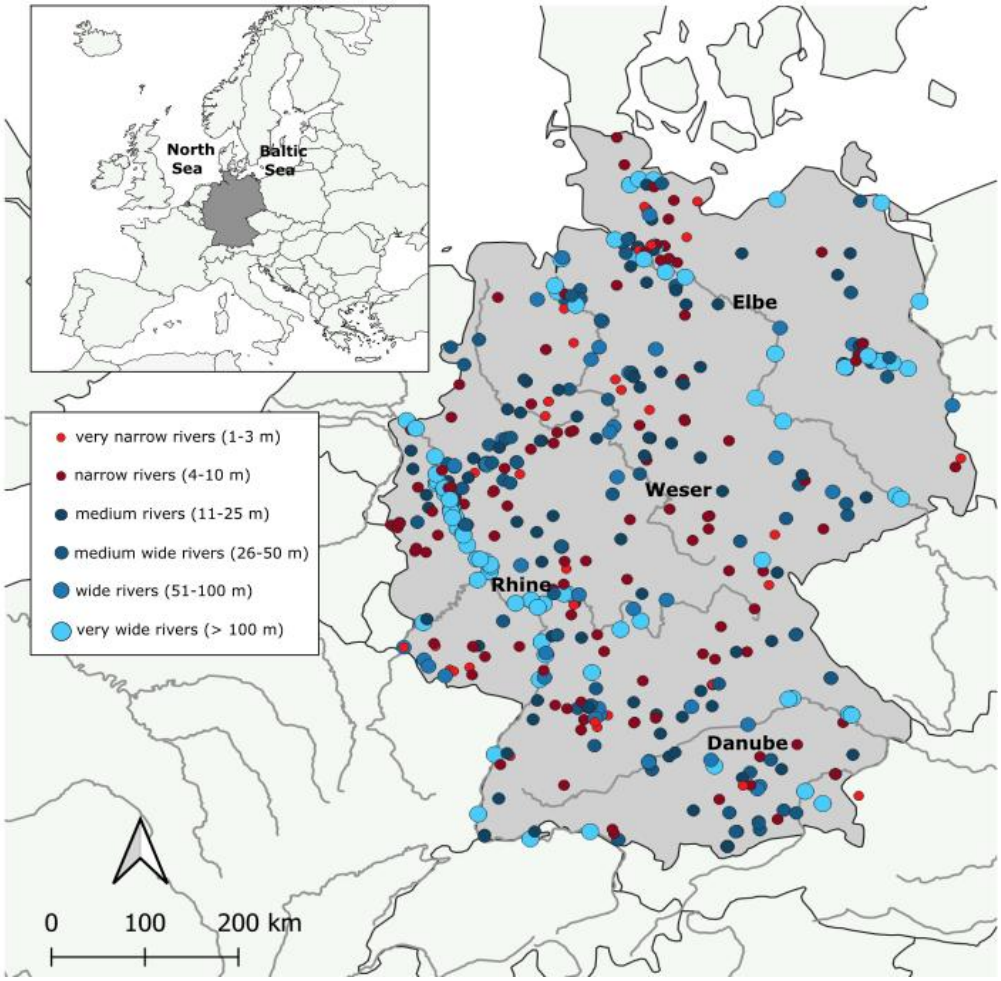
	Riverside litter			Inference of litter source		
	Datasets received	Datasets rejected	**Datasets accepted**	Datasets received	Datasets rejected	**Datasets accepted**
Per year						
2016	176	81	**95**	160	26	**134**
2017	184	100	**84**	154	27	**127**
2018	167	113	**54**	220	89	**131**
2019	91	33	**58**	139	58	**81**
2020	72	23	**49**	126	61	**65**
2021	181	64	**117**	268	122	**146**
2022	174	63	**111**	272	144	**128**
Total	1045	477	**568 (54.4 %)**	1339	527	**812 (60.6 %)**

B2. Reasons for the rejection of datasets from groups participating in the riverside litter sampling

Reasons for the rejection of data sets	**Number of data sets***
No photo available	310
Litter count on photo does not reflect data	65
No data verification possible	139

*Datasets could have been rejected by multiple reasons, meaning that this number differs from the total number of rejected datasets. See details in the study by Kiessling et al., 2019 and Dittmann et al., 2022 for details of the data verification process of the Plastic Pirates.

