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# Towards a North Pacific long-term monitoring program for ocean plastic pollution: A systematic review and recommendations for shorelines☆

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ABSTRACT

Increased organized monitoring is key to improving our understanding of marine debris on shorelines. Shorelines are demonstrated sinks for marine debris but efforts to quantify debris often fail to capture and report core variables and survey design techniques necessary to ensure study repeatability, comparability and to provide meaningful results. Here, we systematically review the available literature regarding marine debris distribution and abundance on shorelines of countries bordering the North Pacific Ocean (NPO), which are demonstrated to have unusually high marine debris abundance and diversity both at the ocean surface and stranded on shorelines. The majority of the 81 papers documenting shoreline debris in the NPO were studies that took place for less than one year (76.5%). Additionally, most sampling sites were visited only once (57.3%). Precise site locations (GPS coordinates) were provided in only 44.4% of the evaluated studies. Debris quantities were reported using nine different measurement units, with item counts per area and item counts per mass being most commonly reported for macro- and microplastics, respectively. Taken together, most of the reviewed studies could not be repeated by others given the information provided. We propose a series of guidelines with regard to marine debris shoreline sampling metrics, indicators, methods, and target goals in the NPO in order to improve comparability and repeatability. These follow the basic tenets of environmental survey design, which when not accounted for, can limit the applicability and value of large-scale shoreline monitoring efforts.

## 1. Introduction

Key to improving our understanding of marine debris on shorelines is the institution of organized shoreline monitoring. Monitoring marine debris on shorelines is essential for assessing if there has been a change in debris type and/or abundance that needs to be addressed through management (surveillance monitoring) or if conditions improve after a management policy was implemented (effectiveness monitoring) (Hutto and Belote, 2013). Both types of monitoring require long-term effort involving repeated measurements that are collected over time. Haphazard site revisits or simply measuring status will fail to produce the trajectory needed to evaluate trends and responses to management intervention. Of all the marine environmental compartments where debris occurs (e.g., shoreline, water surface, seafloor, in and on biota), monitoring of shorelines is perhaps the most practical and efficient manner in which to evaluate the status of marine debris. Owing to ease of access and the relatively non-technical nature of debris collection and visual identification, shorelines are the marine environmental compartment having the most (and consequently, the most robust) information on marine debris abundance (GESAMP, 2019).

Shorelines are demonstrated sinks for marine debris (Rech et al., 2014; Willis et al., 2017; Brennan et al., 2018; Collins and Hermes, 2019; Roman et al., 2020; Olivelli et al., 2020; Ryan, 2020a; van Sebille et al., 2020; Onink et al., 2021). A number of field studies have found that macroplastic debris from land-derived sources often strands close to coastal entry points (Rech et al., 2014; Willis et al., 2017, Ryan, 2020a).

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Model simulations also suggest that a large percentage of land-derived, positively buoyant plastic marine debris ends up stranded on shorelines (Lebreton et al., 2019; Chassignet et al., 2021; Chenillat et al., 2021; Onink et al., 2021) including large proportions of microplastics (Collins and Hermes, 2019; van Sebille et al., 2020). Although modeling scenarios and parameters vary among the models, there is some agreement in that 66–75% of positively buoyant floating plastic released at the coast (via inland rivers, coastal mismanaged waste) ends up beached (Lebreton et al., 2019; Chassignet et al., 2021; Chenillat et al., 2021) and 77% is either beached or floating in nearshore waters (Onink et al., 2021). Thus, critical to balancing any plastic budget, whether regionally or globally, is a comprehensive understanding of the contribution of shorelines as debris reservoirs.

In 2015, all United Nations Member States adopted the 2030 Agenda for Sustainable Development (UN General Assembly Resolution A/RES/70/1) which includes 17 Sustainable Development Goals (SDG). SDG 14 emphasizes sustainable use of the oceans, seas and marine resources and specifically sets a target of significantly reducing marine pollution of all kinds by 2025 (UN General Assembly, 2015). The proposed national-level indicator for beach marine litter is the average count of plastic items per km$^2$ (UNEP, 2021). To achieve this target requires the coordinated collection of shoreline debris data organized at national scales using harmonized data collection with standardized reporting and debris classification. However, a recent global review of shoreline marine debris monitoring efforts highlighted numerous deficiencies in data reporting (Serra-Gonçalves et al., 2019). Nearly half of the 174 studies examined were one-off data collections (46.2%) and only 8% were of potentially sufficient duration ($\geq$6 years) for assessing temporal trends (Serra-Gonçalves et al., 2019). Many of the reviewed studies did not report basic parameters of the survey design. Several studies did not report sampling unit dimensions (i.e., length of shoreline, transect length, quadrat area; 28.5%), number of replicate samples taken (48%), dates of sampling (9.8%), and the categories and size classes of sampled debris (5.0 and 8.6%, respectively) (Serra-Gonçalves et al., 2019). Over half of the studies included in the review did not attempt debris source identification (53.1%) and a large proportion (85.1%) did not employ analytical techniques for polymer identification (Serra-Gonçalves et al., 2019). Further, 27% of the studies did not report debris abundances using comparable metrics (Serra-Gonçalves et al., 2019). Taken all together, most of the reviewed studies could not be repeated by others given the information provided. Thus, improvements are needed in the reporting of basic variables and survey design techniques to ensure study repeatability, comparability and to provide meaningful results.

Likewise, using relational tables, Hapich et al. (2022) evaluated 68 marine debris item categorization lists from a number of countries, organizations and institutions; only 20.8% of debris item classes (the description of the form of the object; e.g., bottle, fragment, can) and 29.9% of debris material classes (the resource used to make the item; e.g., plastic, glass) were common. Additionally, 392 of the 1509 material and item classes evaluated did not fit into the hierarchical scheme developed by the authors which they termed misalignments (Hapich et al., 2022). This was largely due to an organization's use of fine scale descriptors that may not be relevant beyond a local or regional setting (Hapich et al., 2022).

The North Pacific Ocean (NPO) has been demonstrated to have unusually high marine debris abundance and diversity both at the ocean surface and stranded on shorelines (Ribic et al. 2012a, 2012b, Goldstein et al., 2013; Law et al., 2014; Lee et al., 2015; Lebreton et al., 2018). Additionally, global particle tracking simulations performed by Chassignet et al. (2021) found that 75% of simulated particles released monthly from 2010 to 2019 (accumulated total) from global inland river catchments and mismanaged waste at the coast (within 50 km) wound up stranded on shorelines with the highest numbers found on western Pacific shores. Similarly, a 23-year simulation by Chenillat et al. (2021) found that roughly 66% of released particles accumulate at coasts. The distribution of particles along global coastlines was broadly spaced; however, the western Pacific clearly had substantially higher numbers of beached particles versus the eastern Pacific (Chenillat et al., 2021). Even so, only a handful of the 33 countries bordering the NPO and adjacent seas have implemented sustained, multi-year monitoring at spatial and temporal scales sufficient for assessing status and trends, despite the recognition of North Pacific shorelines as potential reservoirs for plastic debris and the practicality and efficiency of shoreline monitoring for marine debris (UNEP, 2007; 2008; Sheavly, 2007; Lippiatt et al., 2013; Burgess et al., 2021). Other regions worldwide have either implemented large-scale shoreline monitoring or are in the planning stages (Europe: OSPAR Commission, 2010, Arctic: AMAP, 2021a, 2021b), but to date, no basin-wide comparative analysis or monitoring scheme has been attempted for shoreline marine debris in the NPO. Here, we review the available literature regarding marine debris distribution and abundance on the shorelines of countries bordering the NPO, including those connected via adjacent seas, with the aim of making recommendations for shoreline debris monitoring and reporting in the region.

This review paper is in response to the Terms of Reference for Working Group 42 of the North Pacific Marine Science Organization (PICES), which is evaluating indicators of marine plastic pollution. The focus of this review is a basin-wide assessment of shoreline marine debris in the NPO, as this system has not yet been synthesized, and an effort is warranted given regional ocean circulation patterns and the transboundary nature of marine debris. Four companion papers were drafted to review the abundance and distribution of plastic pollution in biota, water, sediments and on shorelines and attempted to address the following questions:

- Where comparisons across studies can be made, what are the best metrics for doing so?
- Are the existing data sufficient to allow for spatial trends?
- Are the existing data sufficient to allow for temporal trends?
- Do the existing data bear information on the sources of marine debris?

