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Critical Review

Global review of beach debris monitoring and future recommendations

Catarina Serra-Gonçalves, Jennifer L. Lavers, and Alexander L. Bond

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Global review of beach debris monitoring and future recommendations

Catarina Serra-Gonçalves[1], Jennifer L. Lavers[2*] and Alexander L. Bond[2,3]

[1]University of Tasmania, Institute for Marine and Antarctic Studies, School Road, Newnham, Tasmania, 7250, Australia

[2]University of Tasmania, Institute for Marine and Antarctic Studies, 20 Castray Esplanade, Battery Point, Tasmania, 7004, Australia

[3]Bird Group, Department of Life Sciences, The Natural History Museum, Tring, Hertfordshire, HP23 6AP, United Kingdom

*Corresponding author: phone +61 (03) 6324 3868; e-mail: Jennifer.Lavers@utas.edu.au

ABSTRACT: Marine debris is distributed worldwide and constitutes an increasing threat to our environment. The exponential increase of plastic debris raises numerous concerns and has led to an intensification in plastic monitoring and research. However, global spatial and temporal patterns and knowledge gaps in debris distribution, both on land and at sea, are relatively poorly understood, mainly due to a lack of comprehensive datasets. Here we critically review the quality of the available information on beach plastic debris worldwide to highlight where the most urgent actions are required, and to promote the standardization of reporting metrics and sampling methods among researchers. From a total of 174 studies evaluated, 27.0% reported marine debris densities in metrics that were not comparable. Some studies failed to report basic parameters, such as the date of the sampling (9.8%) or the size of the collected debris (19.5%). Our findings show that current research regarding beach debris requires significant improvement and standardization and would benefit from the adoption of a common reporting framework to promote consensus within the scientific community.

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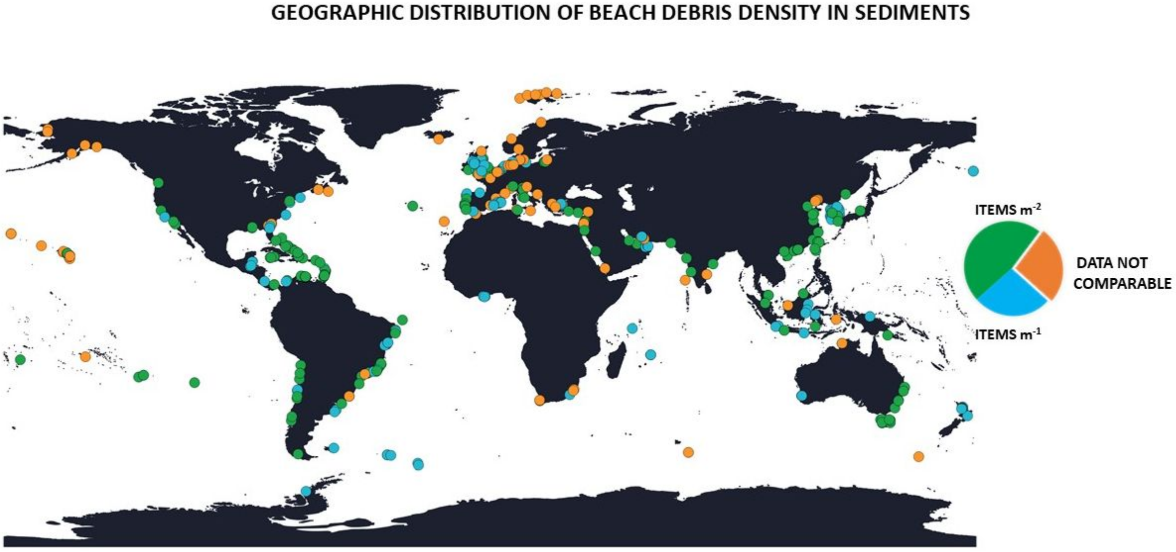

KEYWORDS: baseline data; global review; plastic pollution; reporting metrics, standardised methods

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1. INTRODUCTION

Plastic products, especially single-use items, have become widespread in our society, and as a result, production and disposal has increased drastically in recent decades [1, 2]. A lack of effective waste management and mitigation strategies, particularly in low- and lower-middle-income countries, has resulted in the accumulation of large amounts of plastic debris in the environment [3-5]. Often referred to as marine debris, it is defined as any persistent, manufactured or processed solid material made or used by humans and either deliberately or accidentally discarded, disposed or abandoned in the marine and coastal environment [8]. Monitoring of aquatic environments suggests the overall level of plastic (typically accounting for 61-87% of debris) is increasing [4, 6, 7, 9], with plastic production and consumption rates showing no signs of slowing .

At present, plastic debris represents one of the most rapidly expanding and topical environmental hazards, due to the durability of plastic products and their diverse negative impacts on wildlife, habitats, and economies [11-13]. Most, if not all, marine environments (e.g., coastal zones, open ocean, deep-sea sediments) are now contaminated by debris [14, 15], with significant quantities reported even in the most remote corners of the Earth [16, 17]. Debris distribution is influenced by ocean currents, wind, and waves, all of which can fragment items and transport them over vast distances [18].

Plastic debris can result from numerous human activities, but is broadly categorised into either land- or marine-based sources [19]. Approximately 80% of all debris originates on land, being of particular concern in coastal ecosystems where it represents 60-80% of litter on beaches [14, 20]. These same areas are important to local communities and tourism; therefore, debris has the potential to damage the aesthetic value of shorelines and consequently, their economic value. Furthermore, the degradation of these habitats constitutes a major threat for the myriad marine and coastal species that rely on them [21, 22]. The accessibility of coastal ecosystems, combined with the visible manifestation of debris on beaches, has led to the majority of data on debris being derived from beach surveys [23].

In 2015, all United Nations Member States adopted the 17 Sustainable Development Goals (SDGs) as part of the "2030 Agenda for Sustainable Development" [24]. Goal 14 aims to conserve and promote the sustainable use of the oceans, including the prevention and significant reduction in marine pollution by 2025. Additionally, in 2016 almost 200 countries united as part of the Convention on Biological Diversity to ratify the "Strategic Plan for Biodiversity 2011-2020" which includes Aichi Biodiversity Target 8 that aims to reduce all types of marine pollution by 2020 [25].

It is crucial to measure change and evaluate progress towards established international targets [26]. There has been significant investment in plastic monitoring and research, especially since 2013 , however, our understanding of this environmental issue remains largely based on individual surveys reporting the abundance and type of beach debris at single locations [28-30]. In the dynamic marine environment, these one-off surveys provide no information on changes over time, something which can only be overcome with robust sampling at the same site over many years.

A handful of studies have reviewed the literature to identify factors that may influence the global distribution of beach debris [14, 23, 31-34] and have made recommendations for standardised reporting metrics [32, 35]. However, assessing progress against global environmental policy targets remains difficult as the data generated through dozens of single-year, single-location beach debris studies undertaken in recent decades has not been reviewed. Therefore, there is an urgent need for a review and analysis of existing beach debris data so that researchers can better assess the global scale of this issue.

Here we provide an overview of the available information regarding beach debris abundance worldwide in order to a) identify global geographic distribution trends and gaps in beach debris abundance, and b) evaluate the performance of existing studies against established data standards. Through synthesising research outputs and translating data into a common language (i.e., reporting metrics), we highlight where the most urgent actions are required to better understand the impacts of marine debris, enabling more effective mitigation policies to be developed.

2. METHODS

2.1. Literature review. We conducted a systematic review following established methods [36]. An extensive search of the ISI Web of Knowledge database was conducted in April 2018 to search for publications using the following key words: 'beach debris OR beach OR beach litter' combined with 'marine debris OR plastic debris OR marine pollution OR plastic pollution OR marine litter OR plastic litter OR plastic marine pollution OR marine plastic pollution OR marine plastic litter'. Our search aimed to include all peer-reviewed papers published before 31 December 2017. However, the results missed some entries (see Discussion) and did not include records from the grey literature or popular media. The contemporary literature typically adopts five main categories for debris size, however there is some disagreement regarding the categories used (e.g., micro- and nano-particles). Therefore, we use only the two most common debris size categories: macro- (> 5 mm) and micro-debris (0.2 - 5 mm) [14, 37-40]. We excluded all debris < 0.2 mm.