B3. Spatial representation of river width categories for each sampling location of the riverside litter sampling



B4. Results of a Tukey-adjusted posthoc test for a zero-altered negative binomial hurdle model for riverside litter data

The table only shows the significant differences between the litter findings of the different sampling campaigns (p-value > 0.05).

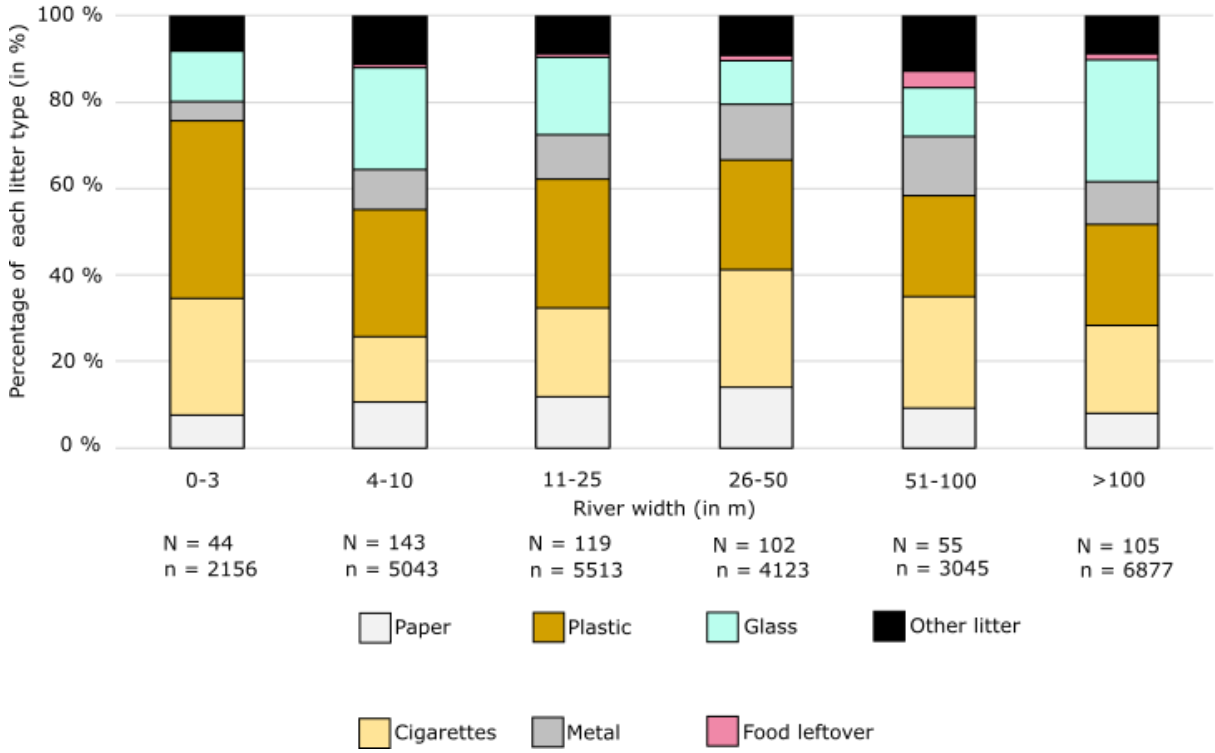
	Estimate	Standard error	Df	t-ratio	p-value
Sampling campaigns					
fall 2016 – spring 2019	-4.0920	0.797	4563	-5.134	<0.0001
fall 2016 – spring 2021	-2.4440	0.675	4563	-3.620	0.0133
fall 2016 – spring 2022	-3.2666	0.666	4563	-4.908	0.0001
spring 2017 – spring 2019	-4.4913	0.792	4563	-5.668	<0.0001
spring 2017 – spring 2021	-2.8433	0.668	4563	-4.256	0.0011
spring 2017 – fall 2021	-1.4039	0.418	4563	-3.361	0.0321
spring 2017 – spring 2022	-3.6659	0.659	4563	-5.561	<0.0001
spring 2019 – spring 2018	2.9990	0.911	4563	3.292	0.0400
spring 2019 – fall 2018	3.9226	0.930	4563	4.218	0.0013
fall 2018 – spring 2022	-3.0971	0.820	4563	-3.776	0.0075

B5. Results of a Tukey-adjusted posthoc test for a zero-altered negative binomial hurdle model for riverside litter data

The table only shows the significant differences between the litter findings of the different river width categories (p-value > 0.05).

