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Review

Global marine litter research 2015–2020: Geographical and methodological trends

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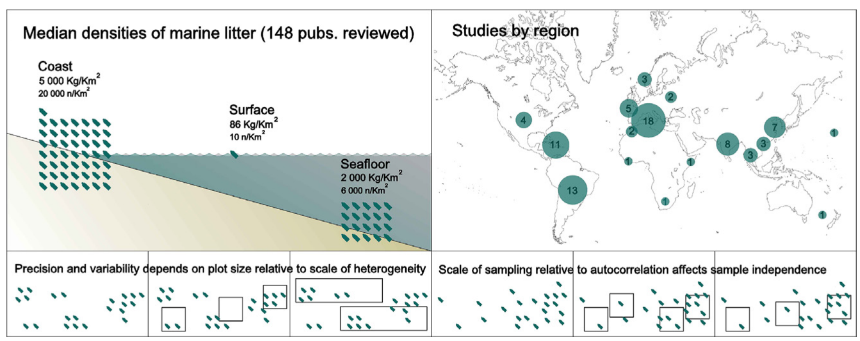
HIGHLIGHTS

- Improved knowledge of the global distribution of litter is important for management.
- A meta-analysis of macrolitter density data published 2015–2020 was conducted.
- Beach surveys dominate; seafloor and pelagic studies from high seas are lacking.
- Litter density is highest on the coast but data from low-income countries are lacking.
- Survey design (method, plot size/shape, replication) influences density estimates.

GRAPHICAL ABSTRACT



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ABSTRACT

A systematic review of research on marine macrolitter densities in the past five years (2015–2020) revealed considerable knowledge gaps in the field. Nearly half he reviewed studies were on stranded litter. Data are scarce from many of the regions estimated to mismanage the largest amounts of plastic waste. In regions where data are available these are typically from coastal areas with few data from the high and deep seas; 57% and 87% of studies on pelagic and seafloor litter, respectively, took place within 100 km from shore. Data on pelagic litter are generally constrained to the sea surface and only two of 30 pelagic studies have measured macrolitter deeper in the water column. Reported litter densities are generally highest for stranded litter, although seafloor litter densities by weight are high in some areas. Reported densities of floating litter are several orders of magnitude lower. However, a lack of standardisation of methods makes it difficult both to assess and to compare litter densities within and across the different environmental compartments in time and space. The review illustrates a great need for survey design development within the field of macroplastics and point to some long-established considerations from ecological research pertaining to independence of data points, spatial autocorrelation, sampling scale, and plot size and shape which are highly relevant also for marine litter research. These considerations are relevant both for global standardisation efforts and for independent studies. Furthermore, the knowledge gaps created by geographic and compartment biases in research needs to be addressed to identify further research needs, validate models and inform policy.

Contents

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1. Introduction

Marine litter is on the global agenda as the awareness of the magnitude and impact of mismanagement of waste, particularly plastics, has increased (MacLeod et al., 2021). Fifteen million tons of plastic is estimated to enter the ocean annually (Forrest et al., 2019). However, there is a general lack of correspondence between the amount of plastics estimated to have entered the oceans and the estimated abundance of plastic litter based on empirical data, and both the coastline and seafloor have been suggested as major sinks (Lebreton et al., 2019; Obbard et al., 2014; Olivelli et al., 2020). Mass balance models have been attempted globally for floating litter (*e.g.*, Lebreton et al., 2019) and regionally across compartments (Harris et al., 2021; Turrell, 2019).

Such models provide useful scales against which to compare mitigation and prevention measures as "stock size" is a key parameter in any management situation (Turrell, 2019). A comparison of litter densities within and among compartments (*e.g.*, sediment, water column) is also of great importance to optimising mitigation strategies by guiding efforts towards areas with the greatest yield for a given clean-up effort (Falk-Andersson et al., 2020a). However, considerable uncertainty remains regarding the parameters and assumptions made during modeling of relevant patterns and processes, and full inter-compartmental global (and regional) mass balance models are not available. A lack of data on marine litter densities is a major driver behind this uncertainty, and previous syntheses on plastic densities in the world oceans have called for standardisation of methods and more observations (Browne et al., 2015; Cózar et al., 2017; Eriksen et al., 2014; Lebreton et al., 2019; Maximenko et al., 2019).

