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Inter-hemispherical shoreline surveys of anthropogenic marine debris – A binational citizen science project with schoolchildren

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ABSTRACT

Anthropogenic marine debris (AMD) is a global problem and the identification of its sources is essential for adequate mitigation strategies. Herein we examined whether AMD density and composition differed between two countries with contrasting socio-economic backgrounds and marine litter sources (i.e. Chile and Germany). In nationwide beach litter surveys, we used a citizen science approach with schoolchildren and their teachers. Litter densities were substantially higher in Chile than in Germany. The different geographic zones surveyed in both countries showed strong grouping tendencies according to their main economic activities (tourism, shipping, fisheries/aquaculture), major litter sources, and AMD composition, in terms of dominance and diversity of AMD types. The results suggest that beach litter composition can be used as a simple proxy to identify AMD sources, and also that law enforcement and education can help mitigate the problem; however, for efficient solutions, production and consumption of plastics must be reduced.

1. Introduction

Anthropogenic marine debris (AMD) has been recognized as a serious environmental, economic, human health, and aesthetic problem worldwide (UNEP, 2016). AMD is found in all oceans, being present at the sea surface, on shorelines, and even in the deep sea, and both its abundance and distribution have increased consistently over the last decades (Derraik, 2002; Moore, 2008; Barnes et al., 2009; Ryan et al., 2009; Chiba et al., 2018). The sources of AMD have been classified into two main types, depending on where the debris entered the coastal and marine environment: (i) land-based (including beach users, rivers, industries, harbors, sewage, landfills, winds, or extreme events), and (ii) sea-based (including commercial shipping, fishing, military and research vessels, pleasure boats, or offshore installations) (UNEP, 2009, 2016; Galgani et al., 2011, 2015).

The study and monitoring of AMD (particularly of its abundance and composition) is essential to identify and quantify its sources, information that is fundamental for administrative decisions to prevent, reduce and control the problems caused by marine litter (UNEP, 2009).

A series of approaches have been used to monitor AMD, including beach surveys, at-sea surveys, estimates of the litter amounts entering the sea, and trend evaluations in interactions between wildlife and plastic litter (Ryan et al., 2009). Among these, beach surveys have been widely used given their advantages over other methods, which include (i) proximity to sources, (ii) ease of access, (iii) simplicity, and (iv) cost-effectiveness to monitor large-scale trends in AMD (Rees and Pond, 1995; Barnes et al., 2009; Ryan et al., 2009; Galgani et al., 2015).

In general, marine litter is predominantly composed of plastics (Derraik, 2002; Pham et al., 2014; Galgani et al., 2015), with over 5 trillion plastic particles currently floating at sea (Eriksen et al., 2014) and up to 12 million additional metric tons entering the ocean each year from land-based sources (Jambeck et al., 2015). Nonetheless, the composition of AMD strongly depends on its sources (Galgani et al., 2015), and therefore the proportion of the different litter items is expected to vary among beaches around the world, conditioned by factors such as the main sources of the litter or the major economic activities carried out in the area.

For instance, recreational activities have been identified as an

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important source of beach litter based on AMD composition, which consisted primarily of either plastic or cigarette butts, or both, closely followed by other items, such as organic materials, metals and glass (Claereboudt, 2004; Kordella et al., 2013). A similar litter composition predominated by cigarette butts was reported by Oigman-Pszczol and Creed (2007) for beaches of a popular Brazilian tourist resort city, where tourism is indeed the most important economic activity and AMD source. In contrast, on the Galician coast fishing and aquaculture have been identified as the main sources of beach litter (Gago et al., 2014). Along the coasts of South Korea, Hong et al. (2014) determined the same activities as major AMD sources based on the prevalence of plastics and Styrofoam, which are materials intensively used in fishing and aquaculture.

Given that AMD is an important problem in virtually every region of the world's oceans, it is of great relevance to be able to collect litter data over extensive spatial scales, which may, however, be very expensive and resource-consuming for professional research teams (Hidalgo-Ruz and Thiel, 2015). The “citizen science” approach (working with volunteers) offers the opportunity to establish extensive networks of sampling stations, which has actually proven to be an ideal and successful tool in large-scale studies on marine litter (Rees and Pond, 1995; Eastman et al., 2014; Hidalgo-Ruz and Thiel, 2015; Zettler et al., 2017). As reviewed by Hidalgo-Ruz and Thiel (2015) and Zettler et al. (2017), citizen science projects on marine litter have been conducted on several spatial scales, including the local, regional, national, and even international level, although studies on the latter are still scarce.

In the present study we have studied marine litter at a binational level by collaborating with citizen scientists who followed a standardized sampling protocol with simple and straightforward litter categories. In order to investigate whether AMD composition varies according to main sources or economic activities, schoolchildren (grades 5–12) and their teachers from two countries in the southern and northern hemisphere (Chile and Germany) conducted nationwide beach surveys along each country's coastline. The two countries show contrasting patterns in economy and litter management. While in Chile the principal AMD sources have been identified as beach tourism (Bravo et al., 2009), riverine input (Rech et al., 2014), aquaculture (Hinojosa and Thiel, 2009), and fishing activities (Perez-Venegas et al., 2017), in Germany the main economic activities and debris sources correspond to maritime transport (see e.g. Vauk and Schrey, 1987), fishing (Galgani et al., 2000), riverine input (van der Wal et al., 2015), and tourism (Schernewski et al., 2017) (Fig. 1). Importantly, Chile and Germany also differ strongly when considering their socio-economic, educational, and environmental backgrounds (Table 1), and with respect to their history of recycling legislation and implementation. For example, while Extended Producer Responsibility became law in Chile only very recently in 2016 (Ministerio del Medio Ambiente de Chile, 2016), the Packaging Ordinance was implemented 25 years earlier in Germany (Fischer and Petschow, 2000), becoming the first country in the EU to introduce producer responsibility (Fischer, 2013).

The above considerations suggest that the AMD problem might be less severe in Germany than in Chile. On the other hand, as population density in Germany is much higher than in Chile, litter densities on German beaches might actually be higher than in Chile. To allow for a direct comparison, herein we applied the same beach survey protocol in both countries (Chile, Germany), to determine whether (i) AMD abundances indeed differ between two countries with very different economic activities and litter sources, and (ii) AMD composition can be used as a simple proxy to identify and pinpoint marine litter sources.