	Estimate	Standard error	Df	t-ratio	p-value
River width categories					
11-25m – >100m	-2.718	0.562	4573	-4.833	<0.0001
51-100m – >100m	-3.434	0.554	4573	-6.201	<0.0001
0-3m – >100m	-2.426	0.743	4573	-3.266	0.0140
4-10m – >100m	-3.644	0.552	4573	-6.599	<0.0001
4-10m – 51-100m	-2.192	0.566	4573	-3.870	0.0015

B6. Litter composition of riverside litter for each river width category. N = number of sites considered for the analysis, n = number of litter items found.



B7. Litter sources identified at each sampling campaign (in % of sites where the respective source has been considered to be a likely source).

		Number of datasets analysed	Visitors	Residents	River depositing litter	Illegal dumping	Ship/ boat traffic	Industry	Agriculture	Fishing
Per sampling campaign										
Overall	-	817	92%	49%	43%	31%	14%	12%	11%	9%
2016	spring	na	na	na	na	na	na	na	na	na
	fall	134	87%	40%	31%	22%	19%	10%	na	na
2017	spring	127	84%	36%	31%	23%	15%	9%	na	na
	fall	na	na	na	na	na	na	na	na	na
2018	spring	60	93%	50%	37%	31%	14%	13%	na	na
	fall	77	97%	58%	51%	49%	11%	10%	na	na
2019	spring	83	94%	47%	39%	25%	13%	17%	na	na
	fall	na	na	na	na	na	na	na	na	na
2020	spring	8	100%	71%	20%	29%	13%	0%	na	na
	fall	58	94%	64%	na	47%	11%	13%	13%	16%
2021	spring	60	95%	40%	na	25%	8%	8%	11%	6%
	fall	84	96%	61%	na	35%	12%	11%	10%	6%
2022	spring	73	83%	42%	na	17%	12%	8%	13%	10%
	fall	53	79%	38%	na	37%	12%	8%	6%	9%

B8. Table of participating schools, institutions and organisations

Name of school or organisation:
Abraham-Frank-Sekundarschule Velen
Adolf-Reichwein-Schule Limburg
Agnes-Wenke-Sekundarschule Arnsberg
Aktive Schule Petershausen
Albert-Magnus-Realschule St. Ingbert
Albert-Schweitzer-Gymnasium Sömmerda
Albertus-Magnus-Gymnasium
Albinus-Gemeinschaftsschule Lauenburg
Albrecht-Weinberg-Gymnasium Rhauderfehn
Alemannenschule Wutöschingen
Alexander-S.-Puschkin-Gymnasium Hennigsdorf
Alexander-von-Humboldt-Realschule Bayreuth
Alice-Salomon-Schule
Allgemeinbildende Werkrealschule und Realschule
Angelaschule Osnabrück
Anna-Schmidt-Schule
Apollonia Oberschule Uelzen
Augst-Schule Neuhäusel
Bertha-von-Suttner Gymnasium Andernach
Bertha-von-Suttner-Gymnasium Andernach
Berufliche Oberschule Rosenheim
Berufliche Schule Elmshorn
Berufsbildungszentrum Rendsburg-Eckernförde
BEST-Sabel Oberschule
Bildungscamp Christes e.V.
Biosphärenreservat Mittelelbe
Biosphärenreservat Mittelelbe (Haus der Flüsse Havelberg)
Birken-Realschule Stuttgart
Bischöfliches Pius-Gymnasium Aachen
Bismarckschule Elmshorn
Bonn International School e.V.
BUND Naturschutz Jugendgruppe Günzburg
Bürgerschule Sonneberg
Burghardt-Gymnasium Buchen
Caritas Schülerzentrum KRABAT
Carl-Bechstein-Gymnasium
Carl-Friedrich-Gauß-Gymnasium Schwedt/Oder
Carl-Orff-Gymnasium Unterschleißheim
Carl-Orff-Schule Neuwied
Carl-Spitzweg-Gymnasium
Carl-Spitzweg-Gymnasium Unterpfaffenhofen
Chiemseepiraten
Christian-Albrechts-Universität zu Kiel