Based on these search terms, we obtained 1060 publications from 1980-2017. Duplicate papers were removed as well as those where the title or abstract was not related to plastic debris located in beach sediments (e.g., papers on ocean-based debris or chemicals adhered to debris; Figure 1). Following this first data filter, a total of 298 papers were considered for future reading, with information extracted from only those papers which included beach sediment debris density data, resulting in a final total of 174 papers (Figure 1). The final references can be found in the Supporting Information.

From these 174 papers, the following information concerning beach debris was extracted, when available, for plastic and non-plastic items: (1) total debris abundance; (2) total debris density; (3) sampling location and year; (4) size class of sampled debris (macro- (≥ 5 mm), micro-plastics (0.2 -5 mm); (5) sampling method (surface (0 - 2 cm) or buried debris (> 2 cm)) with the corresponding depth when applicable; (6) reporting units; and (7) the most common debris item by mass and number. Some studies contained more than one sampling location and where possible, the beach debris density/mass data was reported for each location independently, otherwise a mean was reported for all locations combined. In rare instances where data were reported from vegetated areas (e.g., dunes), it has been excluded from this review. Published values were converted to the same units (items m^{-1} or items m^{-2}), when possible. Macro- and micro-debris densities were split and analysed independently, since micro-debris densities tend to be much higher, therefore not comparable on the same scale with macro-debris densities.

From each study, we also recorded (1) orientation of the sampling location (leeward (LW) or windward (WW)), (2) whether the sampling was conducted on an island or mainland locality, (3) whether it was a community science study, (4) the duration of the study (number of years: single-year *vs* multi-year studies), and if the respective multi-year studies went back to the same site (repeated sampling) (5) the number of locations sampled and (6) if the study recorded information regarding polymer types, colours, type of sediment, and potential debris sources (Table 1). Additionally, to identify possible convenience in selecting the sampling sites the country of affiliation for the first and last author (i.e., institution where the authors are based) was also recorded. In few occasions the extraction of specific information (e.g., size of the items, sampling frequency) was only possible due to being suggestive along the reading (e.g., reported as 'visible debris') but not explicitly reported in the evaluated publication.

2.2 Statistical analysis. A χ^2 test was performed to investigate the relationship between author affiliation location and study location. Kendall's tau coefficient was run to determine the strength of the association between affiliation country of the first and last authors, and the sampling country. Both first and last authors are considered to be the most important contributions to each study [41] and were included in our analysis. Three studies were excluded from this analysis since the first author had more than one country of affiliation. Statistical analyses were performed in R 3.5.0 (R Core Team, 2018). Results were considered significant when $p < 0.05$, and data are presented as mean ± SE.

3. RESULTS

3.1. Geographical patterns of the studies. Most papers referring to beach plastic debris were published in recent years, with half of the publications before 2014 (1980 - 2013) and the other half between 2014 and 2017. The 174 publications considered here contained data from 717 sampling sites in 71 countries (Figure 2), of which only four countries had >10 publications (Australia, Brazil, United Kingdom and United States). The United Kingdom was the most sampled country, with 64 sampling sites from 17 publications. It was closely followed by the United States (54 sites, 18 publications), then Australia (50 sites, 11 publications) and Brazil (48 sites, 18 publications). These same countries also had the highest number of study sites, followed by Indonesia (5 studies, 63 sites of which 59 were from a single publication [42], Figure 2). Most countries benefitted from only one or two studies of beach debris (72.6%, Figure 2) for example; Canada has only two studies (both from Nova Scotia [43, 44]) despite having the longest coastline in the world, and Antarctica only one [45]. Only a handful of studies were completed in Africa (6 publications, 17 sites). Islands (417 sites, 86 publications) were represented with more sites than Mainland (294 sites, 94 publications) but both had approximately the same number of studies (Table 1).

The country in which the study was completed along with the country of the first author's affiliation, were highly related (χ^2 = 20,806, n = 627, p < 0.001), as was study country and country of the last author's affiliation (χ^2 = 21,577, n = 627, p < 0.001). There was also a strong and positive correlation between the affiliation of the first (G = 0.62, n = 627, p < 0.001), and last author (G = 0.71, n = 627, p < 0.001) with the sampling country, which was statistically significant.

3.2. Overall patterns and reproducibility of reporting metrics. Most studies (n = 126, 71.2%; 543 sites) included different types of beach debris, not solely plastic. The proportion of plastic in beach debris among all studies was 70.1% (89 publications, 263 sites). Of the studies that spanned ≥2 years (22.9%, n = 40), nine (22.5%) did not return to the same site on subsequent sampling events (i.e., these 'multi-year' studies sampled different regions or countries in different years). The reported metrics and respective proportions are provided in Table 1.

Overall, 131 papers (73.6%) covering 566 sites (78.9%) reported debris density either by linear meter (items m^{-1}; 47 publications, 259 sites) or per unit area (items m^2; 84 publications, 307 sites; Figure 2). These units are not comparable therefore, the results are presented separately below.

3.3. Macro-debris global distribution and patterns.

3.3.1. Reported unit: items m^{-1}. The mean linear density among all sampling sites (n = 259) was 17.97 ± 4.34 items m^{-1}, with both the maximum (906.35 items m^{-1} [46]) and minimum values (0.01 items m^{-1} [47]) recorded in Brazil.

Of the studies reporting beach debris per m^{-1}, the majority sampled only macro-debris items (80.9%, 38 publications, 235 sites; Figure 3) with a mean density of 18.36 ± 4.77 items m^{-1}. The highest densities of macro-debris were found in Curaçao (253.30 items m^{-1} [29]), Belgium (217.44 items m^{-1} [49]), Israel (126.56 - 201.42 items m^{-1} [50]) and New Zealand (129.38 items m^{-1} [51]; Figure 3).

The lowest densities were distributed across the globe and ranged from 0 - 5 items m^{-1} at many sites (68.3%, 36 publications, 177 sites; Figure 2).

A small number of studies reported both micro- and macro-debris (10.6%, 5 publications, 15 sites). Publications that did not mention the size of the debris sampled (6.4%, 3 publications, 8 sites) were excluded from this analysis.

3.3.2. Reported unit: items m^{-2}. The average density of macro-debris across all sampling sites (50 publications, 182 sites) was 1,264.92 ± 529.72 items m^{-2}. The highest densities were reported for Pakistan (82,964.47 items m^{-2} [52]), South Korea (237.0 - 238.0 items m^{-2} [53]), China (163.0 items m^{-2} [54]), and Brazil (102.0 items m^{-2} [55]). The lowest densities were widely distributed across the globe and ranged from 0 - 5 items m^{-2} representing 64.2% of the sites (48 publications, 197 sites; Figure 4).

Most studies that reported debris densities per unit area included only macro-debris (54.9%, 50 publications, 183 sites; Figure 4) reporting an average of 463.87 ± 455.82 items m^{-2}. Some reported both micro- and macro-debris together (13.1%, 12 publications, 23 sites) and some did not mention the size of debris items sampled (8.8%, 8 publications, 30 sites). Therefore, these were excluded from this analysis.

3.4 Global distribution and patterns of micro-debris. Only one study reported micro-plastic items per linear meter (2.1%, 1 publication, 1 site) finding 2.96 items m^{-1} [48]. Of studies reporting items per unit of area, 23.1% reported densities of micro-debris (21 publications, 71 sites). The average reported micro-debris density was 4,174.74 ± 1,942.23 items m^{-2}, ranging from 0.0 to 119,182.0 items m^{-2} (21 publications, 71 sites; Table 1) The highest densities of micro-debris were found in South Korea (119,182.0 – 8,205.0 items m^{-2} [56, 57]), Jordan (43,947.0 items m^{-2}), China (6,675.0 – 3,242.0 items m^{-2} [54, 59]), and Japan (2,610.0 items m^{-2}) while the lowest densities were recorded in Brazil where no micro-plastics were detected [61].