2. Materials and methods

2.1. Volunteer participation and citizen science approach

In each country, teachers and schools from coastal communities were asked to participate in the marine debris survey. For each school

that agreed to participate, the survey was part of a semester-long project with the students (belonging to one or more courses), in which they acquired insights into the scientific method, the marine ecosystem, and the marine litter problem, guided by their teachers. Each student received a copy of a workbook specifically designed for this activity and printed in Spanish and German, which contained all the required information/activities, as well as the beach survey protocol and simple worksheet tables for the recording of the collected data. Also, prior to the conduction of the beach surveys, teachers were trained to learn the sampling protocol and how to apply it in practice with the schoolchildren. Importantly, most Chilean teachers already had knowledge and training on the protocol, as they had been participating for several years in the Chilean citizen science program coordinating the present project (see below).

Throughout the study, coordinators of the Chilean and German research teams maintained permanent contact with the teachers to ensure that all activities were carried out in an appropriate and timely manner. These research teams correspond to the citizen science programs *Científicos de la Basura* (“Litter Scientists”) of the Universidad Católica del Norte, Chile, and *Kieler Forschungswerkstatt* (“Kiel Science Factory”) of the University of Kiel, Germany (see Thiel et al., 2018, for overview about this international partnership and the citizen science approach). In each of the two countries > 30 teachers and > 600 schoolchildren participated in the project, with slightly higher participation in Chile (Table 2). Since coordination and guidance of participating schools requires a considerable amount of effort, the total number of schools participating in each country was limited to a number that was considered manageable by the research teams.

2.2. Study areas

2.2.1. Chile

Chile is located in the Southern Hemisphere, along the southwestern coast of South America. For the purpose of this study we distinguish two main territories: (1) Continental Chile, which consists of a strip of land 4200 km long and 90 to 440 km wide, extending from 18°S to 56°S; and (2) Oceanic Chile, which comprises a remote, dispersed group of small islands and archipelagos of volcanic origin in the South Pacific Ocean under Chile's sovereignty. The main islands are the Juan Fernandez Archipelago and Easter Island (henceforth Rapa Nui). Considering both territories and the austral islands, archipelagos and fjords, which are part of Continental Chile, the country has a total coastline of approximately 78,563 km (Burke et al., 2001).

Thirty-seven Chilean beaches were surveyed by the participating schools. Of these, 35 were situated in Continental Chile, while two belonged to Oceanic Chile (one on Juan Fernandez and the other on Rapa Nui). Given the coastal extension of Chile, the country presents widely different climatic, geographic, and socio-economic characteristics along its territory. Therefore, for the purpose of this study, the country was subdivided into five zones (zones 1 to 5 in Continental Chile, as separated and described by Bravo et al., 2009), plus Rapa Nui (RN) and Juan Fernandez (JF) (Fig. 1B).

The 35 continental beaches were distributed as evenly as possible along the entire Chilean coast but tended to be closer to each other in the most densely populated zones (zones 2–4) (Table 3). The longest distance between two consecutive beaches in Continental Chile was 1663 km. The two beaches are located in the austral zone of the country (in the cities of Puerto Aysen and Punta Arenas, in zone 5), which is composed mostly of archipelagos and fjords. The beaches on Rapa Nui and Juan Fernandez are 3600 km and 670 km from the mainland, respectively (Table 3).

2.2.2. Germany

Germany is located in the Northern Hemisphere, in central Europe. Most of its territory, which is roughly half the size of Chile (in km²), is landlocked, with relatively small access to the sea (approximately