## 2. Methods

### 2.1. Systematic literature review

In January 2021, we conducted a systematic review of shoreline debris literature (1970–2020) from countries bordering the North Pacific Ocean (NPO), including those connected via adjacent seas, using Web of Science. Here, any country located in the Pacific Basin and north of the equator was considered. We included only peer-reviewed articles written in the English language as the vast majority of scientific journals are published in English, especially in the natural sciences. The query was based on the following search string:

*((TS=(shoreline OR "shoreline debris" OR "shoreline litter" OR beach OR "beach debris" OR "beach litter" OR coast* OR "coast* debris" OR "coast* litter") AND TS=("marine debris" OR "marine litter" OR plastic* OR "plastic pollution" OR "plastic litter" OR "plastic debris") AND TS=(Canada OR "United States" OR US OR Alaska OR Hawaii OR "Pacific Northwest" OR California OR Oregon OR Washington OR Japan OR Korea OR China OR Russia OR Indonesia OR Malaysia OR Taiwan OR "Hong Kong" OR Viet Nam OR Thailand OR Colombia OR Brunei OR Cambodia OR "Christmas Island" OR "Costa Rica" OR Ecuador OR "El Salvador" OR "French Polynesia" OR Galapagos OR Guam OR Guatemala OR Honduras OR Kiribati OR "Mariana Islands" OR "Marshall Islands" OR Mexico OR Micronesia OR Nicaragua OR Palau OR Panama OR Philippines OR Singapore))).*

Our initial search returned 1264 articles which were exported as a list into Microsoft Word. We removed duplicate articles as well as those whose title and abstract clearly revealed that the subject matter was unrelated to shoreline monitoring of marine debris in the NPO region, which left 116 articles for further consideration. These were read and further examined to confirm that they were related to shoreline monitoring of marine debris in the NPO region. Information was extracted from only those papers that clearly estimated shoreline debris density as: 1) a count, mass, or volume of items per specified linear length or area of shoreline, 2) a count, mass, or volume of items per specified mass of shoreline sediment, or 3) a count, mass, or volume of items per specified volume of shoreline sediment. The reported densities were scaled to counts, mass (in grams), or volume (in milliliters) per linear meter, per square meter, per gram or per cubic meter, respectively. Thirty-three of the pre-screened papers were removed for various reasons, most commonly due to issues with the format of the data that could not be resolved (e.g., no data on abundance, unresponsive corresponding author, abundance units unclear). Several rejected studies did not take place on shorelines (e.g. nearshore, urban river, surface water, benthic sediments) or within the NPO region. Debris transport modeling studies, papers on methodologies for classifying debris from remotely sensed images, as well as papers focusing on outreach and social science were also removed. Lastly, one paper was retracted from the publishing journal by the authors during the course of our evaluation. This resulted in a final set of 81 papers whose references may be found in Supplement 1.

Several papers did not include debris density estimates by site or by year of sampling or presented the data by site using figures only (no tabulation). On those occasions, we made an initial email request to the corresponding author with one follow up. Many authors responded and shared the data in the required format. However, there remained a number of non-responses. For these 15 papers, we captured screenshots of the desired figures and extracted numerical data from these images using WebPlotDigitizer Version 4.4 (https://automeris.io/WebPlotDigitizer/), an open source web-based application which has been found to be a reliable and valid tool for data extraction with high accuracy and consistency (Burda et al., 2017; Aydin and Yassikaya, 2021). Based on axis calibration points selected by the user, WebPlotDigitizer maps pixel location in the image to data points on a graph using affine transformations.

Where possible, debris abundance was reported independently for each location surveyed, otherwise a mean value was reported for all locations and years combined. Abundances were categorized by material type (plastic or other) and size (macro or micro) based on reporting. The categories included: (1) total debris, (2) total plastic debris, (3) total other debris, (4) macroplastics (>5 mm in size), (5) microplastics (≤5 mm in size) and (6) other macrodebris. When papers only reported a total count of all observed debris regardless of material type or size class, then abundances were reported as 'total debris.' If papers reporting 'total debris' included separate abundances for plastic and non-plastic materials, then the plastic component was entered as 'total plastic debris' and the non-plastic portion was recorded as 'total other debris.'

From each paper we extracted the (1) study country, (2) sampling dates, (3) site latitude, and (4) site longitude. Several papers did not include the exact latitude and longitude of sampling sites but only a site map, with or without graticules. When authors did not respond to requests for this information, we displayed the site map side-by-side with the approximate study area in Google Maps and made our best evaluation of the potential site location using landmarks and prominent shoreline and/or topographic features in both images (36 papers).

From each study we also recorded the (1) number of sampling sites, (2) duration of the study, (3) sampling frequency, (4) length of shoreline sampled, (5) sample unit, (6) level of replication, (7) shoreline orientation, (8) size classes of debris, (9) minimum size of debris, (10) maximum size of debris, (11) sampling depth, (12) sediment type, (13) island vs mainland, and (14) most commonly observed items (Table 1).

In addition, we recorded (via a yes/no response) whether or not the studies (1) attempted to identify the source of debris, (2) analyzed polymer content of the debris, (3) classified debris by color and shape, (4) included citizen scientists, (5) removed debris, (6) located sampling units in relation to tidal stage, (7) provided sample unit dimensions, (8) replicated sample units, (9) clearly described the methodology, or (10) estimated a temporal trend for debris (Table 1).

### 2.2. *Limitations*

The review was confined to one electronically available database, the Web of Science™. Although an exhaustive list of search terms was used, a search of additional databases could produce a wider array of articles. The review only includes articles written in the English language which limits the scope of our review. Each decision to include or exclude a given article from the original corpus of 1264 was taken by a single reviewer (AVU), while three reviewers with shared responsibility (AVU, SH, HKB) extracted data from the 116 pre-screened articles which may have affected the outcome. However, when a pre-screened article was recommended for exclusion by a single reviewer, consensus was achieved by the remaining reviewers before its rejection.

### 2.3. *Statistical analysis*

To compare plastic pollution loads among countries, a generalized linear mixed model (GLMM) with a negative binomial response structure (log-link, $\varphi = 1.63$) was fit by restricted maximum likelihood to microplastic and macroplastic observations recorded in units of counts per square meter. This was the subset of literature for which sufficient data was available to allow statistical comparisons between plastic types across a range of countries. To conduct statistical inference, countries were excluded from the analysis if they contained observations from fewer than 10 sites, leading to a final dataset containing 195 total records across 15 citations from four countries (China, Indonesia, Korea, and the United States Pacific coast). Fixed effects in the model included country, plastic type (two levels: microplastic, macroplastic), and the interaction of country and plastic type. To account for the non-independence of observations pooled from various data sources, citation was included as a random effect, in addition to site, to account for cases where multiple observations may have been taken at the same location. While survey year was unavailable to use as a continuous term due to the grouped nature of some data sources across multiple years, a random effect of year or year range was included to account for the fact that observations closer in time may be more similar. Studentized residual plots were examined to confirm that model assumptions were appropriately met.

Inference on fixed effects was performed using Type III F-tests with Kenward-Roger adjusted denominator degrees of freedom. Confidence intervals around parameters were adjusted for multiple inference using the Tukey-Kramer method. Analyses were conducted using SAS/STAT software, version 9.4, PROC GLIMMIX. An equivalent model was fitted in R version 4.1.2 using the *lme4* package (Bates et al., 2015) to obtain contrasts between countries adjusted for multiple comparisons using the *multcomp* package (Hothorn et al., 2008).

## 3. Results

### 3.1. *Geographic distribution of studies*

The 81 studies investigated here were distributed across 14 different countries. As a single country, China has produced the most studies (31), examining shoreline marine debris in the North Pacific Ocean (NPO) followed by the United States (13), Korea (9), Indonesia (7), and Mexico (4) (Fig. 1). The Philippines and Thailand each had three studies, while Canada, Japan, Malaysia, and Singapore had two (Fig. 1). Single studies occurred from Colombia, Ecuador, and Viet Nam (Fig. 1).

The majority of studies from China report microplastics only while almost all studies from the United States (including Hawai'i and Alaska) report macroplastics only (Fig. 1). In Korea, macroplastics and microplastics were reported evenly while Indonesian studies were dominated by macroplastics reporting (Fig. 1).