4. DISCUSSION

Overall, from the 174 publications included in this review we obtained 717 data points, covering a total of 71 countries. Reporting units for the beach debris density data were variable, with most contemporary studies reporting the density per m^2 while studies undertaken before 2000 typically reported their data per m^{-1}. For the latter, a lack of information on survey methods means that these studies cannot be reproduced, as there is limited or no information on the actual area sampled. Such a fundamental problem precluded any temporal or spatial comparisons of beach debris, despite considerable effort in the field.

A handful of previous studies strived to understand spatial and temporal patterns in marine debris, identifying the challenges of comparing the available data due to the lack of standardized methods and reporting metrics [33, 62-64]. Even with increasing interest among researchers resulting in a growing number of beach debris studies, we are unable to analyse or predict spatial or temporal patterns at large scales with the available information. Below, we highlight the most common challenges and provide suggestions for possible solutions that can help us to move towards a common goal.

4.1 Geographical patterns of the studies. Spatially, the research effort to describe beach debris (measured as either the number of publications or number of sites) is focused only in a handful of countries (e.g., United Kingdom; Figure 2), with most countries represented by data from < 10 sites (Figure 2). The limited spatial coverage of studies makes it difficult to understand patterns and trends at a larger scale, which is urgently required. The strong relationship between authors' affiliation and study country suggests convenience is often a key driver in selecting sampling sites, likely influenced by funding limitations, the desire to engage with local research communities, or local research priorities. Consequently, current monitoring efforts for plastic debris may not accurately reflect priority locations (e.g., countries with few or no data regarding marine debris), representing a mismatch in the information that is available, and the information that it is required to be able to fill the current gaps and address this global issue.

4.2 Reproducibility and comparability of reporting metrics. A fundamental principle in science is that research should be reproducible. Despite this central tenet, we found a wide range of problems while extracting information regarding the studies' methods and results. For example, some publications did not report the precise sampling location within the chosen site (e.g., berm, high strandline) , a critical piece of information as local topography and geographic position (e.g., orientation) plays a significant role in where and how marine debris accumulates [29, 65-67]. Some studies have previously shown that different areas within the same beach can represent different densities of marine debris [30, 40, 56]. Although the high strandline is the most common area used for microplastic sampling, this area contains higher densities of micro-debris compared to the berm [30]. In contrast, Besley *et al.* suggested the sampling area may not affect the obtained densities for the beach. These opposing results highlight the importance of detailed sampling information; depending of the sampling area, the obtained densities may not be representative of the actual beach pollution status.

Information regarding the sampling depth (superficial or buried) or even the sediment type (e.g., sandy or rocky) was also lacking in some cases, or not reported for all sites (Table 1) [42, 68]. Both parameters can significantly alter study results and interpretation. For example, finer sediments accumulate more debris, especially microplastics [18, 69] and there is often considerably more debris reported buried in the sediment, as it is less affected by wave action and daily tides than superficial debris [16, 70]. Therefore, a consistent depth, usually the top 5 cm of sediment, should be sampled across studies, to maintain temporal and spatial comparability [62].

Reporting the size or size class of the collected debris is imperative, yet 19.5% of publications did not report this information (Table 1), or in some cases, data for both micro- and macro-items were pooled together [72, 73]. Defining a minimum size is fundamental to interpretation: when the same volume of sediment is passed through filters of varying mesh size, and items below a given threshold are discarded, meaningful comparisons depend on knowing the minimum mesh size. Similarly, in beach debris studies, reporting the minimum size detected (and ideally with some discussion of detection probability) is fundamental to meta-analyses and cross-study comparisons. A common agreement on the definition of debris size categories is also required, as suggested by previous studies, as some categories (e.g., meso-debris) lack a consensus among researchers [40].

While debris size is frequently reported among studies (Table 1), this information should also be presented alongside other metrics, such as the shape, origin (provenance), type (e.g., fragment, rope), and chemical composition (polymer type). Polymer identification provides useful information regarding the possible age or origin of the collected items, but often requires specialised equipment that is not always available, or affordable. The colour of debris items can provide useful information on the origin or duration of time spent in the environment through weathering [75]. However, when categorising debris by colour, it's crucial that researchers adopt the standardised colour categories that have been developed to ensure data are comparable over time [63, 64]. The same can be said for plastic type with standardised type categories having been developed [76-79].

We found that only 29% of the studies merely focused on plastic debris and therefore did not report all the types of debris (e.g., wood) or different plastic categories (by type or use). Only 62.6% of publications categorised their debris by type (Table 1), but in some cases, the range of categories used (or vague descriptions) made it impossible to distinguish between plastic and other types of debris. For example, in some studies rubber or polystyrene were assigned their own categories, while other studies pooled this debris in with general plastic or under the category 'other'.

The dimensions or number of transects/quadrats used, together with the number of total surveys, or the frequency of sampling, are also fundamental to the reproducibility of a study. In some cases, we noted an attempt to follow standard reporting protocols. For example, 89.1% of the publications reported the dimensions of their transect/quadrat, but almost half (48.0%) did not provide any information on the number of units of replication (Table 1). As a result, the density of debris could not be calculated based on the limited information provided. Although sampling frequency can determine at fine temporal scales different estimates of debris accumulation on beaches this information is still not uniformly reported within the scientific community [80-82]. The sampling frequency varied significantly among studies, spanning daily to yearly sampling intervals.

Although publications reported different metrics (Figure 2), most of the recently reported densities are per m^2 (46.6%; Table 1, Figure 4) which does not allow us to compare with records from pre-2000s (mostly items m^{-1}, 26.4%; Table 1, Figure 3). Although items per linear meter was frequently reported, this metric does not provide an accurate measure, therefore, we strongly recommend that future studies present items per unit area as a standard metric (See Box 1). Those studies reporting their data per unit area could therefore be viewed as priority locations for follow-up sampling. However, of the 84 publications that did report debris per unit area, 57.1% (n = 48, Figure 4) did not provide the necessary information for the study to be repeatable (e.g., sampling depth, exact sampling location). Unfortunately, only 20.7% (n = 36, see supporting information) of all studies appear to be reproducible. Depending on the density metric used, different debris 'hotspots' would also be identified: using items m^{-1} would identity countries such as Brazil and New Zeeland (Figure 1) as being the most heavily polluted, while Pakistan, South Korea, and China would be flagged if items m^{-2} were used (Figure 2). Very few studies (16.0%; Table 1) undertook a clean-up of the beach prior to beginning data collection. Removal of the 'standing stock' of debris can be important, depending on the research question, as this debris has accumulated over an unknown period of time may cause misinterpretation of the results [23, 42]. Studies that aim to identify patterns in debris density over time should therefore discard data collected during the first sampling period so that subsequent sampling events occur only when a known amount of time has elapsed.

Finally, some studies (9.8%, Table 1) failed to report extremely basic parameters, such as the date of the sampling. This important information impedes our ability to measure change over time, a critical component of assessing performance against local, national, and international environmental agreements and pollution reduction schemes. Also, most of the studies covered by this review were never repeated (i.e., one year or less), being single records in time. We were able to also identify among the multi-year studies a lack of replication. Furthermore, from all the publications only 31 came back to the same exact site in multiple years.

5. PERSPECTIVES AND OUTLOOK

To address issues with global impacts, such as plastic pollution, big datasets with an adopted framework can play an important role**.** In addition, sharing the existing knowledge among researchers and working together can be a key for future research (e.g., open online libraries) Current monitoring and mitigation efforts for plastic debris may not accurately reflect priority issues or locations, representing a mismatch in the information that is available and the information that is required to address this global issue. The standardization of the sampling methodology and of the reporting metrics was identified by Vegter *et. al.* [83] as one of the keys to understand rates and patterns of dispersal, accumulation and abundance of plastic debris in our environments. Despite the abundance of data currently available (717 sites spanning 1980 to 2017) the available data (quantity and quality) regarding marine and plastic pollution abundance is not possible for comparison. Therefore, future research requires an urgent significant improvement and standardization. Researchers' efforts should be more strategic in the future if we want to really understand the global patterns of distribution regarding marine pollution and evaluate progress against international environmental policy targets. Therefore, a framework, such as that recently suggested by Besley *et al*. [62] and Hartmann *et al*. would be crucial to overcome some of the challenges identified in this review by promoting consensus within the scientific community (See Box 1). However, as important as such information may be for future research, gathering these data can be time consuming and requires considerable effort. Acknowledging this, we emphasize there is a crucial need to report such metrics in a standardized way among studies.