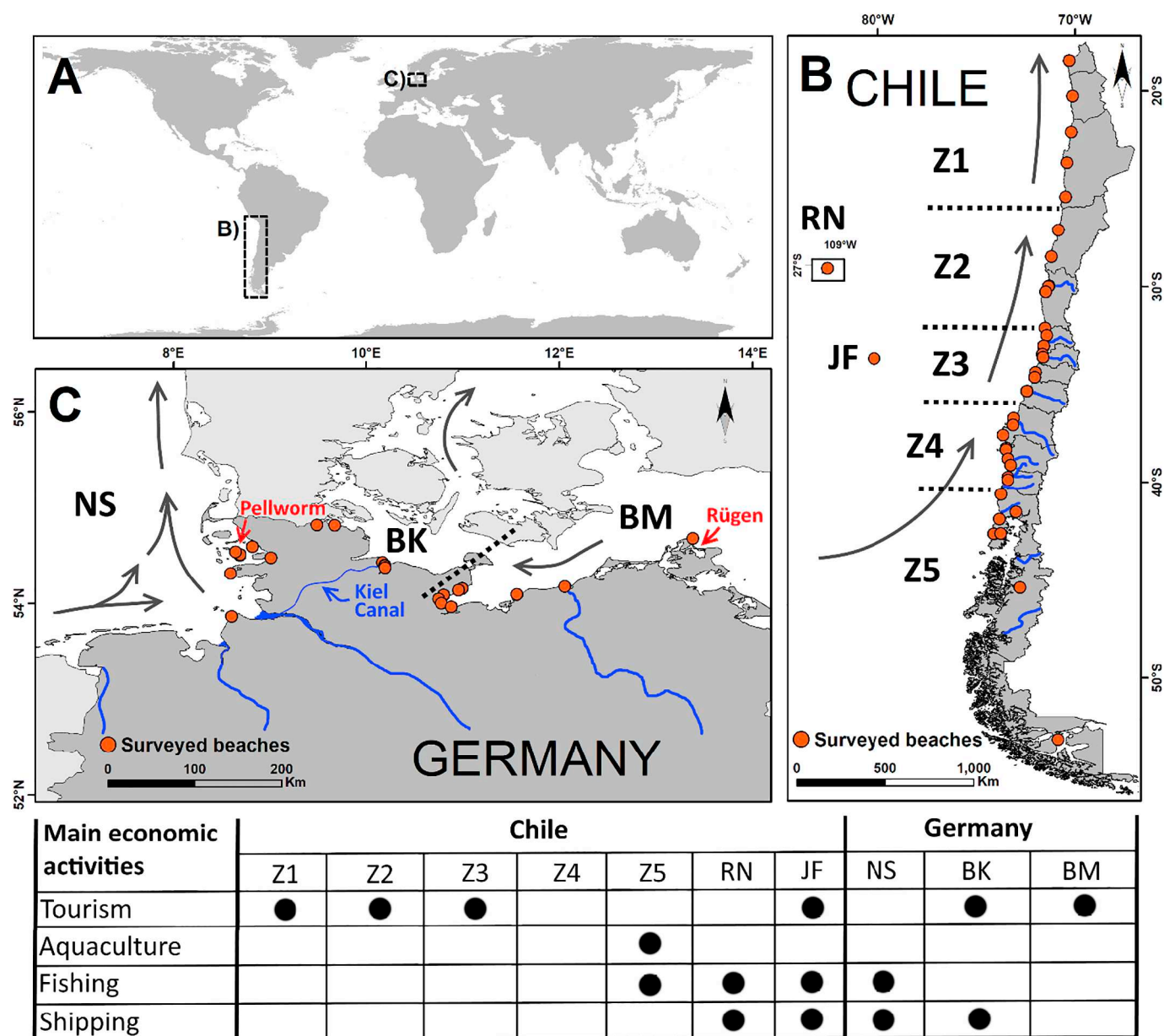


Fig. 1. World map (A) and close up of the study areas in Chile (B) and Germany (C). The different geographic zones (separated by dashed lines), the surveyed beaches (red dots), main surface currents (dark gray arrows), major rivers (blue lines), and the main economic activities (lower table), are shown for each country. Z1–Z5: Zones 1–5; RN: Rapa Nui (Easter Island); JF: Juan Fernandez; NS: North Sea; BK: Bay of Kiel; BM: Bay of Mecklenburg. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3624 km of coastline; Burke et al., 2001). The coasts of Germany face two different seas, the North Sea in the north-western part of the country and the Baltic Sea in the north-eastern part, separated by the German federal state of Schleswig-Holstein south of the Jutland

peninsula (Denmark). Given the different oceanographic characteristics of these two seas, and the fact that the German Baltic area is composed of two different hydrographic systems (i.e. Bay of Kiel and Bay of Mecklenburg), in this study the German coast was subdivided into three

Table 1
Socio-economic, educational, and environmental indicators in Chile and Germany.

	Chile	Germany
GDP per capita (Gross Domestic Product in equivalent USD converted using Purchasing Power Parities (PPPs); OECD, 2016)	22,071 ^b	46,401 ^a
IHDI (Inequality-adjusted Human Development Index; UNDP, 2016)	0.692 ^b	0.859 ^a
Cumulative expenditure per student between 6 and 15 years (in equivalent USD converted using Purchasing Power Parities (PPPs); OECD, 2016)	40,607 ^b	92,214 ^a
Education Index (Mean and Expected Years of Schooling; UNDP, 2013)	0.746 ^b	0.884 ^a
Creation of Ministry of the Environment (Year)	2010	1986
Material recovery (Recycling + Composting; OECD, 2015)	1% ^b	65% ^a

^a Above OECD average.
^b Below OECD average.

Table 2
Summary of characteristics of the volunteer participation in Chile and Germany.

Characteristics of volunteer participation	Chile	Germany
Number of participating schools	41	24
Number of total classes/courses	42	31
Number of participating students	756	627
Number of participating teachers	50	30
Number of students per class/course	9–40	5–41
Ages of participating students	9–17	10–16

zones (as shown in Fig. 1C). Although Rügen Island is officially located outside the Bay of Mecklenburg, for the purpose of this study it was considered as part of it.

In Germany, 23 beaches were surveyed. Seven of these were situated along the North Sea coast, including Pellworm Island, at an average distance of 25 km from each other. In the Bay of Kiel, the seven surveyed beaches were on average 15 km apart from each other, while in the Bay of Mecklenburg the average distance between the nine surveyed beaches was 32 km (Table 3).

2.3. Beach surveys of AMD

Prior to the beach surveys, all students were introduced to the marine litter problem and they learned about the scientific method, through several theoretical and experimental activities and tasks contained in the workbook described above. The preparatory activities were intended to serve as training and motivation for the students to actively participate in a real scientific study.

Each class/course selected a sandy beach close to the school to conduct the survey, taking accessibility and security into account. All beach surveys were conducted between May and June 2016, and, whenever possible, a local scientific advisor was contacted to support the students and teachers during the sampling activity. The advisors, who were mostly volunteer collaborators, were marine biologists or other professionals related to natural sciences. They participated in the beach surveys to instruct teachers and students, to ensure that the surveys were rigorously conducted, and to identify potential problems with the data collected.

Many authors have highlighted the difficulty in comparing data among different beach litter studies due to various factors, such as beach topography, unequal distribution of litter on the beach, hydrographic and geological conditions, differences in sampling protocols and the type of data recorded (see e.g. Ryan et al., 2009; Browne et al., 2015; Gaigani et al., 2015). In order to overcome this and obtain data that are comparable among all surveys conducted in Chile and

Germany, all of the participating schools followed a standardized methodology developed by the Chilean research team and successfully used in previous investigations (see e.g. Bravo et al., 2009; Eastman et al., 2014; Hidalgo-Ruz et al., 2018).

Briefly, each group of students first established on their beach the survey transects, by marking lines perpendicular to the coastline, going from the waterline to the upper edge of the beach (identified by the base of dunes, a road, a promenade, etc.) (Fig. 2). The transects were established at random (i.e. not looking for the cleanest or most contaminated areas), and their number (1–6) depended on the beach length and the number of participating students. Along each transect, students marked between two and six sampling stations, and at each station a 3 m × 3 m quadrat (9 m²). The number of stations (2–6) depended on the width of the beach, i.e. more stations could be placed on wider beaches; regardless of the number of stations, at least one station was positioned close to the waterline and one was at the upper edge of the beach. In general, sampling stations were placed at (1) the waterline, (2) between the waterline and the high tide line, (3) the high tide line, (4) the historic high tide line, (5) the dry zone, and (6) the upper edge of the beach (Fig. 2). Within each 9 m² quadrat, all macrolitter items found on the beach surface were collected, counted, and classified according to the following categories: papers, cigarette butts, plastics, metal, glass, processed wood, natural wood, algae, plants, and other residues (collected items measured 25 mm or larger, thus including cigarette butts or bottle caps). All data were sent by the responsible teachers to the research teams in Chile and Germany, either via e-mail or by uploading to a website specifically developed for the project (www.save-ocean.org).