Prior to the year 2000, most assessments of shoreline marine debris in the NPO focused on macroplastics, typically reported as item counts per linear meter of shoreline (Fig. 2). In the mid-2000s, around 2008,

**Table 1**
Descriptive statistics from the 81 publications and associated study sites (n = 903) used in the systematic review and expressed as a percentage of the total number of publications and total number of sites reporting on a particular variable or metric.

| Debris Focus and Units | | |
|---|---|---|
| | % Pubs | % Sites |
| **Quantity Unit** | | |
| items per area | 55.6 | 52.5 |
| items per length | 11.1 | 13.2 |
| items per mass | 25.9 | 23.5 |
| items per volume | 4.9 | 7.3 |
| item count | 1.2 | 0.2 |
| mass per area | 24.7 | 22.5 |
| mass per volume | 2.5 | 1.3 |
| mass per length | 3.7 | 5.5 |
| items per time | 2.5 | 0.9 |
| **Debris Size** | | |
| macro | 34.6 | 33.8 |
| micro | 40.7 | 45.7 |
| both | 19.8 | 18.1 |
| not reported/unclear | 4.9 | 2.4 |
| **Type of Sampled Debris** | | |
| all debris | 30.9 | 26.2 |
| only plastic | 59.3 | 62.9 |
| specific types only | 12.3 | 11.7 |
| **Source ID** | | |
| yes | 59.3 | 65.9 |
| criteria 1 | 14.8 | |
| criteria 2 | 3.7 | |
| criteria 3 | 19.8 | |
| criteria 4 | 21 | |
| no | 40.7 | 34.1 |
| **Polymer ID** | | |
| yes | 44.4 | 41.4 |
| yo | 55.6 | 58.6 |
| **Color ID** | | |
| yes | 32.1 | 34.2 |
| no | 67.9 | 65.8 |
| **Shape ID (e.g. film, fragment, bead)** | | |
| yes | 45.7 | 49.5 |
| no | 54.3 | 50.5 |

| Space and Time | | |
|---|---|---|
| | % Pubs | % Sites |
| **Duration of Study** | | |
| <1 year | 76.5 | 72.2 |
| 1 year | 4.9 | 5.2 |
| 2–5 years | 14.8 | 19.0 |
| 6 or more | 3.7 | 3.5 |
| **Sampling Frequency** | | |
| once | 61.7 | 57.3 |
| two to five times | 16.0 | 18.8 |
| yearly | 4.9 | 3.1 |
| 2-4 times per year (seasonally) | 3.7 | 5.6 |
| monthly to bimonthly | 12.3 | 14.3 |
| daily | 2.5 | 0.9 |
| **Temporal Trend Reported** | | |
| yes | 24.7 | 22.6 |
| yes (three months) | 1.2 | 0.7 |
| no | 74.1 | 76.7 |
| **Number of Sampling Sites** | | |
| 1 | 12.3 | |
| 2 to 5 | 33.3 | |
| six or more | 54.3 | |
| **Location** | | |
| mainland | 50.6 | 58.8 |
| island | 33.3 | 23.9 |
| both | 16.0 | 17.3 |
| **Shoreline Orientation** | | |
| leeward | 1.2 | 2.3 |
| windward | 0.0 | 0.0 |
| both | 9.9 | 5.5 |
| not reported | 88.9 | 92.1 |
| **Substrate** | | |
| sand | 88.9 | |
| mud | 8.6 | |
| rock/gravel | 8.6 | |

(*continued on next page*)

**Table 1** (*continued*)

| Space and Time | | |
|---|---|---|
| | % Pubs | % Sites |
| vegetation/mangrove | 6.2 | |
| unclear | 1.2 | |

| Methods Comparability and Repeatability | | |
|---|---|---|
| | % Pubs | % Sites |
| **Sampling Depth** | | |
| surface (<3 cm) | 72.8 | 69.8 |
| buried (>3 cm) | 19.8 | 26.8 |
| both | 7.4 | 3.4 |
| **Public Participation in Data Collection** | | |
| yes | 12.3 | 21.2 |
| no | 87.7 | 78.8 |
| **Sampled Debris Removed** | | |
| yes | 85.2 | 90.1 |
| no | 3.7 | 1.1 |
| not reported/unclear | 11.1 | 8.7 |
| **Sample Unit** | | |
| area | 29.6 | 24.4 |
| length/linear | 7.4 | 6.6 |
| transects | 19.8 | 15.9 |
| quadrats/quads in transects | 28.4 | 32.7 |
| cores/cores in transects | 3.7 | 4.1 |
| volume | 7.4 | 9.1 |
| not reported | 4.9 | 7.6 |
| **Sample Location Described (tideline, full width, etc.)** | | |
| yes | 67.9 | 66.1 |
| no | 32.1 | 33.9 |
| **Sample Dimensions Reported** | | |
| yes | 86.4 | 84.9 |
| no | 14.8 | 15.2 |
| **Number of Replicates Reported** | | |
| yes | 82.7 | 83.9 |
| no/not reported | 18.5 | 16.1 |
| **Site Locations by Lat/Long** | | |
| yes | 44.4 | 40.0 |
| map | 44.4 | 52.4 |
| no | 11.1 | 7.6 |
| **Site Length** | | |
| unclear/not reported | 37.0 | 36.1 |
| less than 100 m | 17.3 | 15.8 |
| 100 m | 18.5 | 24.8 |
| 100–500 m | 8.6 | 9.2 |
| greater than 500 m | 7.4 | 2.2 |
| variable | 11.1 | 11.8 |
| **Sampling Method Described** | | |
| yes | 87.7 | 87.8 |
| no | 1.2 | 0.2 |
| somewhat | 11.1 | 12.0 |

there was a shift that included more sampling of microplastics, typically reported in items per square meter of shoreline or items per gram of sand (Fig. 2). Only a handful of studies have reported abundances of mesodebris (5–25 mm in size), since 2003 (Fig. 2). These studies report mesodebris as item counts or grams per square meter (Fig. 2).

Very few countries bordering the NPO and adjacent seas have conducted monitoring at spatial and temporal scales sufficient for assessing status and trends (Canada: Hipfner et al., 2018; China: Ko et al., 2018, Zhou et al., 2016; United States: Ribic et al. 2012b, Uhrin et al., 2020). Oftentimes, replication was sufficient in time but not space and vice versa. In Canada, Hipfner et al. (2018) monitored three locations on Triangle Island, British Columbia for 6 years (2012–2017) as a means to establish a debris baseline and to monitor the arrival of debris generated by the 2011 Tōhoku Japan earthquake and tsunami. These authors estimated a nonlinear trend over time in debris densities (item counts per m$^2$) with annual densities ranging from 0.48 to 0.72, peaking in 2014 (Hipfner et al., 2018). Ko et al. (2018) monitored debris over 5 years at two sites on Dongsha Island in the South China Sea and found that annual total counts varied between the north (75 items per linear meter) and south (28.3 items per linear meter) coasts of the island, and appeared to peak in 2014 although the temporal trend was not explicitly estimated. From 2007 to 2014, Zhou et al. (2016) monitored beach debris at seven sites from the China Sea area (north, east, south) where annual densities ranged from 0.8 to 7.3 items per 100 m$^2$. Ribic et al. (2012b) reported on 26 indicator items counted per 500-m length of shoreline over a ten-year period for Washington, Oregon, and northern California combined (13 sites, mean: 28.2 items/500 m). A nonlinear trend was observed largely driven by temporary peaks in debris or initially high debris loads that declined over time (Ribic et al. 2012b). Uhrin et al. (2020) reported all plastic items greater than 2.5 cm in size per 100-m length of shoreline from 26 sites in the Olympic Coast National Marine Sanctuary (Washington state) surveyed from 2013 to 2019. The mean number of items per 100 m was 32.7 and no temporal trend was apparent (Uhrin et al., 2020). Four sites in Greater Farallones National Marine Sanctuary (California state) were monitored from 2013 to 2015 with a mean abundance of 96.4 items per 100 m (Uhrin et al., 2020). A nonlinear trend was estimated, largely a result of a temporary peak in debris observed in 2015 (Uhrin et al., 2020). Lastly, five sites in Hawaiʻi were monitored over an eight-year period with a mean of 133.8 indicator items per 500 m and a decreasing trend over time (Ribic et al. 2012b).

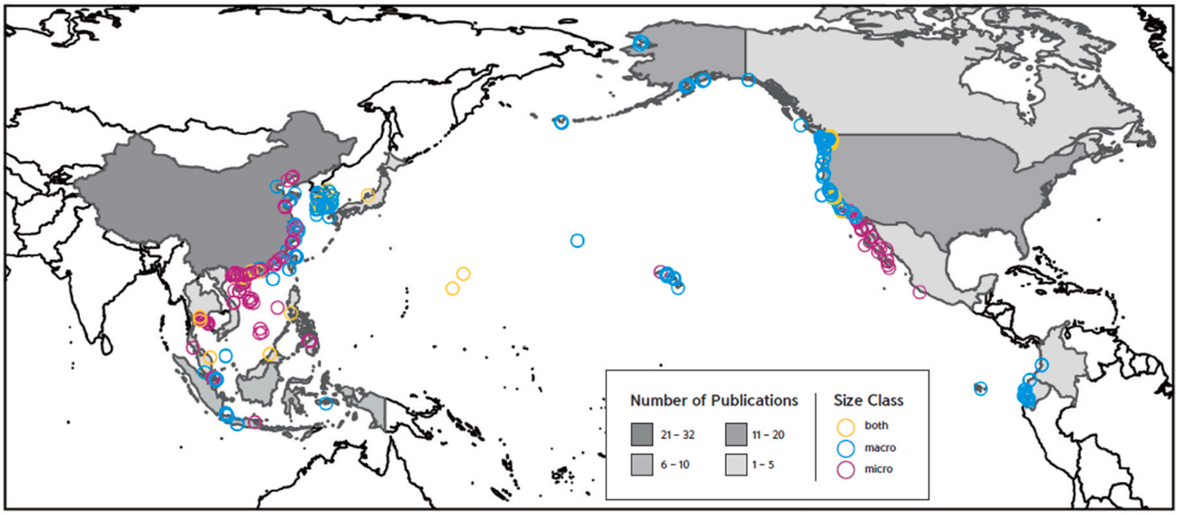

**Fig. 1.** Geographic distribution of 81 studies of shoreline marine debris in the North Pacific Ocean included in this review. Countries are gray-shaded (light to dark) based on the number of publications included in the review. Open circles indicate the size classes of debris reported from a given citation (pink: microplastic; blue: macroplastic; yellow: both). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