Christian-von-Mannlich-Gymnasium Homburg
Christian-Wolff-Gymnasium Halle
Christoph-Jacob-Treu-Gymnasium
CJD Christophorusschule Königswinter
CJD Christophorusschule-Sekundarschule Versmold
Clay-Schule Berlin
Comenius Gymnasium Deggendorf
Comenius-Gymnasium Deggendorf
Copernicus-Gymnasium Philippsburg
Corsten Jugendhilfe GmbH Hellenthal
Das andere Gymnasium
Deutsche Pfadfinderschaft St. Georg Stamm Brand-Kornelimünster
Deutsch-Luxemburgisches Schengenlyzeum Perl
Domgymnasium Verden
Domschule Osnabrück
DPSG Stamm St. Josef
Dr.-Mehler-Schule Georgensgmünd
Dr.-Samuel-Hahnemann-Schule Köthen
Drei-Burgen-Schule Felsberg
Ecologic Institut
Edith-Stein-Realschule Lippstadt
Edith-Stein-Schule Erfurt
Eggeschule
EGN - Evangelisches Gymnasium Nordhorn
Eichendorffschule Veitshöchheim
Eichenlaubschule Weiskirchen
Elbe-Jeetzel-Schule Dannenberg
Elly-Heuss-Gymnasium
Elly-Heuss-Knapp-Gemeinschaftsschule
Elsa-Brandström-Schule Elmshorn
Emanuel-von-Seidl-Grundschule Murnau
Emil-Fischer-Gymnasium Euskirchen
Emmy-Noether-Gymnasium Berlin
Erasmus-Gymnasium Rostock / Leibniz-Institut für Ostseeforschung Warnemünde
Erich-Kästner-Schule Bürstadt
Erich-Kästner-Gemeinschaftsschule Elmshorn
Erich-Kästner-Hauptschule Bergheim
Ernst-Barlach-Gymnasium Kiel
Ernst-Moritz-Arndt-Gymnasium Bonn
Ernst-Reuter-Schule Frankfurt am Main
Ernst-Sigle-Gymnasium Kornwestheim
Erzbischöfliche Mädchenrealschule Heilig Blut Erding
Erzbischöfliches Clara-Fey-Gymnasium Bonn
Eugen-Neter-Schule

Europaschule “Marie & Pierre Curie” Guben
Europaschule am Fließ
Evangelisches Gymnasium Werther
Fasia-Jansen-Gesamtschule Oberhausen
Felix-Klein-Gymnasium
Felix-Klein-Gymnasium Göttingen
Förderverein Waldschule Zootzen e. V.
Förderzentrum-Nord Lünen
Fr.-W.-v.-Steuben-Gesamtschule
Freie Montessori-Gemeinschaftsschule Bad Lobenstein
Freie Montessorischule Huckepack
Freie Schule Kierspe
Freie Schule Köln
Freiherr-vom-Stein-Gymnasium Bünde
Freudberg Gemeinschaftsschule
Frida-Levy-Gesamtschule Essen
Friedrich-Heuss-Schule
Friedrich-Abel-Gymnasium Vaihingen
Friedrich-Anton-von-Heinitz-Gymnasium Rüdersdorf
Friedrich-Leopold-Woeste-Gymnasium
Friedrich-List-Gymnasium Asperg
Friedrich-List-Schule Ulm
Friedrich-Schiller-Gymnasium Marbach am Neckar
Ganztagsgymnasium Johannes Rau
Gemeinschafts- und Sekundarschule Harzgerode
Gemeinschaftsgrundschule Weimarer Straße
Gemeinschaftsschule "Wilhelm Weitling" Magdeburg
Gemeinschaftsschule am Seminarweg Bad Segeberg
Gemeinschaftsschule Bad Lippspringe - Schlangen Bad Lippspringe
Gemeinschaftsschule Gebhard Konstanz
Gemeinschaftsschule In den Fliesen Saarlouis
Gemeinschaftsschule Kronshagen
Gemeinschaftsschule Ossenmoorpark
Gemeinschaftsschule Ossenmoorpark Norderstedt
Gemeinschaftsschule Rheintal Küsserberg
Gemeinschaftsschule Rheydt-Mülfort Mönchengladbach
Gemeinschaftsschule St. Ingbert-Rohrbach
Gemeinschaftsschule Sulzbach
Georg-Christoph-Lichtenberg-Gesamtschule
Gerhart-Hauptmann-Schule Rüsselsheim
Gertrud-Bäumer-Gymnasium Remscheid
Gesamtschule Aachen-Brand
Gesamtschule Bonns Fünfte Bonn
Gesamtschule Eifel Blankenheim
Gesamtschule Eiserfeld