It is important to note that this survey method has been carefully developed to be simple and easy to follow, to minimize potential mistakes by the schoolchildren volunteers that might affect data quality. Furthermore, this protocol has been tested and validated by the *Científicos de la Basura* program throughout 10 years of collaborative research work with schoolchildren and their teachers (see Bravo et al., 2009; Eastman et al., 2014; Hidalgo-Ruz et al., 2018).

2.4. Data evaluation and statistical analyses

To assess the litter problem along the Chilean and German coasts and to compare AMD composition between the two countries, only data for anthropogenic litter were included in the analysis (i.e. papers, cigarette butts, plastics, metal and glass), and therefore debris of natural origin (i.e. natural wood, algae and plants) was excluded. Teachers frequently remarked that participants did not distinguish between processed and natural wood, and schoolchildren also sometimes included natural debris (e.g. feathers and seashells) in the category “others”; thus we decided to exclude these items from the analyses (see

Table 3
Distance between surveyed beaches along the Chilean and German coasts (in km), as measured by following the coastline in Google Earth.

	Surveyed beaches (n)	Distance between surveyed beaches (in km)			
		Average ± SD	Median	Minimum	Maximum
Chile					
Zone 1	5	206.9 ± 5.2	208.3	199.4	211.4
Zone 2	6	128.2 ± 95.2	173.9	11.5	228.3
Zone 3	8	51.6 ± 36.6	62.3	1.8	98.1
Zone 4	9	54.8 ± 30.6	61.4	13.2	98.0
Zone 5	7	481.8 ± 595.5	253.8	99.5	1662.6
Rapa Nui (RN)	1	3600 ^a	–	–	–
Juan Fernández (JF)	1	670 ^a	–	–	–
Germany					
North Sea	7	24.8 ± 22.8	18.4	0.6	63.9
Bay of Kiel	7	15.3 ± 25.2	3.7	0.2	64.7
Bay of Mecklenburg	9	32.1 ± 41.2	12.0	3.0	121.2

^a Distance from oceanic island to mainland.

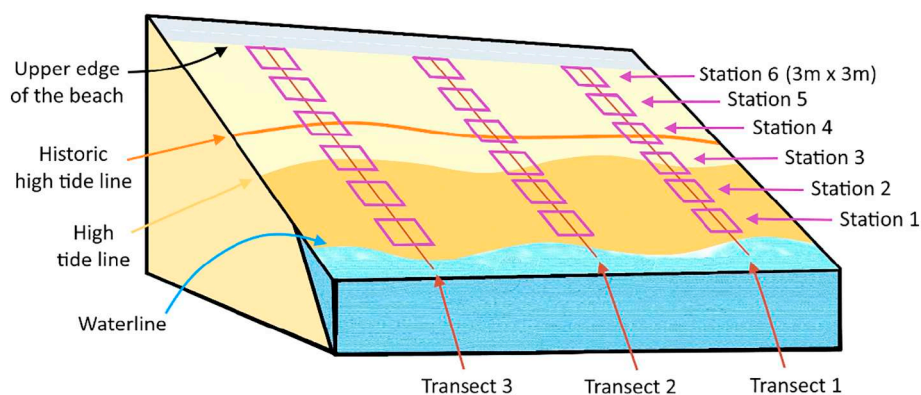


Fig. 2. AMD survey protocol for sandy beaches. Sampling stations of 9 m^2 ($3\text{ m} \times 3\text{ m}$) area are established on transects perpendicular to the coastline, ranging from the waterline to the upper edge of the beach. Modified after Bravo et al. (2009) (Creative Commons BY-NC 4.0 license).

also Hidalgo-Ruz et al., 2018).

Prior to analysis, data were assigned to the respective geographic zone for each country (see “Study areas”). Density of AMD (items per m^2) was calculated and evaluated in order to obtain comparable measures of the magnitude of the marine litter problem in Chile and Germany. For this, graphical representations of AMD density data per beach and per zone were generated. Regarding AMD composition, the main litter categories were evaluated in terms of percentage (%) of the total AMD for each zone. Hierarchical Clustering and Principal Coordinates Analysis were used to examine the relative similarities in the composition (categories) of AMD among zones (Clarke and Warwick, 2001). These multivariate analyses were conducted in PRIMER v6 (Primer-E Ltd., Plymouth, UK). We used Bray-Curtis similarity matrices and square-root transformation on observed abundances (items per m^2) of different AMD types from the different zones and/or islands of each country.

The data on the Chilean beaches analyzed herein represent part of the data utilized in a previous study that examined the temporal tendencies of beach litter in Chile from three different study years (2008, 2012, and 2016; see Hidalgo-Ruz et al., 2018). In the present study we re-analyzed the 2016 Chilean data and compared them with the beach litter situation in Germany during the same year, thus conducting a geographical (i.e. inter-hemispherical) comparison. Please, note that Hidalgo-Ruz et al. (2018) considered the surveys carried out on 39 Chilean beaches in 2016, whereas herein we include only the data of beaches surveyed by the schools formally participating in the binational citizen science project (i.e. 37 beaches).

3. Results

3.1. AMD densities on Chilean and German beaches

The average density of AMD on beaches from Chile was 2.2 items per m^2 , showing high variability among all the surveyed beaches and geographic zones (Fig. 3). There was no consistent pattern in the variability of AMD density, but overall litter seemed to be more abundant in the northern half of the country (zones 1–3) than in the south (zone 5). Debris density showed a maximum in the Antofagasta region ($44.5\text{ items per m}^2$ on the beach Balneario Municipal de Antofagasta, in zone 1), which considerably exceeded the national average. Densities of AMD on the beaches of the oceanic islands were low and below the national average: 0.5 items per m^2 on Anakena beach (Rapa Nui), and 0.7 items per m^2 on El Arenal (Juan Fernandez).

In Germany, beaches had a lower national average of 0.4 items per m^2 (Fig. 3). Among the three German zones (North Sea, Bay of Kiel and Bay of Mecklenburg), AMD densities were fairly similar; however, in general, they seemed to be slightly lower on the beaches of the North Sea than the beaches of the Baltic Sea. The maximum AMD density was

registered on Warnemünder Strand in the Bay of Mecklenburg (1.9 items per m^2).