### *3.2. Patterns in reporting metrics*

Although all studies quantified the presence of marine debris on shorelines, the items being documented varied across studies in several ways. With respect to size, relatively few studies documented both macro- and microdebris (19.8%; Table 1). Microdebris studies were slightly more represented, especially in more recent years, although 5% of studies did not report information that could be used to determine size class at all (Table 1). We found that macrodebris studies tended to report all marine debris (48%), and sometimes only plastic (33%) or only specific categories or items (19%), whereas microdebris was always reported as a measure of plastic only (microplastics). Sometimes studies classified the items being reported. For example, studies reporting all debris might subclassify according to materials (e.g. plastic, wood, metal; or classify plastic according to polymers), shape (e.g. fibers, fragments, beads), use categories (e.g. fishing gear, domestic use items), or specific item categories (e.g. gillnet floats, food wrappers). Microplastic studies more frequently (51%) included plastic polymer identification, compared to macro debris studies (20%) (Table 1). Debris quantities were reported in nine different units, with items per area and items per mass being most commonly reported for macro and micro debris respectively (Table 1, Fig. 2).

### *3.3. Study characteristics and repeatability*

Sampling methods were also variable, and variably reported. Most sites were sampled only once (57.3%), and most studies took place for less than one year (76.5%) (Table 1). Precise site locations (latitude and longitude) were provided in only 44.4% of studies, and roughly a third (32.1%) of studies did not report where samples were collected within the shoreline (i.e. across the entire width, only at the strandline, etc.) (Table 1). Sample units were typically reported (e.g. defined area, quadrats, transects, or cores) but the overall site length from which replicate samples were collected was frequently unclear or not reported at all (37%) (Table 1). At the same time, the method for selecting replicates within a site (i.e., randomly) was typically described (87.7%; Table 1). Very few studies used citizen or community science for data collection or as data sources (12.3%; Table 1). Temporal trends were infrequently reported (24.7% of studies; Table 1).

### *3.4. Source identification*

It was difficult to objectively assess the manner in which the source of debris items was identified in the studies, but generally, source was evaluated in one of four ways: 1) applying a debris classification system specifically based on source and calculating the relative proportion of each ($n = 12$ studies, 14.8%); 2) identifying labels or manufacturer trademarks found on the surface of the debris items ($n = 3$, 3.7%); 3) ranking debris items and applying deductive reasoning to assign sources to the most common items ($n = 16$, 19.8%); and 4) using correlation between debris abundance and site characteristics that reflected the influence of a source such as sites located near industry or other debris-generating human activity, sites associated with land use types that promote debris release (i.e., agriculture, urban), or sites sampled during seasons known for debris loading (i.e., wet seasons that flush specific items downstream) ($n = 17$, 21.0%; Table 1). Using these evaluation criteria, 48 of the 81 studies (59.3%) attempted to elucidate possible sources of debris. Of these, 20 reported on macrodebris (plastic + other materials) only, 11 reported on both macro- and microdebris (which were always microplastics), and 13 studies examined microplastics only. Identifying debris sources appeared to be more easily demonstrated when macrodebris was the focus (31 studies). When sources could be identified, points of origin were in close proximity to the sampling area (45 studies). Only three studies reported on long-distance transport of debris, including debris along the western coast of North America as a result of the 2011 Tōhoku Japan earthquake and tsunami, and debris found in Alaska attributed to open ocean, non-local fishing vessels.

### *3.5. Geographic distribution of macroplastic*

Twenty-five studies (226 sites total) representing eight countries (People's Republic of China, Ecuador, Indonesia, Japan, Republic of Korea, Malaysia, Philippines, United States) clearly reported debris as macroplastic ($\geq$2.5 cm in size) (Fig. 3, Table S1). The United States had the most sites overall ($n = 82$), followed by the Republic of Korea ($n = 44$), Indonesia ($n = 40$), the People's Republic of China ($n = 30$), and Ecuador ($n = 26$) (Table S1). The remaining countries each had two sites or one site (Table S1). (In Japan, 26 sites were surveyed but only the mean value was available. Most sites reported macroplastic as items per square meter ($n = 136$, 60.2%) (Table S1). Four countries (People's Republic of China, Indonesia, Republic of Korea, United States) reported debris as both items per linear meter and items per square meter, while

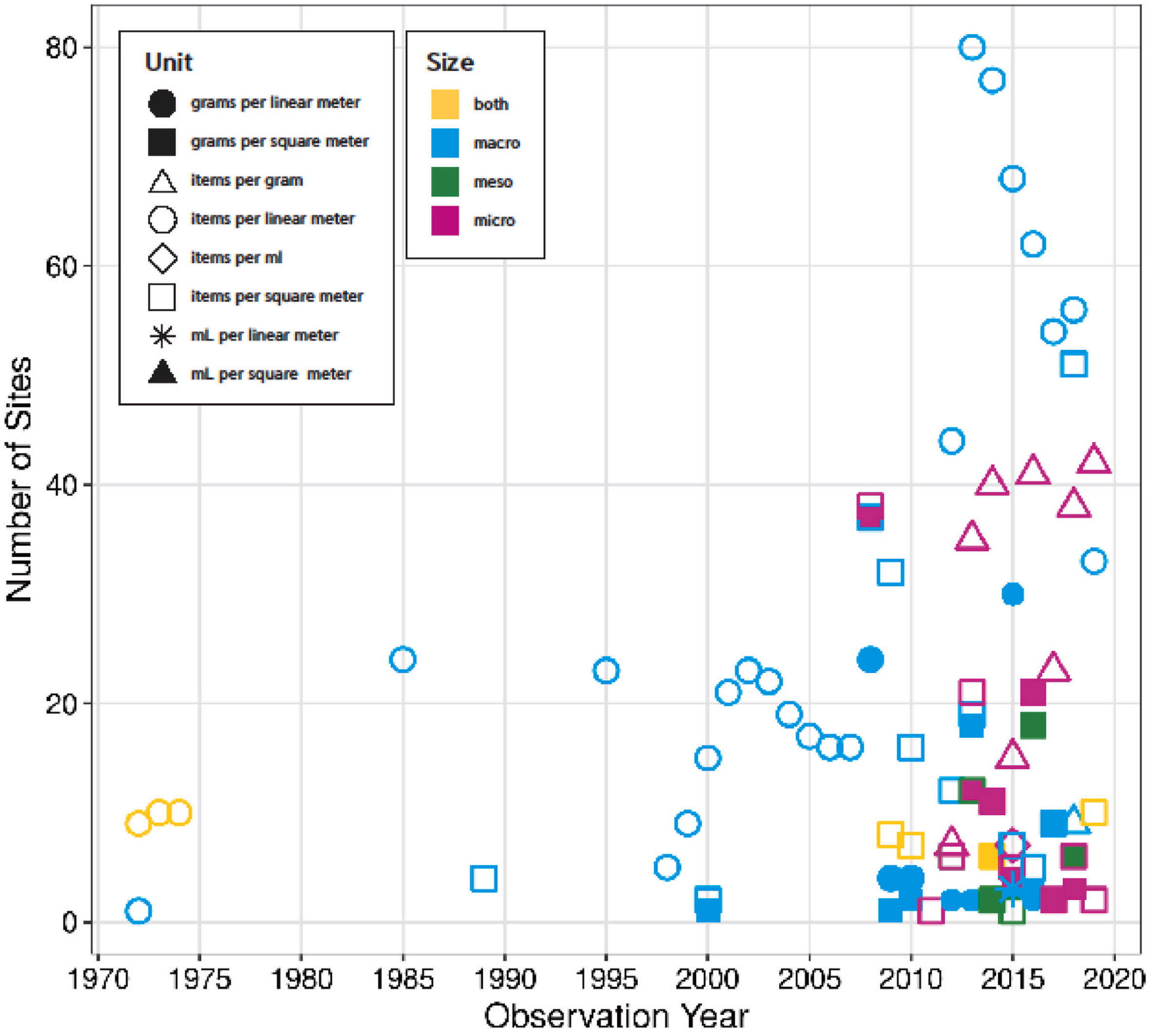

**Fig. 2.** Reporting of various plastic size classes (pink: micro, green: meso, blue: macro, yellow: both micro + macro) and units of measurement (open triangle: counts per gram, open circle: counts per linear meter, open diamond: counts per mL, open square: counts per square meter, closed circle: grams per linear meter, closed square: grams per square meter, asterisk: mL per linear meter, closed triangle: mL per square meter) at 903 sites over time. The year is based on the survey year rather than the publication year. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the remaining four countries reported only items per square meter (Ecuador, Japan, Malaysia, Philippines) (Table S1).