Gesamtschule Emmerich am Rhein
Gesamtschule Geistal
Gesamtschule Kaarst Büttgen
Gesamtschule Kierspe
Gesamtschule Langerfeld
Gesamtschule Schlitzerland Schlitz
Gesamtschule Stettiner Straße
Gesamtschule Troisdorf Sieglar
Gesamtschule Warendorf
Geschwister-Scholl-Gymnasium Fürstenwalde
Geschwister-Scholl-Gymnasium Nossen
Goethe Gymnasium Bensheim
Goethe Realschule Löhne
Goethe-Gmynasium Karlsruhe
Goethe-Gymnasium Auerbach
Goethe-Gymnasium Karlsruhe
Goethe-Gymnasium/Rutheneum seit 1609
Goethe-Oberschule Kremmen
Graf-Engelbert-Schule
Graf-Zeppelin-Gymnasium Friedricshhafen
Greenpeace Halle / Martin-Luther-Universität Halle-Wittenberg
Greenpeace Nordrhein-Westfalen
Grund- und Gemeinschaftsschule an der Bek
Grund und Gemeinschaftsschule im Quellental
Grund und Gemeinschaftsschule im Quellental Pinneberg
Grund- und Mittelschule Eggolsheim
Grund- und Mittelschule Offingen
Grundschule am Stadtpark Steglitz
Grundschule Lage
Grundschule Otzing
Grundschule Rheinschule
Grundschule Rheinschule Bobenheim-Roxheim
Grundschule Veitshöchheim
Grundschule Zeitlofs
Gymnasium "Prof. Dr. Max Schneider" Lichtenstein/Sa.
Gymnasium Altona
Gymnasium am Kurfürstlichen Schloss
Gymnasium am Kurfürstlichen Schloss Mainz
Gymnasium am Römerkastell
Gymnasium Am Wall
Gymnasium am Wirteltor Düren
Gymnasium an der Vechte
Gymnasium Antonianum Geseke
Gymnasium Aspel der Stadt Rees
Gymnasium Bondenwald

Gymnasium Bruckmühl
Gymnasium Corvinianum
Gymnasium Corvinianum Northeim
Gymnasium der Montessori-Schule Chemnitz
Gymnasium Ernestinum Celle
Gymnasium Essen-Werden
Gymnasium Gerabronn
Gymnasium Glinde
Gymnasium Gosheim-Wehingen
Gymnasium Herkenrath Bergisch Gladbach
Gymnasium Horn
Gymnasium Horn-Bad Meinberg
Gymnasium Landschulheim
Gymnasium Lilienthal
Gymnasium Michelstadt
Gymnasium Miesbach
Gymnasium Münchberg
Gymnasium Nidda
Gymnasium Olching
Gymnasium Penzberg
Gymnasium Pfarrkirchen
Gymnasium Ritterhude
Gymnasium Rutheneum seit 1609
Gymnasium Sarstedt
Gymnasium Schloss Plön
Gymnasium Schwarzenbek
Gymnasium Siegburg Alleestraße
Gymnasium St. Leonhard
Gymnasium St. Leonhard Aachen
Gymnasium Stolzenau
Gymnasium Sulingen
Gymnasium Thomaeum Kempen
Gymnasium Trudering München
Gymnasium Uslar
Gymnasium Wellingdorf Kiel
Gymnasium Wesermünde Bremerhaven
Gymnasium-Bildungszentrum Markdorf
Halepaghen-Schule Buxtehude
Hannah-Arendt-Gymnasium Barsinghausen
HAP Grieshaber Gymnasium im Bildungszentrum Nord Reutlingen
Hebel-Gymnasium Lörrach
Heimsonderschule Haus Arild
Heinrich-Böll-Schule Rodgau
Heinrich-Heine-Gymnasium Hamburg
Heinrich-von-Kleist-Schule Eschborn