BOX 1 – basic requirements to include in future beach debris studies:

- Date of the sampling
- GPS coordinates of the precise locations
- The specific size of the collected debris
- The specific depth of sampling
- Item categorization (type and use): best to present data for each category individually
- Reporting metric per area of sampling (or the total area covered)

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REFERENCES

1. UNEP and GRID-Arendal *Marine Litter Vital Graphics*; 2016.

2. Plastics Europe *Plastics—the Facts 2017: An analysis of European plastics production, demand and waste data Technical Report, Market Research Group, Brussels, Belgium.* https://www.plasticseurope.org/application/files/5715/1717/4180/Plastics_the_facts_2017_FINAL_for_website_one_page.pdf *(Accessed: August 2019*; 2017.

3. van Sebille, E.; Wilcox, C.; Lebreton, L.; Maximenko, N.; Hardesty, B. D.; van Franeker, J. A.; Eriksen, M.; Siegel, D.; Galgani, F.; Law, K. L., A global inventory of small floating plastic debris. *Environ. Res. Lett.* **2015,** *10*, (12), 124006.

4. Eriksen, M.; Lebreton, L. C.; Carson, H. S.; Thiel, M.; Moore, C. J.; Borerro, J. C.; Galgani, F.; Ryan, P. G.; Reisser, J., Plastic pollution in the world's oceans: more than 5 Trillion plastic pieces weighing over 250,000 tons afloat at sea. *PLoS One* **2014,** *9*, (12), e111913.

5. Lebreton, L.; Slat, B.; Ferrari, F.; Sainte-Rose, B.; Aitken, J.; Marthouse, R.; Hajbane, S.; Cunsolo, S.; Schwarz, A.; Levivier, A.; Noble, K.; Debeljak, P.; Maral, H.; Schoeneich-Argent, R.; Brambini, R.; Reisser, J., Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. *Sci. Rep.* **2018,** *8*, (1), 4666.

6. Law, K. L.; Thompson, R. C., Oceans. Microplastics in the seas. *Science* **2014,** *345*, (6193), 144-145.

7. Lebreton, L. C.; Greer, S. D.; Borrero, J. C., Numerical modelling of floating debris in the world's oceans. *Mar. Pollut. Bull.* **2012,** *64*, (3), 653-661.

8. UNEP *Marine Litter: A Global Challenge. 232.*; 2009.

9. Tekman, M. B., Gutow, L., Macario, A., Haas, A., Walter, A., Bergmann, M., LITTERBASE. In Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research: Germany. http://litterbase.awi.de/interaction_detail, 2017 (Accessed: July 2019).

10. PlasticsEurope *Plastics - the Facts 2014/2015: an analysis of European plastics production, demand and waste data.*; 2015. PlasticsEurope Market Research Group, Brussels, Belgium. https://www.plasticseurope.org/application/files/5515/1689/9220/2014plastics_the_facts_PubFeb2015.pdf (Accessed: November 2018).

11. Ballance, A.; Ryan, P. G.; Turpie, J. K., How much is a clean beach worth? The impact of litter on beach users in the Cape Peninsula, South Africa. *S. Afr. J. Sci.* **2000,** *96*, (5), 210-213.

12. Free, C. M.; Jensen, O. P.; Mason, S. A.; Eriksen, M.; Williamson, N. J.; Boldgiv, B., High-levels of microplastic pollution in a large, remote, mountain lake. *Mar. Pollut. Bull.* **2014,** *85*, (1), 156-163.

13. Gall, S. C.; Thompson, R. C., The impact of debris on marine life. *Mar. Pollut. Bull.* **2015,** *92*, (1-2), 170-179.

14. Barnes, D. K.; Galgani, F.; Thompson, R. C.; Barlaz, M., Accumulation and fragmentation of plastic debris in global environments. *Philos. Trans. R. Soc. Lond., B, Biol. Sci.* **2009,** *364*, (1526), 1985-1998.

15. Chiba, S.; Saito, H.; Fletcher, R.; Yogi, T.; Kayo, M.; Miyagi, S.; Ogido, M.; Fujikura, K., Human footprint in the abyss: 30 year records of deep-sea plastic debris. *Mar. Policy* **2018,** *96*, 204-212.

16. Lavers, J. L.; Bond, A. L., Exceptional and rapid accumulation of anthropogenic debris on one of the world's most remote and pristine islands. *Proc. Natl. Acad. Sci. U.S.A.* **2017,** *114*, (23), 6052-6055.

17. Waller, C. L.; Griffiths, H. J.; Waluda, C. M.; Thorpe, S. E.; Loaiza, I.; Moreno, B.; Pacherres, C. O.; Hughes, K. A., Microplastics in the Antarctic marine system: An emerging area of research. *Sci. Total Environ.* **2017,** *598*, 220-227.

18. Browne, M. A.; Galloway, T. S.; Thompson, R. C., Spatial patterns of plastic debris along estuarine shorelines. *Environ. Sci. Technol.* **2010,** *44*, (9), 3404-3409.

19. Thompson, R. C.; Moore, C. J.; vom Saal, F. S.; Swan, S. H., Plastics, the environment and human health: current consensus and future trends. *Philos. Trans. R. Soc. Lond., B, Biol. Sci.* **2009,** *364*, (1526), 2153-2566.

20. Gregory, M. R.; Ryan, P. G., Pelagic plastics and other seaborne persistent synthetic debris: A review of southern hemisphere perspectives. In *Marine Debris: Sources, Impacts, and Solutions*, Coe, J. M.; Rogers, D. B., Eds. Springer New York: New York, NY, 1997; pp 49-66.

21. Defeo, O.; McLachlan, A.; Schoeman, D. S.; Schlacher, T. A.; Dugan, J.; Jones, A.; Lastra, M.; Scapini, F., Threats to sandy beach ecosystems: A review. *Estuar. Coast. Shelf Sci.* **2009,** *81*, (1), 1-12.

22. Fujisaki, I.; Lamont, M. M., The effects of large beach debris on nesting sea turtles. *J. Exp. Mar. Biol. Ecol.* **2016,** *482*, 33-37.

23. Ryan, P. G.; Moore, C. J.; van Franeker, J. A.; Moloney, C. L., Monitoring the abundance of plastic debris in the marine environment. *Philos. Trans. R. Soc. Lond., B, Biol. Sci.* **2009,** *364*, (1526), 1999-2012.

24. United Nations General Assembly *Transforming our world: the 2030 Agenda for Sustainable Development. http://www.un.org/ga/search/viewdoc.asp?symbol=A/RES/70/1&Lang=E.*; UNEP/EA.3/L.19 UN General Assembly: 2015.

25. CBD. COP decision X/2 *Strategic plan for biodiversity 2011–2020. http://www.cbd.int/decision/cop/?id=12268. https://www.cbd.int/sp/targets/. (Accessed: November 2018).* 2010. .

26. Butchart, S. H.; Di Marco, M.; Watson, J. E., Formulating smart commitments on biodiversity: lessons from the Aichi Targets. *Conserv. Lett.* **2016,** *9*, (6), 457-468.

27. do Sul, J. A. I.; Costa, M. F., The present and future of microplastic pollution in the marine environment. *Environ. Pollut.* **2014,** *185*, 352-364.

28. Merrell, T. R., Accumulation of plastic litter on beaches of Amchitka Island, Alaska. *Mar. Environ. Res.* **1980,** *3*, (3), 171-184.

29. Debrot, A. O.; Tiel, A. B.; Bradshaw, J. E., Beach debris in Curacao. *Mar. Pollut. Bull.* **1999,** *38*, (9), 795-801.