### 3.6. Macroplastic items per square meter

Overall, most sites (n = 62) reported one item or less per square meter, followed by one to 10 items per square meter (n = 48), and 10 to 100 items per square meter (n = 22) (Fig. 3, Table S1). A few sites had macroplastic abundances greater than 100 items per square meter (n = 4) (Table S1).

In the United States, the majority of sites (87%) had macroplastic abundances ranging either from one to 10 items per square meter (n = 20) or from 10 to 100 items per square meter (n = 20) (Fig. 3, Table S1). Only one site in the United States, located in the Salish Sea of Washington state, had a macroplastic abundance greater than 100 items per square meter (Fig. 3, Table S1). Over half of China's sites (n = 16, 59.3%) had macroplastic abundances that were one item per square meter or less, with a handful of sites (n = 7) having abundances ranging from one to 10 items per square meter (Fig. 3, Table S1). China had three sites with abundances greater than 10 to 1000 items per square meter, and was the only country where macroplastic abundance greater than 1000 items per square meter was reported, from one site on Linkun Island located in the mouth of the Ou River, southeast Zhejiang (Fig. 3, Table S1). All sites in Korea and Ecuador had macroplastic abundances of less than 10 items per square meter (Fig. 3, Table S1). Macroplastic abundance in Indonesia included eight sites with one to 10 items per square meter and one site with 10–100 items (Fig. 3, Table S1).

### 3.7. Macroplastic items per linear meter

When abundances were measured as items per linear meter, most sites (n = 44, 48.9%) reported one to 10 items per linear meter, followed by 0.5 to less than one item per linear meter (n = 17), 0.1 to 0.5 items per linear meter (n = 16), and 10 to 100 items per linear meter (n = 9) (Fig. 3, Table S1). No sites had macroplastic abundances greater than 100 items per linear meter.

All of the sites in the United States (n = 36) had macroplastic abundances of less than 10 items per linear meter (Fig. 3, Table S1). The abundance of 0.1–0.5 items per linear meter was reported at 13 sites and that of one to 10 items per linear meter at 12 sites (Fig. 3, Table S1). Only three sites reported the abundances of items per linear meter in China (0.1–0.5 at one site, 10 to 100 at two sites) (Fig. 3, Table S1). Most sites in Korea (n = 14, 70%) had abundances of one to 10.0 items per linear meter and the other sites (n = 6) reported less than one macroplastic

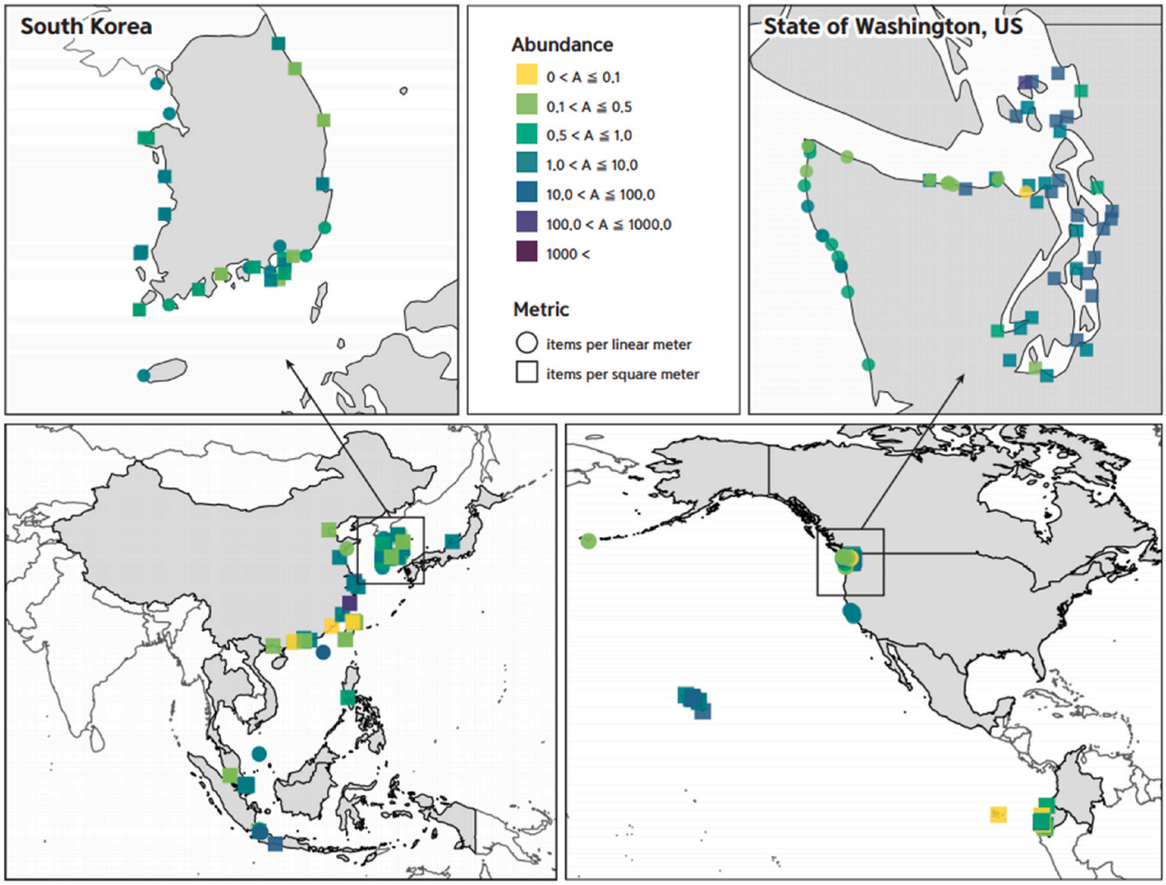

**Fig. 3.** Abundance of macroplastic debris by site across the North Pacific Ocean reported as item count per linear meter (circles) and item count per square meter (squares). Data used to construct the figure may be found in the Supplement (Table S1). In the case of multi-year surveys at the same site, the average abundance is presented. Increasing item counts are color-ramped (light to dark). A number of papers reporting 'total debris' included a ratio of plastic to non-plastic debris items. In these cases, plastic abundance was calculated by multiplying the total abundance by the ratio in order to be included here. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

item per linear meter (Fig. 3, Table S1). Most sites in Indonesia (n = 18, 58.1%) had abundances of one to 10 items per linear meter with seven sites having 10 to 100 items per linear meter (Fig. 3, Table S1).

### 3.8. *Geographic distribution of microplastic*

Where studies had clearly defined debris size classes and reported these as either macroplastic, microplastic or both, nine countries had data on microplastics in 38 papers (312 sites total) (People's Republic of China, Republic of Korea, Malaysia, Mexico, Philippines, Singapore, Thailand, Viet Nam, United States) (Fig. 4, Table S2). The People's Republic of China had the most sites overall (n = 118), followed by Mexico (n = 50), the Republic of Korea (n = 42), United States (n = 38), and Thailand (n = 36) (Fig. 4, Table S2). The remaining countries had less than 10 sites (Table S2).

Microplastics were reported from 201 sites with items per gram as the most common unit of measure (64.4%), largely driven by China (n = 99) and Mexico (n = 47) (Fig. 4, Table S2). Of the nine countries with microplastic data, five (People's Republic of China, Republic of Korea, Mexico, Philippines, Thailand) reported debris as both items per square meter and items per gram of sand (Fig. 4, Table S2). Singapore and Viet Nam only reported items per gram while Malaysia and the United States only reported items per square meter (Fig. 4, Table S2).

### 3.9. *Microplastic items per gram*

Overall, most sites (n = 74) reported 0.1 to 0.5 items per gram, followed by less than 0.1 or one to 10 items per gram (n = 42, respectively) (Fig. 4, Table S2). Fifteen sites had microplastic abundances from 10 to 100 items per gram and only three sites showed greater than 100 items per gram (Fig. 4, Table S2).

Six countries had sites where abundances were less than one item per gram (China: n = 80, Korea: n = 2, Mexico: n = 46, Philippines: n = 1, Singapore: n = 10, Thailand: n = 2) (Fig. 4, Table S2). Mexico (n = 1) and Thailand (n = 19) had sites with abundances ranging from one to 10 items per gram. China (n = 1) and Thailand (n = 12) had sites with abundances ranging from 10 to 100 items per gram (Fig. 4, Table S2). China (n = 2) and Thailand (n = 1) had sites with abundances ranging from 100 to 1000 items per gram (Fig. 4, Table S2). No sites exceeding 1000 items per gram were reported.