3.2. AMD composition on Chilean and German beaches

In general, in most geographic zones from both Chile and Germany plastics and/or cigarette butts dominated, but in some zones there were also relatively high percentages of other items (papers, metals, and/or glass) (Table 4). In Chile, all continental zones (1 to 5) strongly followed this pattern, while the composition of AMD types in Juan Fernandez was conspicuously different, with the most abundant item being glass, followed by plastics and metals. In both qualitative and quantitative terms, AMD composition was diverse in zones 1 to 5 and Juan Fernandez, as seen by the presence of the five litter categories, with at least three of them contributing $> 10\%$ (Table 4). The beach on Rapa Nui, on the contrary, presented a high predominance of plastics (75.3%) and a very low diversity of AMD items.

Similarly, AMD diversity was low on German beaches of the North Sea, where plastics accounted for almost 85% of the total AMD (Table 4; see also Table S1). The other zones of Germany, i.e. the two bays of the Baltic Sea, had a more diverse AMD composition, although showing different proportionate compositions: in the Bay of Kiel, plastics dominated, followed by cigarette butts and glass items, whereas in the Bay of Mecklenburg, the most abundant items were cigarette butts, then plastics and papers (Table 4 and Table S1).

These findings were supported by the Hierarchical Clustering, showing that the composition of AMD from Continental Chile (zone 2 to zone 5) and Germany (Bay of Kiel and Bay of Mecklenburg) were relatively similar. Interestingly, there was also an 82.2% similarity in AMD composition between Rapa Nui (Chile) and North Sea beaches (Fig. 4A). The AMD composition at Juan Fernandez and in zone 1 from Continental Chile were relatively different from the AMD composition from all other locations (Fig. 4A).

The Principal Coordinates Analysis clearly separated locations from continental Chile and Germany in the ordination space, where negative values of the first axis (PCO1) were attributed to the Chilean locations and positive values to the German locations. The first axis explained 64.7% of the total variation of the analysis (Fig. 4B). Rapa Nui had also positive values of PCO1 aggregating it with German locations. Similar as in the cluster analysis, zone 1 from Continental Chile and Juan Fernandez were different from all other locations.

4. Discussion

4.1. Volunteer participation and citizen science approach

The present study employed a beach survey protocol that had been successfully used in previous investigations (Bravo et al., 2009;

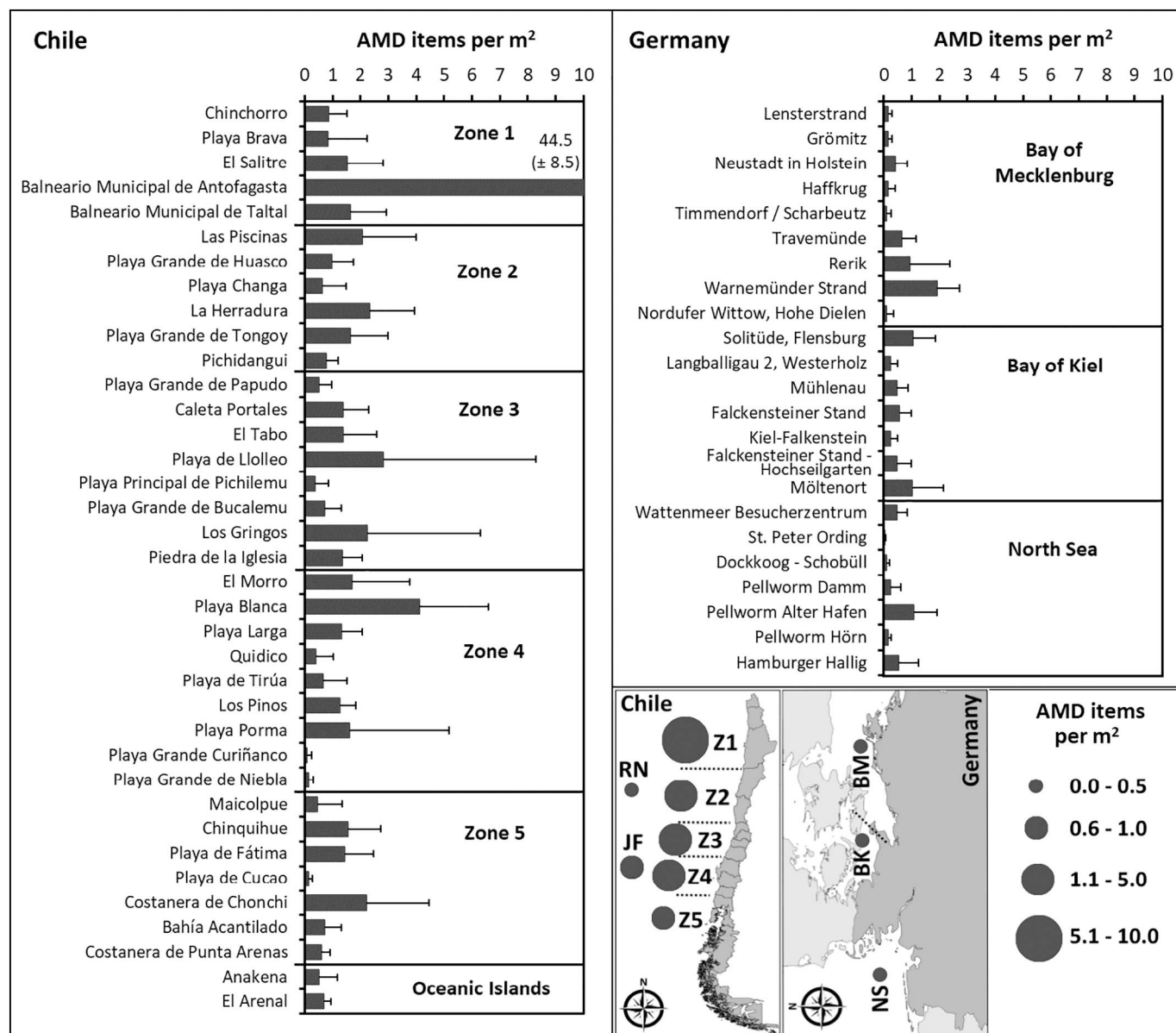


Fig. 3. Top: AMD densities (items per m²) on each surveyed beach in Chile and Germany (error bars show standard deviations). Bottom-right: Visual representation of AMD densities (items per m²) in each geographic zone in Chile and Germany, respectively. Z1–Z5: Zones 1–5; RN: Rapa Nui (Easter Island); JF: Juan Fernandez; NS: North Sea; BK: Bay of Kiel; BM: Bay of Mecklenburg. Dashed lines separate the different zones.