Synthesising quantitative data at global scales is challenging both because of a general lack of empirical data in comparison to the vast areas affected (Blettler et al., 2018; Falk-Andersson et al., 2020a) and because of a lack of standardisation of methods used and metrics reported (Browne et al., 2015). Beach studies report litter densities using several measures from standing stock to accumulation over various time intervals, and from census or sub-sampling surveys of varying design. This may affect the amounts and types of litter measured and, if treated as equivalent, confound spatial or temporal patterns (Browne et al., 2015). Seafloor litter is also surveyed by a variety of methods, such as manual scuba diver surveys, trawl surveys or remote sensing (imaging using *e.g.,* ROVs or towed cameras) (Canals et al., 2020). The pros and cons of these different methodologies in terms of logistics and feasibility is discussed in detail by Canals et al. (2020), yet this review did not cover methodological differences in terms of plot size, shape and replication, nor did it assess potential differences in resulting density estimates. Only when methods do not vary in ways that influence the results is it possible to synthesise information from multiple studies (Browne et al., 2015). Plot size, replication, site selection and other aspects of survey designs are known to impact density and abundance estimates in ecological studies (Fortin et al., 1989; Griffith, 2005; Zhang et al., 1994). However, the potential influence of different sampling methods on density estimates has not been quantified for stranded marine litter, and not assessed at all for pelagic or seafloor litter.

Standardisation of monitoring protocols is key to securing effective regulations and evaluating the results of implementation of measures (Maximenko et al., 2019). Good quality monitoring data on marine litter can aid decision makers at multiple levels, from evaluating regulations to guiding mitigation efforts, as well as researchers in understanding marine litter dynamics and interactions of plastics with the ecosystem, and the implications of this (Maximenko et al., 2019). The need, benefits and recommendations for standardisation have been addressed by various expert communities working with plastic pollution, for example, the NOAA Marine Debris Program (Lippiatt et al., 2013), the MSFD Technical Subgroup on Marine Litter (European Commission, 2013) and the Arctic Monitoring and Assessment Programme (AMAP, 2021). The European financed coordination action EUROqCHARM (www.euroqcharm.eu) is an on-going initiative.

The objectives of this study were to synthesise research on marine macrolitter density across the globe and in different marine compartments and to assess (1) the geographic distribution of research efforts, (2) global trends and relative densities among ocean compartments to the extent possible given the limitations of such a dataset, and (3) the sampling methods used and their potential influence on density estimates. The aim of the first two objectives is to identify key spatial knowledge gaps, and the aim for the third is to help inform decision-making regarding study design. We considered the same three compartments as Schwarz et al. (2019): beach, pelagic (including water column) and sediment (henceforth referred to as seafloor as we did not include studies of microplastics within the sediment), but in oceanic environments only. We restricted our review to the past five years (2015–2020), both to synthesise recent research following the review by Galgani et al. (2015) and because the marine litter situation changes over time due to increasing input to the oceans (Jambeck et al., 2015).