30. McDermid, K. J.; McMullen, T. L., Quantitative analysis of small-plastic debris on beaches in the Hawaiian archipelago. *Mar. Pollut. Bull.* **2004,** *48*, (7-8), 790-794.

31. Barnes, D. K., Remote islands reveal rapid rise of southern hemisphere, sea debris. *ScientificWorldJournal* **2005,** *5*, 915-921.

32. Galgani, F.; Hanke, G.; Maes, T., Global Distribution, Composition and Abundance of Marine Litter. In *Marine Anthropogenic Litter*, Bergmann, M.; Gutow, L.; Klages, M., Eds. Springer, Cham: 2015; pp 29-56.

33. Monteiro, R. C. P.; Ivar do Sul, J. A.; Costa, M. F., Plastic pollution in islands of the Atlantic Ocean. *Environ. Pollut.* **2018,** *238*, 103-110.

34. Van Cauwenberghe, L.; Devriese, L.; Galgani, F.; Robbens, J.; Janssen, C. R., Microplastics in sediments: A review of techniques, occurrence and effects. *Mar. Environ. Res.* **2015,** *111*, 5-17.

35. Hanvey, J. S.; Lewis, P. J.; Lavers, J. L.; Crosbie, N. D.; Pozo, K.; Clarke, B. O., A review of analytical techniques for quantifying microplastics in sediments. *Anal. Methods* **2017,** *9*, (9), 1369-1383.

36. Rochman, C. M., Strategies for reducing ocean plastic debris should be diverse and guided by science. *Environ. Res. Lett.* **2016,** *11*, (4), 014006.

37. Wagner, M.; Scherer, C.; Alvarez-Munoz, D.; Brennholt, N.; Bourrain, X.; Buchinger, S.; Fries, E.; Grosbois, C.; Klasmeier, J.; Marti, T.; Rodriguez-Mozaz, S.; Urbatzka, R.; Vethaak, A. D.; Winther-Nielsen, M.; Reifferscheid, G., Microplastics in freshwater ecosystems: what we know and what we need to know. *Environ. Sci. Eur.* **2014,** *26*, (1), 12.

38. Blair, R. M.; Waldron, S.; Phoenix, V.; Gauchotte-Lindsay, C., Micro- and Nanoplastic pollution of freshwater and wastewater treatment systems. *Springer Sci. Rev.* **2017,** *5*, (1), 19-30.

39. Andrady, A. L., Microplastics in the marine environment. *Mar. Pollut. Bull.* **2011,** *62*, (8), 1596-605.

40. Lee, J.; Lee, J.; Hong, S.; Hong, S. H.; Shim, W. J.; Eo, S., Characteristics of meso-sized plastic marine debris on 20 beaches in Korea. *Mar. Pollut. Bull.* **2017,** *123*, (1-2), 92-96.

41. Duffy, M. A., Last and corresponding authorship practices in ecology. *Ecol. Evol.* **2017,** *7*, (21), 8876-8887.

42. Willoughby, N. G.; Sangkoyo, H.; Lakaseru, B. O., Beach litter: an increasing and changing problem for Indonesia. *Mar. Pollut. Bull.* **1997,** *34*, (6), 469-478.

43. Lucas, Z., Monitoring persistent litter in the marine environment on Sable-Island, Nova-Scotia. *Mar. Pollut. Bull.* **1992,** *24*, (4), 192-199.

44. Walker, T. R.; Grant, J.; Archambault, M. C., Accumulation of marine debris on an intertidal beach in an urban park (Halifax Harbour, Nova Scotia). *Water Qual. Res. J. Canada* **2006,** *41*, (3), 256-262.

45. Convey, P.; Barnes, D. K. A.; Morton, A., Debris accumulation on oceanic island shores of the Scotia Arc, Antarctica. *Polar Biol.* **2002,** *25*, (8), 612-617.

46. da Silva, M. L.; de Araujo, F. V.; Castro, R. O.; Sales, A. S., Spatial-temporal analysis of marine debris on beaches of Niteroi, RJ, Brazil: Itaipu and Itacoatiara. *Mar. Pollut. Bull.* **2015,** *92*, (1-2), 233-236.

47. Santos, I. R.; Friedrich, A. C.; Barretto, F. P., Overseas garbage pollution on beaches of northeast Brazil. *Mar. Pollut. Bull.* **2005,** *50*, (7), 782-786.

48. Acosta-Coley, I.; Olivero-Verbel, J., Microplastic resin pellets on an urban tropical beach in Colombia. *Environ. Monit. Assess.* **2015,** *187*, (7), 435.

49. Van Cauwenberghe, L.; Claessens, M.; Vandegehuchte, M. B.; Mees, J.; Janssen, C. R., Assessment of marine debris on the Belgian Continental Shelf. *Mar. Pollut. Bull.* **2013,** *73*, (1), 161-169.

50. Bowman, D.; Manor-Samsonov, N.; Golik, A., Dynamics of litter pollution on Israeli Mediterranean beaches: a budgetary, litter flux approach. *J. Coast. Res.* **1998,** *14*, (2), 418-432.

51. Gregory, M. R., The hazards of persistent marine pollution - drift plastics and conservation islands. *J. R. Soc. N. Z.* **1991,** *21*, (2), 83-100.

52. Ali, R.; Shams, Z. I., Quantities and composition of shore debris along Clifton Beach, Karachi, Pakistan. *J. Coast. Conserv.* **2015,** *19*, (4), 527-535.

53. Lee, R. F.; Sanders, D. P., The amount and accumulation rate of plastic debris on marshes and beaches on the Georgia coast. *Mar. Pollut. Bull.* **2015,** *91*, (1), 113-119.

54. Fok, L.; Cheung, P. K.; Tang, G. D.; Li, W. C., Size distribution of stranded small plastic debris on the coast of Guangdong, South China. *Environ. Pollut.* **2017,** *220*, 407-412.

55. Widmer, W. M.; Hennemann, M. C., Marine Debris in the Island of Santa Catarina, South Brazil: Spatial Patterns, Composition, and Biological Aspects. *J. Coast. Res.* **2010,** *26*, 993-1000.

56. Kim, I. S.; Chae, D. H.; Kim, S. K.; Choi, S.; Woo, S. B., Factors influencing the spatial variation of microplastics on high-tidal coastal beaches in Korea. *Arch. Environ. Contam. Toxicol.* **2015,** *69*, (3), 299-309.

57. Lee, J.; Lee, J. S.; Jang, Y. C.; Hong, S. Y.; Shim, W. J.; Song, Y. K.; Hong, S. H.; Jang, M.; Han, G. M.; Kang, D.; Hong, S., Distribution andsize relationships of plastic marine debris on beaches in South Korea. *Arch. Environ. Contam. Toxicol.* **2015,** *69*, (3), 288-298.

58. Abu-Hilal, A.; Al-Najjar, T., Marine litter in coral reef areas along the Jordan Gulf of Aqaba, Red Sea. *J. Environ. Manage.* **2009,** *90*, (2), 1043-1049.

59. Cheung, P. K.; Cheung, L. T. O.; Fok, L., Seasonal variation in the abundance of marine plastic debris in the estuary of a subtropical macro-scale drainage basin in South China. *Sci. Total Environ.* **2016,** *562*, 658-665.

60. Kusui, T.; Noda, M., International survey on the distribution of stranded and buried litter on beaches along the Sea of Japan. *Mar. Pollut. Bull.* **2003,** *47*, (1-6), 175-179.

61. Moreira, F. T.; Balthazar-Silva, D.; Barbosa, L.; Turra, A., Revealing accumulation zones of plastic pellets in sandy beaches. *Environ. Pollut.* **2016,** *218*, 313-321.

62. Besley, A.; Vijver, M. G.; Behrens, P.; Bosker, T., A standardized method for sampling and extraction methods for quantifying microplastics in beach sand. *Mar. Pollut. Bull.* **2017,** *114*, (1), 77-83.