Table 4
Contributions (%) of the different categories of AMD surveyed on Chilean and German beaches, subdivided by geographic zone in each country. Values represent the mean of all beaches from each zone. Maximum values for each zone are shown in bold numbers, while extreme values are underlined.

	Papers	Cigarette butts	Plastics	Metals	Glass
Chile					
Zone 1	12.8	54.9	24.1	3.0	5.1
Zone 2	10.5	39.3	40.4	3.3	6.6
Zone 3	7.5	32.8	49.9	2.9	7.0
Zone 4	16.7	19.1	40.3	8.8	15.1
Zone 5	12.1	11.1	53.9	5.6	17.4
Rapa Nui (RN)	3.7	16.0	75.3	2.5	2.5
Juan Fernandez (JF)	10.7	1.3	30.0	20.0	38.0
Germany					
North Sea	9.6	4.0	84.9	1.2	0.3
Bay of Kiel	9.6	28.2	40.9	5.7	15.5
Bay of Mecklenburg	13.0	43.4	29.9	6.0	7.7

Eastman et al., 2014; Hidalgo-Ruz et al., 2018). Compared to other methods, our protocol generates AMD density data and is simple with regard to the sampling area and the variety of litter categories reported, allowing for straightforward and standardized comparisons of litter abundances between beaches and countries. Other methodologies, such as the OSPAR protocol for beach litter surveys (OSPAR, 2010), produce more ambiguous data on AMD densities and require very large areas to be sampled (i.e. 100 m of length per beach width). Similarly, the International Coastal Cleanup (ICC), while achieving broad international coverage, generates a total number of items but no rigorous standardization of sampling effort (per area, or per time) per beach, and thus has only limited value for spatial and temporal comparisons of litter densities (see e.g. Ocean Conservancy, 2017). Nevertheless, even though our protocol presents the aforementioned advantages, it is also important to highlight its shortcoming. Since this protocol was meant to be carried out by schoolchildren volunteers, it needed to be kept simple and thus AMD items were classified into only very broad categories. While this is beneficial for the work with volunteers, it might make it

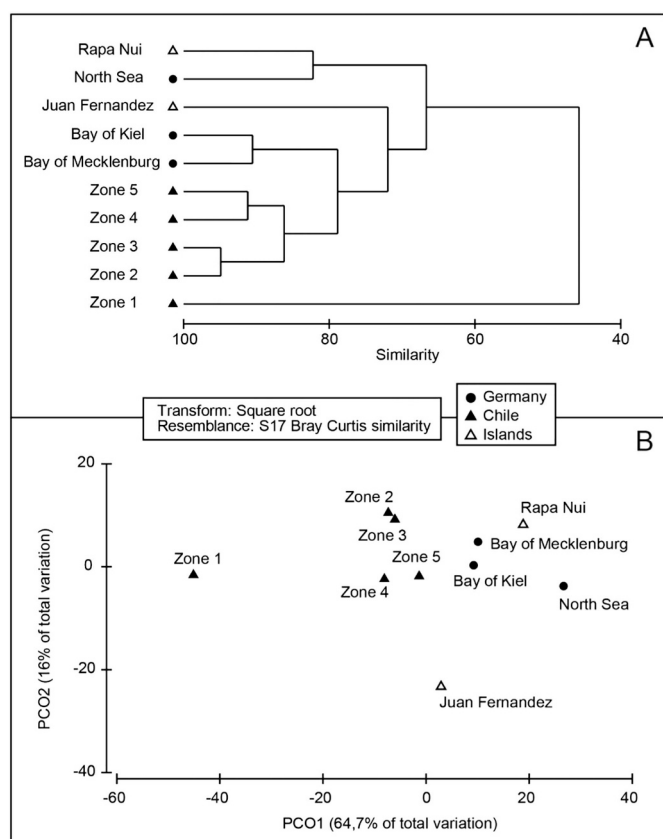


Fig. 4. Multivariate analysis based on the similarity coefficient of the abundance (items per m^2) of the different types of AMD in beaches from Continental Chile, Oceanic Islands of the South Pacific, and Germany. (A) Dendrogram for Hierarchical Clustering; and (B) Principal Coordinates Analysis based on Bray-Curtis similarity matrices and square root data transformation.

more difficult to pinpoint potential AMD sources.

On the other hand, citizen science presents the advantage to cover wide geographic areas, and it has been previously demonstrated that this approach is effective in studying the marine litter problem at regional and national levels (see e.g. Bravo et al., 2009; Ribic et al., 2010, 2012a, 2012b; Kordella et al., 2013). When working with volunteers the quality of data must be ensured (Hidalgo-Ruz and Thiel, 2015). In the present study this was achieved by three means: (i) support of local scientific advisors during beach surveys, whenever possible, (ii) simplicity of survey protocols and materials required for the activity, and (iii) training of responsible teachers and constant contact between them and project coordinators. Therefore, it can be affirmed that both Chilean and German students generated valid and reliable scientific data, making citizen science an ideal approach to investigate marine litter in two different countries, located even on different continents. Nonetheless, future studies might apply an even more rigorous approach, e.g. by having other schools or professional scientists take replicate samples on the beaches surveyed by the participating schools; alternatively, participants could be requested to submit a photographic record of all the items found in a sampling quadrat (see e.g. methodology of Kiessling et al., 2019).