Heinz-Nixdorf-Gesamtschule Paderborn
Helene-Lange-Schule Oldenburg
Hellenstein-Gymnasium
Hellenstein-Gymnasium Heidenheim
Helmholtz-Gymnasium Hilden
Herder-Gymnasium der Stadt Minden
Herderschule Gießen
Hermann-Schulz-Grundschule
Hermann-von-Helmholtz Gymnasium Potsdam
Hinterlandschule Biedenkopf
Hofenfels-Gymnasium Zweibrücken
Hoffmann-von-Fallersleben-Schule Braunschweig
Holstenschule Neumünster
Hornbergschule Mutlangen
Hulda-Pankok-Gesamtschule Düsseldorf
Humboldtschule Hannover
IGS Delmenhorst
IGS Eisenberg
IGS Remagen
IGS Stöcken
IGS Stöcken Hannover
Immanuel-Kant-Schule
INI Gesamtschule Bad Sassendorf
Integrierte Gesamtschule Buchholz
Integrierte Gesamtschule Delmenhorst
Integrierte Gesamtschule Einbeck
Integrierte Gesamtschule Georg Friedrich Kolb Speyer
Integrierte Gesamtschule Lüneburg
Internat Solling Staatlich anerkanntes Gymnasium
Jakob-Brucker-Gymnasium Kaufbeuren
Jakob-Kaiser-Realschule Hammelburg
Jan-Joest-Gymnasium der Stadt Kalkar
Johann-Christian-Reinhart-Gymnasium Hof
Johannes-Butzbach-Gymnasium Miltenberg
Johannes-Kepler-Schule/ Gymnasium der Stadt Leipzig
Johannes-Scharrer-Realschule Hersbruck
Johannes-Widmann-Gemeinschaftsschule Maichingen
Johannisberg-Schule Witzenhausen
Johann-Schöner-Gymnasium Karlstadt
Johann-Sebastian-Bach Schule Weinheim
Joseph-von-Fraunhofer-Gymnasium
Joseph-von-Fraunhofer-Gymnasium Cham
Jungmannschule Eckernförde
Kalkbergschule Meißen
Karl-Kessler-Schule Aalen

Karls-Gymnasium Stuttgart
Käte-Lassen-Schule Flensburg
Katholische Schule Salvator
Kepler-Gymnasium Weiden
KGS Bad Bevensen
Kieler Forschungswerkstatt Kiel
Kinder- und Jugendstadtrat Nordhausen
Kita "Spatzenhaus"
Kleine Forschergruppe Niederspree
Klosterfeld-Grundschule
König-Wilhelm-Gymnasium Höxter
Konrad-Adenauer-Gymnasium Kleve
Konrad-Adenauer-Realschule plus mit Fachoberschule Technik – Fort Landau
Kooperative Gesamtschule Sittensen
Kopernikus-Gymnasium Lintorf
Kopernikus-Gymnasium Ratingen Lintorf
Kopernikusschule Köln
Kreisgymnasium Neuenburg
Kurfürst-Balduin-Gymnasium Münstermaifeld
Kurpfalz-Gymnasium Schriesheim
Küstengymnasium Neustadt in Holstein
Landesfischereiverband Baden-Württemberg e. V.
Leibniz Universität Hannover
Leibniz-Gymnasium Potsdam
Leonardo da Vinci Grund- und Gesamtschule Wolfsburg
Lessing Gymnasium
Lessing-Gymnasium Winnenden
Lindenauschule Hanau
Liselotte-Funcke-Schule
Lise-Meitner-Gymnasium Geldern
Lore-Lorentz-Schule Düsseldorf
Lornsenschule Schleswig
Lothar-Kahn-Schule Rehlingen-Siersburg
Mandelberg-Grundschule Dertingen Wertheim am Main
Maria-Montessori-Gesamtschule Düsseldorf
Maria-Theresia-Mittelschule Günzburg
Maria-Ward-Gymnasium Altötting
Mariengymnasium Warendorf
Marienschule Münster
Marion-Dönhoff-Gymnasium Nienburg/Weser
Martin-Luther-Gymnasium Eisenach / Thüringen
Max-Brauer-Schule
Max-Planck-Schule Kiel
Max-von-Laue-Gymnasium