63. Hartmann, N. B.; Huffer, T.; Thompson, R. C.; Hassellov, M.; Verschoor, A.; Daugaard, A. E.; Rist, S.; Karlsson, T.; Brennholt, N.; Cole, M.; Herrling, M. P.; Hess, M. C.; Ivleva, N. P.; Lusher, A. L.; Wagner, M., Are We Speaking the Same Language? Recommendations for a Definition and Categorization Framework for Plastic Debris. *Environ. Sci. Technol.* **2019,** *53*, (3), 1039-1047.

64. Provencher, J. F.; Bond, A. L.; Avery-Gomm, S.; Borrelle, S. B.; Bravo Rebolledo, E. L.; Hammer, S.; Kühn, S.; Lavers, J. L.; Mallory, M. L.; Trevail, A.; van Franeker, J. A., Quantifying ingested debris in marine megafauna: a review and recommendations for standardization. *Anal. Methods* **2017,** *9*, (9), 1454-1469.

65. Martins, J.; Sobral, P., Plastic marine debris on the Portuguese coastline: a matter of size? *Mar. Pollut. Bull.* **2011,** *62*, (12), 2649-2653.

66. Critchell, K.; Grech, A.; Schlaefer, J.; Andutta, F. P.; Lambrechts, J.; Wolanski, E.; Hamann, M., Modelling the fate of marine debris along a complex shoreline: Lessons from the Great Barrier Reef. *Estuar. Coast. Shelf Sci.* **2015,** *167*, (Part B), 414-426.

67. Whiting, S. D., Types and sources of marine debris in Fog Bay, northern Australia. *Mar. Pollut. Bull.* **1998,** *36*, (11), 904-910.

68. Hong, S.; Lee, J.; Kang, D.; Choi, H. W.; Ko, S. H., Quantities, composition, and sources of beach debris in Korea from the results of nationwide monitoring. *Mar. Pollut. Bull.* **2014,** *84*, (1-2), 27-34.

69. Lourenco, P. M.; Serra-Goncalves, C.; Ferreira, J. L.; Catry, T.; Granadeiro, J. P., Plastic and other microfibers in sediments, macroinvertebrates and shorebirds from three intertidal wetlands of southern Europe and west Africa. *Environ. Pollut.* **2017,** *231*, (Pt 1), 123-133.

70. Schmuck, A. M.; Lavers, J. L.; Stuckenbrock, S.; Sharp, P. B.; Bond, A. L., Geophysical features influence the accumulation of beach debris on Caribbean islands. *Mar. Pollut. Bull.* **2017,** *121*, (1-2), 45-51.

71. Somerville, S. E.; Miller, K. L.; Mair, J. M., Assessment of the aesthetic quality of a selection of beaches in the Firth of Forth, Scotland. *Mar. Pollut. Bull.* **2003,** *46*, (9), 1184-1190.

72. Fauziah, S. H.; Liyana, I. A.; Agamuthu, P., Plastic debris in the coastal environment: The invincible threat? Abundance of buried plastic debris on Malaysian beaches. *Waste Manage. Res.* **2015,** *33*, (9), 812-821.

73. Hardesty, B. D.; Lawson, T. J.; van der Velde, T.; Lansdell, M.; Wilcox, C., Estimating quantities and sources of marine debris at a continental scale. *Front. Ecol. Environ.* **2017,** *15*, (1), 18-25.

74. Lavers, J. L.; Oppel, S.; Bond, A. L., Factors influencing the detection of beach plastic debris. *Mar. Environ. Res.* **2016,** *119*, 245-251.

75. Andrady, A. L., Persistence of Plastic Litter in the Oceans. In *Marine Anthropogenic Litter*, Bergmann, M.; Gutow, L.; Klages, M., Eds. Springer, Cham: 2015; pp 57-72.

76. Opfer, S.; Arthur, C.; Lippiatt, S., *NOAA Marine debris shoreline survey field guide*. US National Oceanic and Atmospheric Administration Marine Debris Program: 2012; p 19.

77. Cheshire, A. C.; Adler, E.; Barbiere, J.; Cohen, Y.; Evans, S.; Jarayabhand, S.; Jeftic, L.; Jung, R. T.; Kinsey, S.; Kusui, E. T.; Lavine, I.; Manyara, P.; Oosterbaan, L.; Pereira, M. A.; Sheavly, S.; Tkalin, A.; Varadarajan, S.; Wenneker, B.; Westphalen, G., *UNEP/IOC guidelines on survey and monitoring of marine litter*. 2009; Vol. 186, p xii + 120.

78. Commission, O., *Marine Litter in the North-East Atlantic region: Assessment and Priorities for Response*. 2009; p 127.

79. van Franeker, J.; Meijboom, A., Marine litter monitoring by Northern Fulmar: a pilot study (Alterra-rapport No. 401). *Green World Research, Wageningen, Alterra* **2002**.

80. Eriksen, M.; Maximenko, N.; Thiel, M.; Cummins, A.; Lattin, G.; Wilson, S.; Hafner, J.; Zellers, A.; Rifman, S., Plastic pollution in the South Pacific subtropical gyre. *Mar. Pollut. Bull.* **2013,** *68*, (1-2), 71-76.

81. Ribic, C. A.; Sheavly, S. B.; Rugg, D. J.; Erdmann, E. S., Trends and drivers of marine debris on the Atlantic coast of the United States 1997-2007. *Mar. Pollut. Bull.* **2010,** *60*, (8), 1231-1242.

82. Ryan, P. G.; Lamprecht, A.; Swanepoel, D.; Moloney, C. L., The effect of fine-scale sampling frequency on estimates of beach litter accumulation. *Mar. Pollut. Bull.* **2014,** *88*, (1-2), 249-254.

83. Vegter, A. C.; Barletta, M.; Beck, C.; Borrero, J.; Burton, H.; Campbell, M. L.; Costa, M. F.; Eriksen, M.; Eriksson, C.; Estrades, A.; Gilardi, K. V. K.; Hardesty, B. D.; do Sul, J. A. I.; Lavers, J. L.; Lazar, B.; Lebreton, L.; Nichols, W. J.; Ribic, C. A.; Ryan, P. G.; Schuyler, Q. A.; Smith, S. D. A.; Takada, H.; Townsend, K. A.; Wabnitz, C. C. C.; Wilcox, C.; Young, L. C.; Hamann, M., Global research priorities to mitigate plastic pollution impacts on marine wildlife. *Endanger. Species Res.* **2014,** *25*, (3), 225-247.

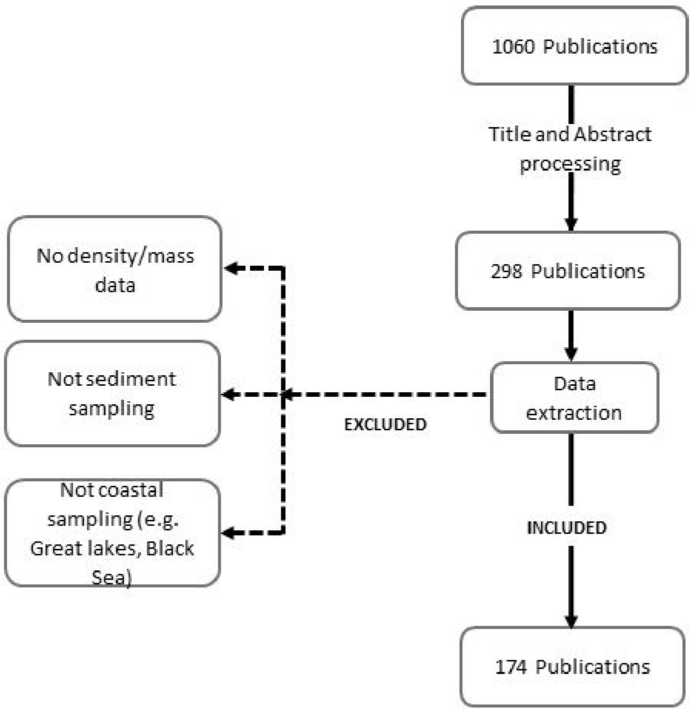

Figure 1. Flow chart showing the decision process for inclusion and exclusion of candidate beach
530 debris literature identified using an ISI Web of Knowledge search.