### 3.10. *Microplastic items per square meter*

Only one site (United States) reported less than one item per square meter (Fig. 4, Table S2). Sixteen sites from four countries had abundances ranging from one to 10 items per square meter (Korea: n = 4, Philippines: n = 3, Thailand: n = 1, United States: n = 8) (Fig. 4, Table S2). Most sites (n = 43) had microplastic abundances ranging from 10 to 100 items per square meter (China: n = 5, Korea: n = 11, Mexico: n = 2, Thailand: n = 1, United States: n = 24) (Fig. 4, Table S2). Microplastic abundances ranging from 100 to 1000 items per square meter were reported from China (n = 3), Korea (n = 13), Malaysia (n = 6), Mexico (n = 1), and the United States (n = 5) (Fig. 4, Table S2). Only China and Korea had microplastic abundances greater than 1000 items

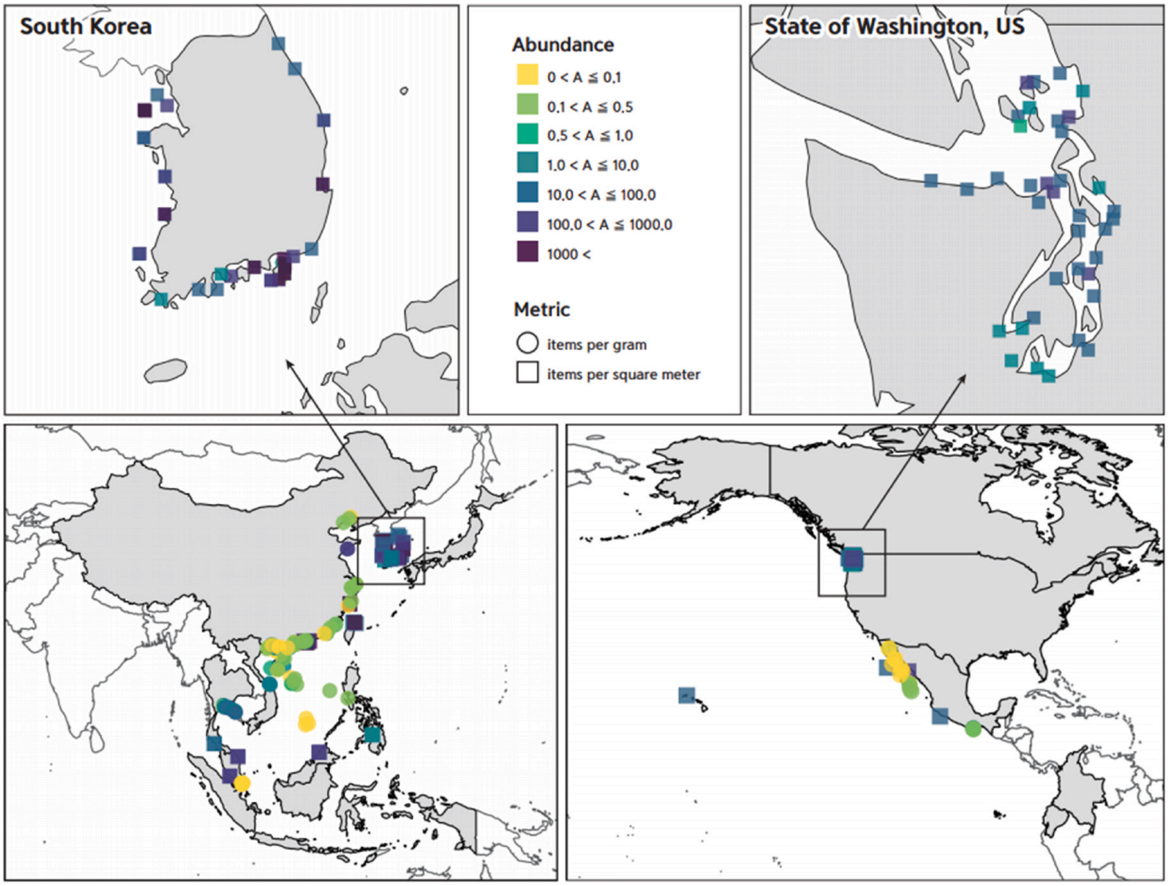

**Fig. 4.** Abundance of microplastic by site in the North Pacific Ocean reported as item count per gram (circles) and item count per square meter (squares). Data used to construct the figure may be found in the Supplement (Table S2). In the case of multi-year surveys at the same site, the average abundance is presented. Increasing item counts are color-ramped (light to dark). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

per square meter at 11 and 12 sites, respectively (Fig. 4, Table S2).

### 3.11. Generalized linear mixed model

There was strong evidence of an association between the abundance per unit area of plastic type and country ($F_{2,\ 51.6} = 104.1$, $p < 0.0001$, Table 2). That is to say, the relative magnitudes between microplastic and macroplastic counts seem to differ between countries among locations included in each study. Due to high variability, there was not sufficient evidence to suggest differences in abundance between any set of country pairs within each plastic type (all $p > 0.16$, Table 3, Fig. S1), though there was strong evidence that microplastic counts were greater than macroplastic counts in all countries with data available to make the comparison, being an estimated 3.1 times greater in the US Pacific, 16.1 times greater in China, and 1263.8 times greater in Korea (all $p < 0.0001$, Table 4). Additionally, there was evidence that these differences in relative plastic type magnitudes differed between all country pairs (China - Pacific US: $p = 0.039$; Korea - China: $p < 0.0001$; Korea - Pacific US: $p < 0.0001$; Table 5).

**Table 2**
Type III tests for fixed effects in the generalized linear mixed model (negative binomial [log-link, $\varphi = 1.63$]) fit by restricted maximum likelihood to microplastic and macroplastic observations recorded in units of counts per square meter.

| Term | *Ndf* | *ddf* | *F* | *p*-value |
|---|---|---|---|---|
| Country | 3 | 10.1 | 0.4 | 0.76 |
| Plastic Type | 1 | 46.4 | 213.2 | <0.0001 |
| Country x Plastic Type | 2 | 51.6 | 104.1 | <0.0001 |

## 4. Discussion

### 4.1. Best metrics for cross-study comparison, spatial and temporal trends

Only papers from four countries (Republic of Korea, People's Republic of China, Indonesia, and the United States) provided adequate data to conservatively model differences among countries in debris abundance, limited to the metrics of item counts of macroplastic and microplastic per $m^2$. Even so, these comparisons should be treated with caution given the differences among studies in terms of goals, survey design, sampling methods, and units of measure. Efforts that attempt to aggregate or compare multiple datasets should bear these caveats in mind. Although these countries did not differ statistically in terms of micro- and macroplastic abundance, there was country variation in terms of the magnitude of differences in micro-versus macroplastic abundance.

Several factors made it difficult to perform a comprehensive basin-wide assessment of shoreline marine debris within the North Pacific Ocean (NPO) in terms of spatial and temporal trends. These include limited geographic distribution of shoreline sampling locations, lack of spatial and temporal replication within locations, shortcomings associated with sample positioning on a beach (i.e., in relation to tide), classification of target debris (size classes, material type), and units of measure (counts or mass per unit area or length of shoreline), echoing issues identified by others (Browne et al., 2015, Serra-Gonçalves et al., 2019; Hapich et al., 2022). Additionally, many studies appear to have

**Table 3**
Model estimated means for microplastic and macroplastic items per $m^2$ by country as approximated by the generalized linear mixed model (negative binomial [log-link, φ = 1.63]) fit by restricted maximum likelihood.

| Plastic Type | Country | Estimate | Lower 95% | Upper 95% |
|---|---|---|---|---|
| Micro | China | 492.1 | 49.5 | 4889.6 |
| | Korea | 985.6 | 71.6 | 13,565 |
| | Pacific Coast US | 28.5 | 0.09 | 9267 |
| Macro | China | 30.6 | 2.6 | 352.8 |
| | Indonesia | 8.6 | 0.15 | 507.5 |
| | Korea | 0.78 | 0.06 | 11.0 |
| | Pacific Coast US | 9.2 | 0.03 | 3005.7 |

**Table 4**
Model estimated means for multiplicative differences in microplastic vs. macroplastic counts by country as approximated by the generalized linear mixed model (negative binomial [log-link, φ = 1.63]) fit by restricted maximum likelihood.

| Country | Estimate | Lower 95% | Upper 95% | *t* | *df* | *p*-value |
|---|---|---|---|---|---|---|
| China | 16.1 | 4.5 | 57.6 | 4.4 | 39.8 | <0.0001 |
| Korea | 1263.8 | 609.0 | 2397.1 | 19.5 | 79.0 | <0.0001 |
| Pacific Coast US | 3.1 | 2.1 | 4.6 | 5.7 | 46.9 | <0.0001 |

chosen sites based on proximity to known pollution sources or activities, or because sites are known to be dirty, and these cannot be assumed to be representative of a larger area.

Datasets represented in this study originated for a variety of purposes so, in turn, they do not collectively fulfill the role of a coordinated, intentionally designed basin-wide monitoring program. Basic criteria for surveillance or effectiveness monitoring include repeated measurements collected over time (Hutto and Belote, 2013). Only 15 of 81 papers loosely meet these criteria where study sites were sampled repeatedly within a year (at least quarterly) and over multiple years (at least two years). However, not all shoreline monitoring data are published in the peer reviewed literature, but to our knowledge most monitoring programs publish results at least intermittently, and in turn their data structure and methods are represented here. Given that our review was constrained to peer-reviewed literature only, it is possible that additional true monitoring data exist but were not included in our evaluation. These may reside in agency, academic, or NGO-maintained databases (with varying accessibility) or summary reports. For example, long-term beach monitoring data from across the Northwest Pacific region are provided in a United Nations report (UNEP, 2020) while NOAA MDMAP data reside in a publicly available database with piecemeal publication in the peer-reviewed literature.