4.2. Density of AMD on Chilean and German beaches

Many studies have been carried out to quantify AMD on beaches around the world (e.g. Ivar do Sul and Costa, 2007; Browne et al., 2015). Herein, we sought to determine AMD densities on Chilean and German beaches to compare the marine litter situation among both countries, which are considerably different regarding several aspects

(Table 1). We determined a national average density of 2.2 litter items per m^2 for beaches of Chile, which seems to be in the range of other studies carried out in Latin American countries. For example, in Baja California, Mexico, an average AMD density of 1.5 items per m^2 was found on a municipal beach (Silva-Iñiguez and Fischer, 2003), while a slightly higher value (3.6 items per m^2) was reported as the average AMD density for 19 surveyed beaches in Panama (Garrity and Levings, 1993). In Brazil, on the contrary, Oigman-Pszczol and Creed (2007) measured a much lower litter density (0.14 items per m^2) on several beaches of a tourist resort city, which may be due to potentially regular beach cleanups because of the economic importance of tourism in that region (Armação dos Búzios, Rio de Janeiro). In the case of Chile, the most littered region (Antofagasta in zone 1) is also a hotspot for beach tourists during austral summer, but the local government and residents of Antofagasta do not perceive AMD on beaches as a main issue (Kiessling et al., 2017; Hidalgo-Ruz et al., 2018).

Average litter densities found on German beaches (0.4 items per m^2) are also comparable to densities on beaches in other European countries of similar characteristics, i.e. densely populated and highly industrialized. In Scotland, for example, one study reported an average density of 0.4 items per m^2 (Velander and Mocogni, 1999), while another reported values in the range of 0.16 to 3.06 litter items per m^2 (Storrier et al., 2007). Similarly, average AMD densities of 0.2 items per m^2 were measured on an Irish beach (Benton, 1995), as well as on five Italian beaches along the Adriatic Sea coast (Munari et al., 2016). Interestingly, in our study the beaches near Kiel (Mölnertor, Falckenstein) had relatively low AMD densities even though the results from transport modeling suggest local accumulation of abundant marine litter from shipping (Schernewski et al., 2017). Likewise, the beaches in Travemünde and near Rostock (i.e. Warnemünder Strand) should present relatively high densities of AMD (Schernewski et al., 2017). This was confirmed by our survey only for the latter beach, probably because the transport modeling by Schernewski et al. (2017) considers only sea-based litter sources (e.g. shipping) whereas our results suggest mainly land-based sources (i.e. recreational activities) for AMD on many Baltic Sea beaches (see next section).

In consistency with the first goal of the present study, differences in AMD densities between Chilean (2.2 items per m^2 on average) and German beaches (0.4 items per m^2 on average) could be observed, which might be due to differences in littering habits and law enforcement. Industrialization and population density are substantially higher in Germany than in Chile and, therefore, more litter might be expected on German beaches. However, our data showed the opposite. In Chile, the most contaminated beaches were the northern and central ones (zones 1–3), with Antofagasta beaches contributing significantly to the high national AMD density. In addition, most beaches from zones 1–3 are highly recreational, receiving many tourists all year round, with a peak during summer. This situation differs from Germany, where the most recreational and touristic beaches are visited primarily during summer. Importantly, the most touristic beaches are located along the North Sea coast, which is entirely protected by National Parks. Thus, strong regulations for tourists and regular cleanings may explain the low AMD densities on these German beaches (the lowest among all the surveyed zones considering both countries, as seen in Fig. 3). Also, among the local population from the North Sea coast there is a strong sense of belonging and caring for the environment (Ratter and Gee, 2012), which may also contribute to low incidences of littering and cleaner beaches. In contrast, while people in Chile expressed concerns about beach cleanliness, a comparatively large proportion of beach users also admitted to have littered on the beach (Eastman et al., 2013). Differences in environmental awareness might thus lead to the observed differences in AMD abundances on beaches in Chile and Germany. Better implementation and enforcement of already existing laws may play an important role as well, given that, for instance, the Chilean Extended Producer Responsibility Law is pending its implementation (Ministerio del Medio Ambiente de Chile, 2016), whereas a similar

norm has been in force for 25 years in Germany (Fischer and Petschow, 2000).

4.3. Composition and sources of AMD in Chile and Germany

Studying the composition of AMD is relevant for identifying major sources (Galgani et al., 2015), and although plastics have been shown to dominate marine litter (Derraik, 2002; Galgani et al., 2015), particular sources may substantially influence the specific composition and proportion of the different AMD items (see e.g. Oigman-Pszczol and Creed, 2007). Furthermore, Wilson and Verlis (2017) have recently suggested that plastic items are currently so ubiquitous, that focusing on other types of litter may be more meaningful for determining AMD sources; consequently, in this study we have concentrated on the proportions of the different AMD types. Contrary to what was expected based on the considerable socio-economic, educational and environmental differences between Chile and Germany (Table 1), AMD composition did not consistently differ between the two countries overall, but instead it varied among zones within the countries, according to their economic activities and AMD sources.

In Chile, the litter composition on beaches reflects well the previously identified AMD sources: on the highly recreational beaches of the northern and central zones (1 to 3), massive tourism (i.e. beach users) was identified as the main litter source (Bravo et al., 2009), which is inferred from the predominance of both cigarette butts and plastics, and the greater diversity of litter types reported here. As shown by Corbin and Singh (1993) and Madzena and Lasiak (1997), activities of beachgoers are usually resulting in a greater diversity of AMD types (e.g. plastics, cigarette butts, glass, metals, etc.) on recreational beaches (see also Wilson and Verlis, 2017), whereas on non-recreational beaches plastics are highly dominant, accounting for ~80% of total AMD. For southern-central Chile (zone 4) large rivers are regarded as the principal input of beach AMD and plastics dominate (Bravo et al., 2009; Rech et al., 2014), which could be confirmed by our findings. However, contrary to Rech et al. (2014), where non-buoyant items (i.e. glass and metal) were usually very scarce, we observed relatively high proportions of glass, suggesting that other local, land-based sources may also contribute AMD. In the austral region (zone 5), Bravo et al. (2009) and Hinojosa and Thiel (2009) suggested aquaculture activities as an important source of AMD on local beaches, while Perez-Venegas et al. (2017) found the artisanal fishery as the main source of litter on a remote island from the fjord region. These findings are in agreement with the higher percentage of plastics found in that zone, as Styrofoam and other plastic materials are intensively used in aquaculture and fishing.