2. Methods

2.1. Literature review

Systematic literature searches were performed using ScienceDirect, as well as back-referencing from reviewed articles (Fig. 1). Science Direct encompasses over 4500 journals, including their full texts (https://www.sciencedirect.com). Thorough back-referencing from articles returned in searches further expanded the scope of studies included. Only original research articles published from 2015 onwards were considered (search finalised August 2020). All articles returned in each search were evaluated based on title, keywords and abstract, and articles appearing to contain quantitative data on litter density were reviewed. Articles reviewed were assessed for data on the density of macrolitter (*i.e.,* excl. items <5 mm),

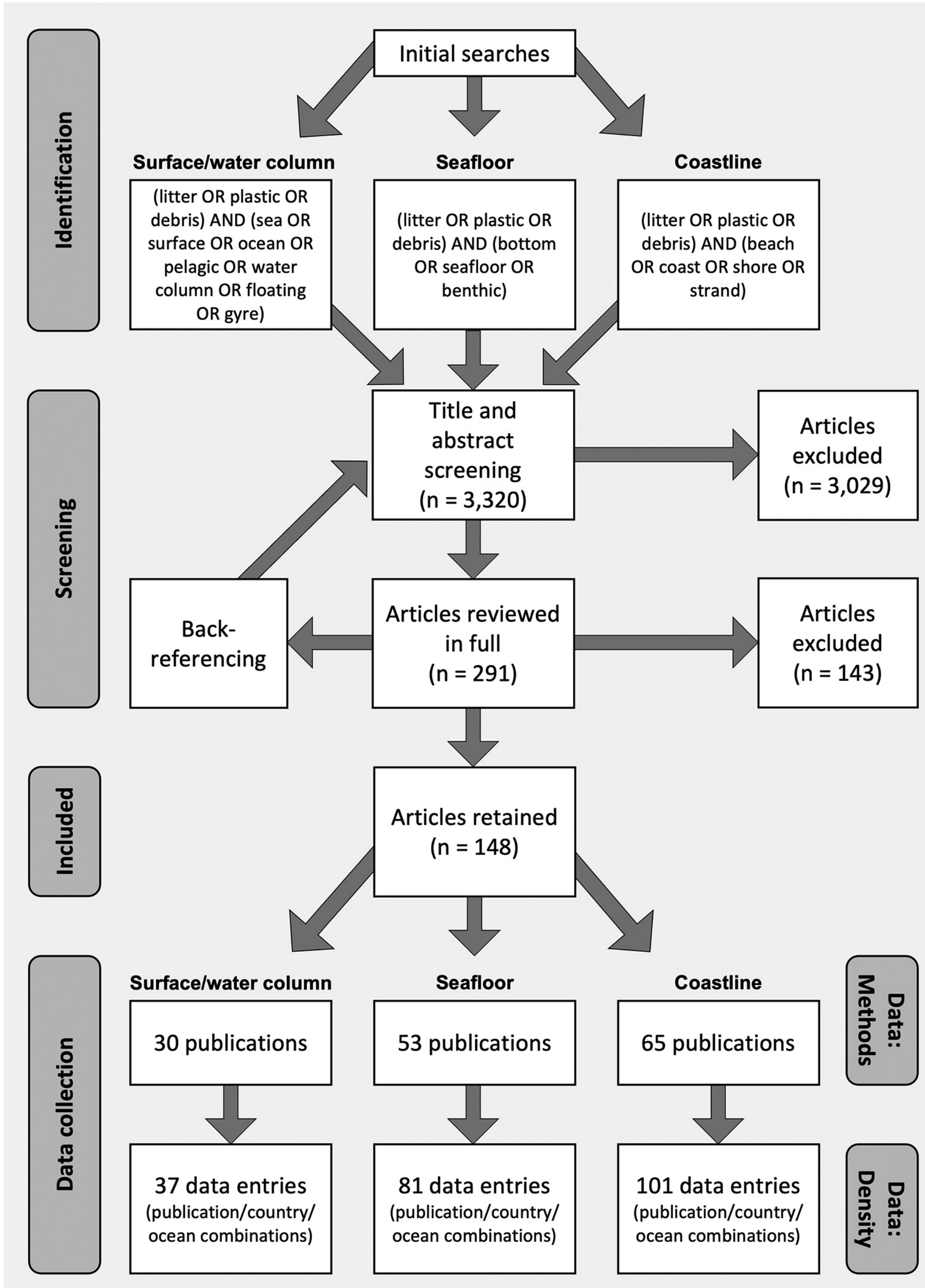

Fig. 1. Flow chart outlining the systematic review process. Initial searches were carried out in Science Direct (indexes over 4500 journals). See Tables S1 to S3 for the full lists and references of retained publications. Data entries refer to study, country, and body of water combinations. For example, a study reporting data from both the Atlantic and Pacific coasts of the US would be counted as two entries.