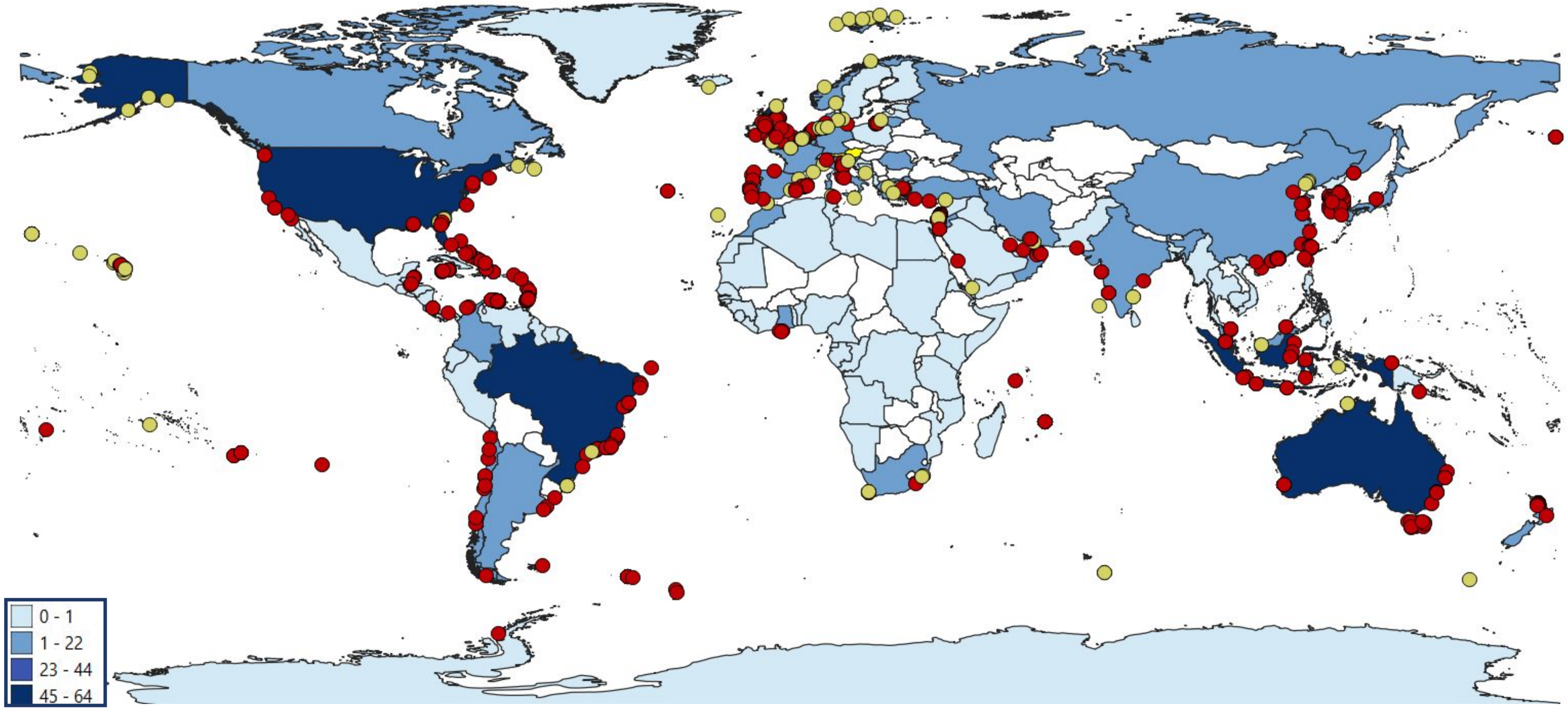

Figure 2. Geographic distribution of studies of beach debris density in sediments using a Web of Knowledge search that were included in this review (174 publications, 717 sites, circles). Yellow circles represent studies that reported their data as items/kg (10 publications, 42 sites), items per unit time (4 publications, 12 sites), items per volume (5 publications, 23 sites) or mass per unit area (e.g., g/m^2; 9 publications, 40 sites). Also represented by the yellow
535 circles are studies that reported the total number of items across all sites (18 publications, 33 sites). Red circles represent the studies that reported the number of debris items per linear meter or items m^2 (131 publications, 566 sites). Countries for which studies are available (n = 71, are shown in blue and

absence of beach debris studies in white). The different tones of blue represent the number of sites (darker blue for more publications) Countries with absence of coast line are shown in white (n=42).

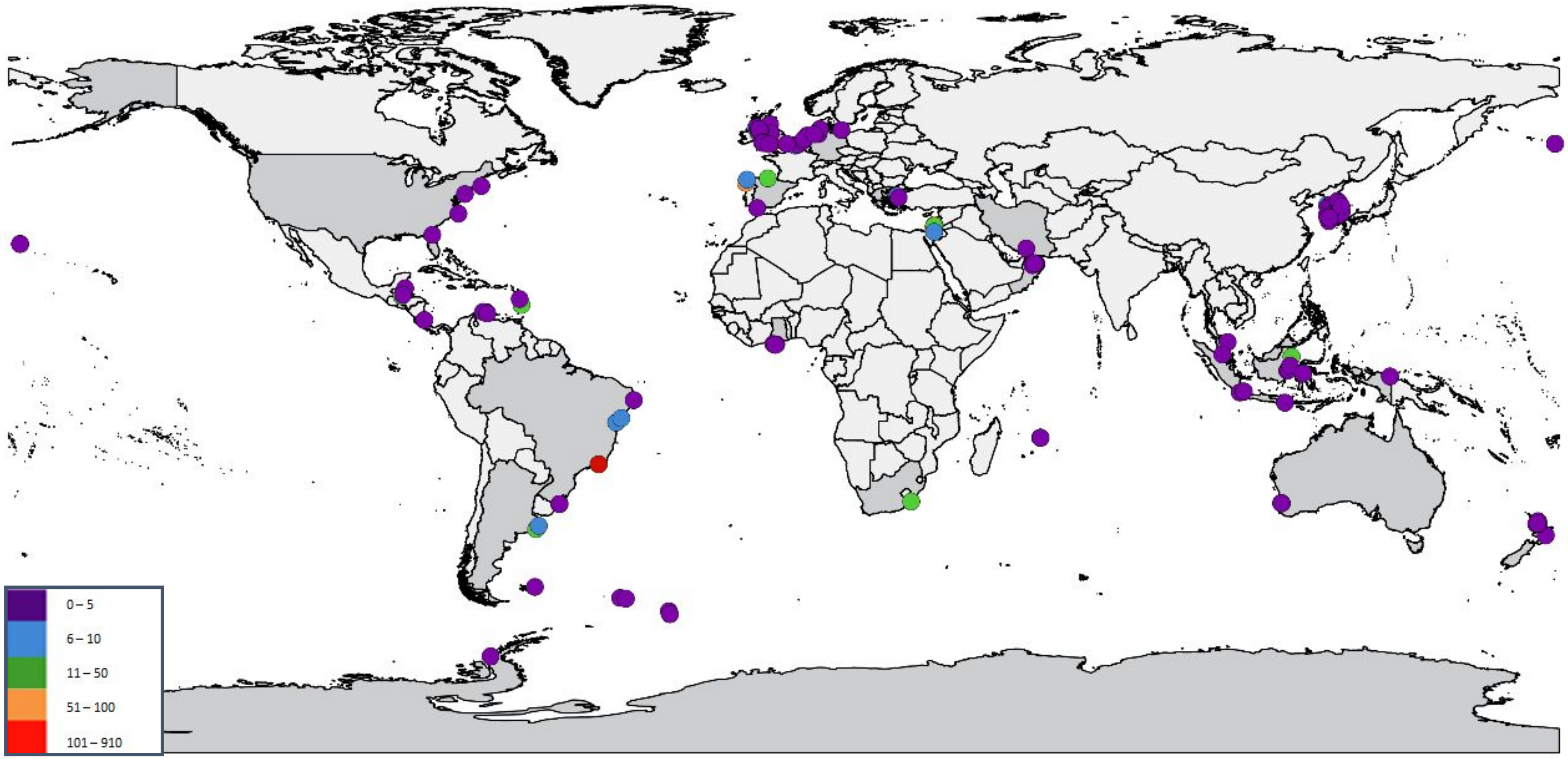

Figure 3. Average density of macro-debris reported in items m-1 for each site considered in this review (38 publications, 235 sites) between 1980-2017. The colour spectrum reflects different beach debris densities with red indicating higher density and purple lowest densities at each site. Countries for which
545 publications were available (n = 28, grey) and the countries which lacked beach debris studies (white).