In Germany, both bays of the Baltic Sea (Kiel and Mecklenburg) present a composition that is typical of recreational beaches, as seen by the predominance of cigarette butts and plastics (see e.g. Clareboudt, 2004; Bravo et al., 2009), similarly to zones 1–3 in Chile. This suggestion agrees with the findings by Schernewski et al. (2017) and Hengstmann et al. (2017), who found that tourism was the most important source of litter on several German Baltic beaches and four beaches on Rügen Island, respectively. On Rügen Island, at the easternmost part of the Bay of Mecklenburg, Hengstmann et al. (2017) identified shipping and fishing as secondary sources, as plastic waste from ships float and may get stranded on beaches (e.g. Vauk and Schrey, 1987; Garrity and Levings, 1993; Bergmann et al., 2017; Watts et al., 2017). Our study indicates that these sources are of minor importance in the Bay of Mecklenburg, while shipping through the Kiel Canal may contribute to the slightly higher proportion of plastics found in the Bay of Kiel. Riverine input is unlikely for these bays, given that the only large river in the area (the Oder river) discharges to the east of the Bay of Mecklenburg and is separated from it by Rügen Island.

The North Sea, in contrast, is an important zone for maritime transport with some of the most frequented shipping routes in the world, as well as being one of the world's most important fishing grounds (EEA, 2002; see also Fig. S6 in Halpern et al., 2015). Therefore,

these two major AMD sources may explain the high dominance of plastics on the North Sea beaches (~85%) found in this study, as also suggested by Schernewski et al. (2017). These observations and suggestions also agree with previous findings for the North Sea (Schulz et al., 2013, 2015). For instance, Vauk and Schrey (1987) and Thiel et al. (2011) inferred that a large proportion of beached and floating litter, respectively, in the German Bight originated from passing ships, being highly dominated by plastic items (> 70% of total). Kammann et al. (2018) and Gutow et al. (2018) found high proportions of plastic litter (83% and 95%, respectively) on the North Sea's seafloor, which were in both studies mostly composed of items attributed to intense fishing activity. The former authors also suggested a possible long-range transport from distant sources into the North Sea, since light litter items, such as plastic, can be floating before sinking to the seafloor (Kammann et al., 2018). As reported elsewhere (Galgani et al., 2000; Lebreton et al., 2017), rivers may also be a major input of AMD into the North Sea, and plastic items are also dominant in these cases (van der Wal et al., 2015). Even though the North Sea is an important recreational and touristic area (EEA, 2002), beach litter composition reported herein suggests that coastal tourism unlikely is a major source of AMD, albeit it might have some contribution (Schulz et al., 2015). Thus, we suggest that a large proportion of floating AMD (mostly plastics) arrives on the North Sea beaches coming from the western North Sea, the British Channel, passing ships, and rivers (see also Gutow et al., 2018).

When comparing between the two countries, it is most notable that AMD composition on Rapa Nui (Chile) was very similar to that of the North Sea, for which we suggest two possible explanations. First, AMD sources and transport of litter via oceanic currents may be similar on Rapa Nui and North Sea beaches. A previous study on small plastic debris by Hidalgo-Ruz and Thiel (2013) indicated that the beaches of Rapa Nui might be acting as a filter for floating plastic debris that is transported by the oceanic surface currents towards the center of the South Pacific Gyre (Lebreton et al., 2012; Maximenko et al., 2012; Eriksen et al., 2013). Accordingly, Rapa Nui may accumulate plastic litter coming from distant sources around the South Pacific (Miranda-Urbina et al., 2015) and oceanic offshore fishing fleets (Kiessling et al., 2017). Likewise, the surface circulation of the North Sea “captures” floating litter from ships, fishing vessels and rivers, accumulates it and casts it onto nearby beaches (see Thiel et al., 2011, and Gutow et al., 2018). Two recent studies have reported similar situations in other parts of the world's oceans. Jang et al. (2018) suggested that the Bengal Current transports plastic items from distant sources to the Bengal Gyre east of Sri Lanka, where they then accumulate. Ourmieres et al. (2018) suggested that a coastal current in the northern Mediterranean Sea, along with onshore winds, affects the accumulation and transport of floating marine debris which is then pushed onto beaches of the Antibes coastline in France. Secondly, the high proportion of plastics and low diversity of AMD items observed on the beaches of Rapa Nui and the North Sea may also be explained by a specific fractionating of the litter assemblage, given by the properties of the different litter types. For instance, most plastic debris floats and can thus travel longer distances across the ocean before sinking, as opposed to non-buoyant items (e.g. glass and metal) and rapidly degrading items (e.g. paper). This may also be affected by biofouling, which causes the smallest and less buoyant fraction of AMD to sink, limiting its dispersal in the ocean, whereas the larger and highly buoyant debris items, such as plastic litter, persist at the sea surface and are able to reach farther distances from their sources (Ryan, 2015; Fazey and Ryan, 2016).

5. Conclusions and outlook

In the present citizen science project schoolchildren from both Chile and Germany generated valid and reliable AMD data, as ensured by the application of three strategies (i.e. field support by scientific advisors, simple protocols, and constant contact between teachers and project coordinators), demonstrating that the citizen science approach can

successfully be used to study marine litter on very broad spatial scales.

Our data showed that overall AMD densities are substantially higher on Chilean beaches than in Germany, possibly due to better environmental education, efficient law implementation and enforcement, and consequently more awareness, in the latter country. We thus recommend improved education and enforcement of already existing laws in Chile, but also the reduction of production and consumption of mainly plastic products, in order to achieve effective solutions of the marine litter problem. Additionally, identifying the sources of marine litter is the basis for the establishment of adequate public policies and administrative decisions to solve this problem, specific to each region. In this study, we found that AMD composition most consistently differs among the different zones investigated (instead of overall Chile and Germany), according to their main economic activities and litter sources. Therefore, given the AMD sources identified herein (i.e. local sources, mainly beach users, in Continental Chile and the German Baltic beaches; sea-based sources in Rapa Nui and the North Sea), we recommend that in northern-central Chile and the Baltic Sea, the focus should be placed on policies addressing tourists and beachgoers, and especially on the smoker population. In the North Sea and the Southern Pacific Ocean, by contrast, maritime regulations and control should be strengthened.

Finally, in view of these findings, our study contributes to establish that beach litter composition can be used as a simple and straightforward proxy to determine AMD sources. In the marine litter field, it is important to keep in mind that there is not a unique and ‘one size fits all’ solution (see e.g. Chen, 2015). On the contrary, solutions may vary strongly depending on the country or region, and therefore it is important to adequately diagnose the problem and identify its sources around the globe.

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