### 4.2. *Sources of shoreline debris*

When we were confident of the identification of debris source within a publication, we found that shoreline debris seems to be generally introduced from nearby sources rather than from distant sources, particularly in the western Pacific. Most of Korea's shoreline debris was identified as items from local aquaculture and commercial fishing activities (Lee et al., 2013; Hong et al., 2014; Jang et al., 2014). In China, shoreline debris was largely attributed to coastal/recreational activities, river outfalls or sewage treatment plants (Chen et al., 2020; Cheung et al., 2016, Lo et al., 2020) and some localized contributions from fishing activities or mollusk aquaculture along the southern coast (Fok et al., 2017; Li et al., 2018). Most shoreline debris in Indonesia was inferred to originate from coastal communities or beach goers (Willoughby et al., 1997; Syakti et al., 2017; Hayati et al., 2020). In the eastern Pacific (United States west coast), debris varies regionally with land-based indicator items (metal cans, motor oil containers, balloons, six-pack rings, straws, syringes, personal care items) dominating in Southern California (60% of total) linked to local population density within 40 km of the survey site (Ribic et al. 2012b). Ocean-based indicator items (various forms of derelict fishing gear, gloves plastic sheets, light bulbs, oil/gas containers, pipe-thread protectors, cruise line logo items) were more common along the North Pacific Coast (Northern California, Oregon, Washington; 44% of total) and these were related to upwelling events (Ribic et al. 2012b).

**Table 5**
Model estimated means for multiplicative differences in plastic type magnitudes (micro vs. macro) between country pairs as approby the generalized linear mixed model (negative binomial [log-link, φ = 1.63]) fit by restricted maximum likelihood.

| Contrast | Estimate | Lower 95% | Upper 95% | *Z* | *p*-value |
|---|---|---|---|---|---|
| China - Pacific Coast US | 4.88 | 1.07 | 22.4 | 2.42 | 0.039 |
| Korea - China | 91.1 | 16.4 | 507.7 | 6.11 | <0.0001 |
| Korea - Pacific Coast US | 444.9 | 147.1 | 1346.1 | 12.8 | <0.0001 |

Many types of debris, when discarded anywhere in the NPO, may circulate for years in the North Pacific Subtropical Gyre (Dotson et al., 1977; Ingraham and Ebbesmeyer, 2000). Debris accumulates in the Subtropical Convergence Zone which lies just above the Northwestern Hawaiian Islands. Because of the geographic location of islands such as Midway Atoll and the Hawaiian archipelago in relation to basin-wide circulation patterns, large amounts of debris become stranded on their shores (Brainard et al., 2000; Moy et al., 2017). Debris on Midway Atoll, which is nearly equidistant between North America and Asia, is dominated by fishing and shipping related debris as well as beverage bottles and household products (Ribic et al., 2012a). Even though source categories were considered land-based, it is clear that this type of debris did not originate on-island. The island is inhabited by a small number of staff from the U.S. Fish and Wildlife Service (∼40 individuals) but there are no rivers, no industry and no commercial fisheries on the island, suggesting that the debris is transported from non-local sources. Similarly in Hawai'i (Oahu), ocean-based indicator debris (various forms of derelict fishing gear, gloves plastic sheets, light bulbs, oil/gas containers, pipe-thread protectors, cruise line logo items) were found in greater abundance than land-based indicator debris (metal cans, motor oil containers, balloons, six-pack rings, straws, syringes, personal care items) and general-source indicator debris (plastic bags, strapping bands, plastic bottles) again highlighting the influence of non-localized sources (Ribic et al., 2012b). There are also differences in debris sources between windward and leeward sides of the main Hawaiian Islands (Brignac et al., 2019). Debris on the leeward sides of islands appeared to originate from land-based, local sources with cigarette filters (48% of total) as the most common whole item. Windward beach debris was similar to sea surface debris presumably from non-local sources (i.e., Eastern Pacific Garbage Patch) and here, oyster spacers (42% of the total) dominated (Brignac et al., 2019).

Collecting information that can identify or indicate the source of marine debris is critical to develop preventive strategies and governmental intervention and to evaluate policy effectiveness through long-term monitoring (Lovett et al., 2007). This remains challenging given that debris enters the environment via numerous direct or diffuse sources of origin and can be transported far from the point of origination before settling in the environment. Further complicating the issue is lack of a consistent definition in the literature. Our review found that source can be taken to mean 1) the actual product or material (i.e., synthetic textiles), 2) the pathway of entry to the environment (i.e., rivers, atmospheric deposition), 3) the specific human activity responsible for the initial release (i.e., smoking, littering), 4) the company that produced the original product, or 5) the industry or economic sector responsible for the initial release (i.e., coastal tourism, shipping). Veiga et al. (2016)

recommend a two-part definition that includes the source (economic sector or human activity from which the item originates) as well as identification of the means of release (mechanism by which the item leaves the intended cycle and/or enters the environment). To further understand debris source, these authors suggest that additional information is needed on the item's geographic origin, pathway (the physical and/or technical means by which litter enters the environment), and transport mechanism (how debris is moved into and within the environment) (Veiga et al., 2016).

### 4.3. *Recommendations*

The focus of this analysis is an NPO assessment of shoreline marine debris, as this basin has not yet been synthesized, and an effort is warranted given regional ocean circulation patterns and the transboundary nature of marine debris. It is worth noting that the challenges identified here apply not only to this region, but would extend to any effort intended to compare and combine datasets at any scale. As the spatial and temporal scale of interest increases, so does method variability, and in turn, the structure of error, making even comparison of like units more uncertain. For this reason, we do not feel it is appropriate to attempt an analysis that makes comparisons across regions with the current state of data. Current efforts led by the Global Partnership on Marine Litter toward harmonizing and integrating multiple data streams into a Global Platform on Marine Litter will face these challenges, but may underscore the need for better harmonization/standardization if global comparisons are desired.

Our review highlights a number of deficiencies in the published literature on marine debris shoreline abundance that continue to be perpetuated (Browne et al., 2015, Serra-Gonçalves et al., 2019; Hapich et al., 2022) and which hinder data reusability and inference beyond the scale of an individual study. We offer the following recommendations for marine debris shoreline sampling design, indicators, metrics, on-site methods, and targets in the NPO, with the understanding that the overall goal is to identify shoreline debris trends in space and time basin-wide. Because of the challenges associated with developing large-scale, long-term monitoring programs such as this, it is strongly recommended to consult with a survey design statistician at all stages of program planning including implementation through to completion.

#### 4.3.1. *Survey design - spatial scale*

As with any environmental monitoring endeavor, a large-scale, long-term monitoring program for shoreline marine debris (i.e., in the NPO) will require a robust survey design that is spatially balanced, permitting extrapolation from sampled sites to the entire study area. Some common designs for site selection used in environmental monitoring programs include systematic sampling, general random sampling, generalized random tessellation stratified design and balanced acceptance sampling. The reader is encouraged to consult McDonald (2012) and Robertson et al. (2013) for thorough treatments of survey designs for long-term ecological monitoring. Because the extent of this proposed monitoring program includes the entire NPO, replicate sampling will need to occur at the scale of the entire basin (scale of inference). The number of replicate samples needed for a basin-wide trend assessment may be determined through the use of power analysis and will depend on the level of detectable change that is desired and the acceptable error rate (Ribic and Ganio, 1996) and also the amount of resources available to conduct the surveys. The spatial resolution will be a 100-m length of shoreline at each survey site. A complete discussion of power analysis and its application for sampling the NPO is beyond the scope of this paper (see Quinn and Keough, 2002).

Due to the vastness of the NPO, it may be necessary to spatially stratify survey sites using strata that are defined by ocean circulation processes, shoreline topography and the types of marine debris known to occur there, similar to what was done in the United States as part of the National Marine Debris Monitoring Program (Sheavly, 2007; Ribic et al., 2010; 2011; 2012a; 2012b). In this way, different strata within the basin may be compared to one another.

#### 4.3.2. *Survey design - temporal scale*

Sampling frequency per survey site (e.g., temporal resolution of the monitoring program) will necessarily be high to permit trend assessment and will also be driven by the timescale of processes that influence shoreline debris abundance across the basin which will need to be identified and could be daily, weekly, monthly or quarterly. This becomes challenging as debris abundance at different geographic locations within the NPO are variably influenced by temporal drivers such as ocean circulation, nearshore circulation, river outfall, seasonality of rainfall, seasonality of recreation (beach usage) and so on. However, in order to compare among different strata, especially for rates of debris accumulation, the same sampling temporal resolution must be used.