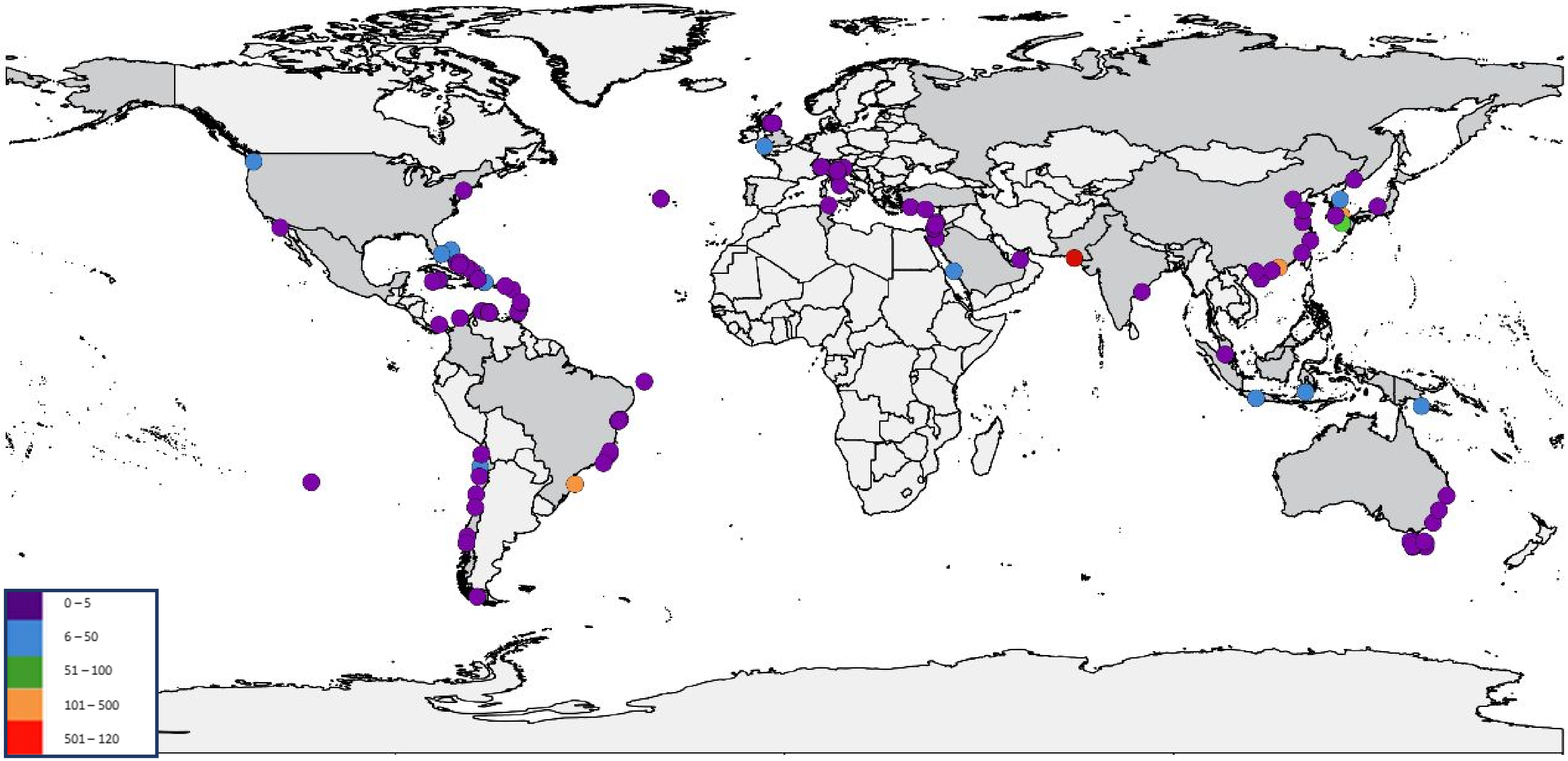

Figure 4. Average density of macro-debris reported in items m^{-2} for each site considered in this review (50 publications, 183 sites) between 1980-2017. Red indicates a higher density of debris, and blue a lower density of debris. Countries for which publications were available (n = 35, grey) and the countries
550 which lacked beach debris studies (white).

Table 1. Proportion of publications and sampling sites included in this review with the reported factors known to influence marine debris densities (174 publications, 715 sites; 1980 - 2017).

Variables	**Reported metrics**	**% publications**	**% sites sampled**
Density	Items m^{-1}	26.4	36.1
	Items m^{-2}	47.2	42.8
	Volume	2.8	3.2
	Mass	5.6	5.9
	Total items	10.1	4.6
	Others[a]	7.9	7.4
Size	Macro	58.4	67.6
	Micro	22.2	19.8
	Both	10.8	5.9
	Not reported	8.6	6.7
Sediment	Sandy	54.6	49.4
	Mix	18.9	18.7
	Others	7.0	4.2
	Not reported	19.5	27.8
Sampling depth	Surface (< 3 cm)	68.9	75.2
	Buried (≥ 3 cm)	16.9	15.9
	Not reported	14.2	8.9
Provenance of items (source)	Reported	46.9	47.8
	Not reported	53.1	52.2
Duration of the study	≤ 1 year	67.2	52.4
	2 - 5 years	14.9	22.3

	≥ 6 years	8.0	17.0
	Not reported	9.8	8.2
# of sampling sites	1	17.8	-
	2 - 5	32.8	-
	≥ 6	49.4	-
Location	Mainland	51.1	41.1
	Island	46.7	58.3
	Both	2.2	0.6
Type of sampled debris	All debris	71.2	75.7
	Only plastic	28.8	24.3
Item categorization (some examples of the categories used by authors are provided to the right)	Material type (e.g., wood, plastic)	55.3	42.5
	Use (e.g., footwear)	7.3	14.6
	Both (type & use)	26.8	33.3
	Only one item (e.g., pellet)	5.6	3.2
	Not reported	5.0	6.3
Beach orientation[b]	Leeward	31.9	31.5
	Windward	52.4	59.4
	Both	15.7	9.1
Polymers identified	Yes	14.9	13.
	No	85.1	87.0
Colours reported	Yes	11.5	7.7
	No	88.5	92.3

Community participation	Yes	18.4	-
	No	81.6	-
Standing stock removed	Yes	16.1	8.4
	No	83.9	91.9
Transect/quadrat location (e.g., high tide)	Yes	71.4	70.0
	No	28.5	30.0
Dimensions reported (e.g., transect size)	Yes	89.1	85.9
	No	11.4	14.1
Number of replicates reported (e.g., transects)	Yes	51.4	39.3
	No	48.0	60.7
Frequency of sampling	Once (single event)	46.2	23.4
	Twice	17.6	17.7
	Specific number (> 2)	11.5	3.8
	Daily	5.5	2.6
	Weekly	1.1	1.5
	Fortnightly	1.6	1.1
	Monthly	2.2	14.8
	Bi-monthly	15.9	0.3
	Seasonally	1.1	3.6
	Annually	5.5	3.2
	Irregular	3.8	3.3
	Not Reported	3.3	24.5

[a] A range of other units were used to report the debris density, for example, some studies reported per weight (e.g., items/kg) or per unit time (e.g., items g/day). See Figure 2.

[b] Beach orientation (note: only 46.0% of published papers included in this review reported beach orientation, in cases where this was not reported, orientation was determined by the authors of this paper).