Max-von-Laue-Gymnasium Koblenz
Meranier-Gymnasium Lichtenfels
Merian-Schule Berlin
Mittelschule Albert-Schweitzer-Straße München
Mittelschule Miesbach
Mittelschule Sankt Martin
Mittelschule Vilseck
Montessori Bildungshaus Hannover
Montessori-Bildungshaus Hannover
Montessori-Schule Chemnitz
Montessori-Schule Dachau
Montessori-Schule Göttingen
Montessori-Schule Oettingen
Moseltal Realschule plus Trier
mountain2ocean
Musisch-aktive Montessori-Schule Bad Tölz
Naturschutzstation östliche Oberlausitz e.V.
NEST Naturerkundungsstation Wolfsburg
Oberlandschulen Weilheim
Oberrhein-Gymnasium, Weil am Rhein
Oberschule "Werner Seelenbinder" Bad Lausick
Oberschule am Barkhof
Oberschule an der Egge mit Gymnasialer Oberstufe Bremen
Oberschule Bevern
Oberschule im Park Bremen
OBS Papenteich
Offene Ganztagsgrundschule Rühme
Offene Schule Köln
Offene Schule Waldau Kassel
Olympia-Morata-Gymnasium Schweinfurt
Oranienschule Wiesbaden
Ostschule Gießen
Otto-Hahn-Gymnasium Springe
Otto-Kühne-Schule Godesberg
Pädagogium Schwerin
Parler Gymnasium Schwäbisch Gmünd
Partnerschaftsverein Langenargen – Bois-le-Roi e. V.
Paula-Modersohn-Schule
Peeneschule Groß Gievitz
Peter-Ustinov-Schule Städtische Realschule Köln
Peter-Schöllhorn-MS
Private Montessori-Volksschule Neu-Ulm
Rahel-Varnhagen-Kolleg
Rahel-Varnhagen-Kolleg Hagen
Ratsgymnasium Peine

Realschule Bissingen
Realschule Diepholz
Realschule Gaggenau
Realschule Gute Änger
Realschule Hamborn II Duisburg
Realschule Maria Stern Nördlingen
Realschule Neuried
Realschule plus Altenglan
Realschule plus August-Sander-Schule
Reichswald-Gymnasium Ramstein-Miesenbach
Reuchlin-Gymnasium Ingolstadt
Rhein-Maas-Gymnasium Aachen
Rhein-Wied-Gymnasium Neuwied
Richard-Schirrmann-Schule Hennef
Rotteck-Gymnasium Freiburg im Breisgau
Rudolf-Koch-Schule Offenbach
Ruhr-Universität Bochum
Runge-Gymnasium Wolgast
Sachsenwaldschule Gymnasium Reinbek
SBBZ St. Fridolin
Schiller Gymnasium Hof
Schiller-Gymnasium Hof
Schloss Ising
Schloss-Realschule Gaildorf
Schrenzerschule Butzbach
Schubart-Gymnasium Aalen
Schubart-Gymnasium Ulm
Schule am Katzenberg
Schule an der Höh
Schülerforschungszentrum Hamburg
Schulzentrum der Sekundarstufe II an der Bördestraße
Sekundarschule Olpe
Selma-Lagerlöf-Gemeinschaftsschule Ahrensburg
Siebenpfeiffer-Gymnasium Kusel
SIS Swiss International School
Sonderpädagogische Bildungs- und Beratungszentrum (SBBZ) der Niefernburg
Sophie-Scholl-Gesamtschule Hamm
Spalatin-Schule Spalt
St. Leonhard Gymnasium
St. Lioba Schule Bad Nauheim
St. Marien-Gymnasium der Schulstiftung der Diözese Regensburg
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St.-Ursula-Gymnasium Schloss Hohenburg Lenggries
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Staatliche Realschule Naila
Staatliche Realschule Wasserburg
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Städtisches Gymnasium Gevelsberg
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Städtisches Gymnasium Sundern
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Windthorst-Gymnasium Meppen
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Declaration of ethical conduct

I hereby declare that the work presented in this dissertation is my own in both format and content, apart from advice provided by my supervisors and co-authors. Chapters 2, 3 and 4 have been published in peer-reviewed scientific journals. Chapter 5 was published in German in a journal intended for the general public, but it also addressed a major peer group beyond the scientific community.

This is my first dissertation and its contents have not yet been used in any previous attempt to obtain a PhD. The dissertation complies with the standards for good scientific practice as defined by the German Research Foundation. I confirm that I have not been deprived of an academic degree.

Kiel, 09.10.2025



Sinja Dittmann