### 4.4. *Metrics, debris categories and indicators*

We agree with Ryan et al. (2020*b,c*) with regard to measurement units for shoreline marine debris in that attention should focus on macrodebris. Although defined as items >5 mm in size (GESAMP, 2015), we recommend increasing this detection limit to ≥ 2.5 cm to align with existing shoreline monitoring programs in the European Union (EU) (Galgani et al., 2013b), the Republic of Korea (Hong et al., 2014; Jang et al., 2014) and the United States (Lippiatt et al., 2013; Burgess et al., 2021) and the guidelines of the United Nations Environment Programme (Cheshire et al., 2009). Visual counting of macrodebris on shorelines does not require complicated sampling methods and owing to their larger size, macrodebris items are often identifiable allowing for inference of polymer type and source attribution. Thus, macroplastics found on shorelines can be more readily addressed through prevention and policy interventions due to knowledge regarding their connection to production processes and source.

We recommend that all debris items observed be counted. We agree with Hapich et al. (2022) in that limiting debris classifications to high level terms describing material and item type at a minimum, will better facilitate comparability. Debris descriptors vary locally to regionally and fine scale terms are unlikely to be consistently comparable at larger geographic scales. For example, one category list may simply refer to items as “fishing gear” while another classification scheme may specifically call out “monofilament”, “wood traps”, “wire leaders,” etc. When such fine scale descriptors are used, these must be mapped back to a more general/universal category.

Debris items should be reported as counts per length of shoreline, integrated across the width of the beach, from the water's edge to the beginning of the back barrier (Ryan et al., 2009, 2020b, 2020c). Ideally, shoreline monitoring would include both count and mass of items, but this is often not feasible or practical for large macrodebris items or items that are wet and encrusted. Counts per length of shoreline are appropriate to inform policy interventions when the goal is to address the abundance of total plastic or specific items of interest. Within a given monitoring program, a standard length of shoreline should be consistently adopted to facilitate comparability (GESAMP et al., 2019). We recommend a 100 m length of shoreline as the sample unit for the NPO, in keeping with several well-established monitoring methodologies across the globe (United States: Lippiatt et al., 2013, Burgess et al., 2021; the European Union: OSPAR, 2010, Galgani et al. 2013b; the Republic of Korea: Hong et al., 2014, Jang et al., 2014, NOWPAP, 2021; UNEP: Cheshire et al., 2009; Australia: Schuyler et al., 2020). Use of a fixed length of shoreline combined with sampling that occurs across the entire width of the beach (with measurement and reporting of said beach width) permits debris counts to also be expressed per unit area, which may preferable to some (Serra-Gonçalves et al., 2019, UN SDG 14.1).

We propose that spatial and temporal trends in the amount of shoreline debris in the NPO, measured as counts of items ≥2.5 cm per 100 m of shoreline, serve as an indicator for the basin. This aligns with the aforementioned published monitoring methods as well as the guidelines established by the EU Marine Strategy Framework Directive (MSFD) (Galgani et al. 2013a, 2013b) and the recent guidelines recommended for Arctic shores (AMAP, 2021b).

### 4.5. Guidelines for threshold values and reduction targets

Before threshold values or reduction targets can be agreed upon for the NPO, a basin-wide dataset with adequate spatial and temporal resolution must be generated from which to estimate current debris loads and to set reduction targets against. This should be informed by the recommendations above. Efforts in this region could follow approaches by others. EU Member States, operating through experts from within the MSFD Technical Group on Marine Litter, were tasked with developing baseline abundance and threshold values for shoreline debris pursuant to the Directive. In 2020, the European Threshold Value of 20 debris items per 100 m of shoreline was published (Van Loon et al., 2020). Determination of the threshold was based on the 15th percentile of existing baseline data for shoreline debris abundance from 21 European beaches during the period 2015–2016 (Hanke et al., 2019; Van Loon et al., 2020).

The MSFD established four separate marine regions located within the geographic boundaries of the existing Regional Sea Conventions and these regions are at liberty to pursue their own reduction goals. For example, the latest North-East Atlantic Environmental Strategy (Agreement, 2021–01; https://www.ospar.org/convention/strategy) developed by OSPAR defines the following beach litter reduction target, “By 2025 OSPAR will reduce by at least 50% the prevalence of the most commonly found single-use plastic items and maritime related plastic items on beaches in order to contribute to the achievement of relevant regional and EU threshold values building upon requirements for EU Member States in the EU Single Use Plastics Directive (Directive, 2019/904), and by at least 75% by 2030.” For the NPO, a similar regional approach could be applied, likely based on the ocean circulation patterns driving debris transport in around the basin.

### 4.6. Summary of recommendations for survey/sampling design

- Question to be addressed by monitoring shorelines of the North Pacific Ocean (NPO): How are the types and amounts of shoreline marine debris changing over space and time (trend assessment) across the NPO?
- Spatial extent: NPO; Spatial resolution: 100 m length of beach
- Temporal extent: 5 years minimum; Temporal resolution: to be determined
- Ecological extent: all macrodebris on all beaches within the NPO that meet the collection criteria; Ecological resolution: individual debris items meeting the collection criteria
- Replicate samples must be taken at the scale of the entire NPO basin, recognizing that this may necessitate stratification according to ocean circulation (or other) patterns.
- In consultation with a statistician, estimate the desired power, detectable change and error rate to determine appropriate sample size. Develop a spatially-balanced survey design for site selection, recognizing that the NPO may need to be stratified based on ocean circulation (or other) patterns.
- Conduct multi-year sampling over a minimum of 5 years.
- For comparability, use a debris item classification scheme from an existing monitoring program while making necessary modifications to improve source identification. However, any fine scale descriptors must be map back to a more general/universal category.
- Count the number of macrodebris ($\geq$2.5 cm) items per 100 m length of shoreline across the entire width of the beach from the water’s edge to the back barrier.

### 4.7. Summary of recommendations for reporting variables

- Precise GPS coordinates of the sample locations
- Date and time of each sample collection
- Site characteristics that may influence debris observations (i.e., river outfall etc.)
- If the entire beach width cannot be sampled, indicate where along the beach profile that samples are collected (i.e., above high tide line).
- Location of sample collection in relation to the sediment surface (i.e., at the surface, down to 2 cm, etc.)
- Describe sample unit (i.e., transects, quadrats, cores) with dimensions, number and placement of replicate samples collected
- Clearly specify the size classes into which debris will be categorized including the limit of detection. We recommend all macrodebris items $\geq$2.5 cm.
- Clearly specify the debris material types to be categorized. If debris types other than plastic are being considered, ensure that plastics are also quantified separately in addition to total abundance. The NOAA MDMAP Marine Debris Item Categorization Guide (photos) may be found here: https://marinedebris.noaa.gov/protocol/mdmap-marine-debris-item-categorization-guide. The monitoring guidelines of the OSPAR Commission (2010) also contains a Photo Guide.
- If not enumerated on site, describe how debris is stored, transported and enumerated elsewhere.
- Measurement (i.e., item counts) and unit (i.e., per 100 m length)
- If summarizing, report data as individual site averages by year
- Include access to raw data (at the replicate level in both space and time)
- Follow FAIR Data Principles (Wilkinson et al., 2016) to promote reusability of data
- If microplastics must be sampled, conduct polymer identification. If subsampling is necessary, provide clear justification of the subsampling method. A detailed checklist of additional reporting requirements for microplastics can be found in Cowger et al. (2020).

## 5. Conclusions

Shorelines are demonstrated sinks for marine debris but efforts to quantify debris often fail to incorporate established survey design techniques or include basic reporting variables. Many of the shoreline debris datasets available for the North Pacific Ocean (NPO) are one-off studies that simply document debris status at a snapshot or slice in time but do not collectively fulfill the role of a coordinated, intentionally designed monitoring program, thus precluding a basin-wide assessment of distribution and trends. An intergovernmental organization such as PICES could attempt to harmonize/standardize shoreline monitoring across the NPO.

Some considerations for harmonizing aspects of shoreline monitoring survey design and standardizing reporting variables include: use of a standardized length of shoreline (we recommend 100 m) and integrating across the width of the beach to allow for reporting debris both as item counts per linear distance (preferred) or per area. We suggest that shoreline surveys focus on all macrodebris ($\geq$2.5 cm) as these items can be more readily addressed through prevention and policy interventions, although this requires a clearly defined debris classification scheme modified from existing lists and identifies both the economic sector or human activity from which the item originates (source) as well as the mechanism by which the item leaves the intended cycle and/or enters the environment (means of release). Any threshold value or reduction target for the greater NPO should be informed by data collected basin-wide using comparable methods such as those performed in the European Union under the Marine Strategy Framework Directive.

In the absence of consistent/harmonized methods, bias will be structured variably such that even comparisons of like units will have uncertainty (Browne et al., 2015). Vast improvements in the design and reporting structure of shoreline marine debris data are needed. We hope that our recommendations are considered should a unified shoreline monitoring program be developed for the NPO and as nations contemplate approaches for achieving the goals of UN SDG 14.

## Credit author statement

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2022.119862.

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