either by counts or weight and standardised either by area or linear distance. Only papers providing empirical data on standing stock, and where either all litter, or all plastic litter, was surveyed were included (*i.e.,* studies where litter density was standardised by effort or unit time were excluded). Studies were also required to present sufficient information on sampling locations to at least enable the estimation of central coordinates from figures, and to report sampling year and frequency. Articles meeting these criteria were retained for a meta-analysis (Fig. 1).

Data on litter density were extracted to the highest spatiotemporal resolution possible (*i.e.,* each publication may generate multiple rows in the datasheet). Coordinates were recorded to the highest resolution possible (*i.e.,* multiple discrete sampling locations were recorded when available), in addition to continent, country, ocean (North/South Pacific, North/South Atlantic, Indian, Arctic or Southern Ocean), and marginal sea (*e.g.,* the Mediterranean). For pelagic litter surveys, sampling methodology was classified as visual observations, remote sensing (*i.e.,* satellite or other image-based surveys), or trawl. For seafloor litter surveys, methodology was classified as either scuba dive, remote sensing (any video- or image-based survey using *e.g.,* ROVs or towed underwater cameras), or trawl. For stranded litter surveys, methodologies were classified as either manual or remote sensing, and further classified into census (entire location surveyed) or sub-sampling (transect/quadrat) surveys. Data on plot size and replication were recorded whenever available. For ship-based surveys reporting only travel speed and haul/deployment duration, plot length was estimated. Data on pelagic and seafloor litter were classified as having been recorded within the following distance from shore categories: <100 m, 100 m–1 km, 1–100 km, 100–1000 km, >1000 km. The image analysis software ImageJ (https://imagej.nih.gov/ij/) was used to extract location and density data from articles where these were presented in figure form only.

2.2. Statistical analyses

Data were summarised at two levels: studies and data entries. Summary statistics pertaining to methodology were assessed at the study level. Data entries combine publications and geographic location at the country and ocean basin/marginal seas resolution. For example, Honorato-Zimmer et al. (2019) provided data from the coast of Chile, as well as the North Sea and Baltic Sea coasts of Germany and was therefore counted as three entries. Entries were used for all summary statistics pertaining to litter density. This was done to better reflect the true geographic spread in published data.

The global distribution of macrolitter research over the past five years was compared to projected plastic waste emissions. This was done for stranded litter alone as the largest dataset. Data entries were pooled to the country level only (*i.e.,* different coasts of the same country were not separated into multiple entries as for other spatial analyses) and grouped into the regions specified by Lebreton and Andrady (2019). The number of entries per region was then compared to the midpoint mismanaged plastic waste (MPW) estimated produced in 2020 (see Table S2 in Lebreton and Andrady, 2019). The comparison was made by ranking the regions in descending order, first according to annual MPW production and then to number of studies. The publication rate rank was then subtracted from the MPW rank of each region. A positive difference indicates that a region contributes relatively little MPW but was relatively well studied in the past five years and *vice versa*.

Geographic and compartmental trends in litter densities were compared among sets of regions defined following different criteria (*e.g.,* continents, distance from shore categories) and sampling methods (*e.g.,* diver-based, remote sensing or trawl surveys for seafloor litter) using Kruskal-Wallis sum rank tests. This non-parametric test was chosen over parametric ANOVAs due to litter density data generally showing highly right-skewed frequency distributions. When plotting results notched boxplots were used. Notches show confidence intervals around the medians estimated as the median ± 1.58 the interquartile range (IQR)/sqrt(n); when these notches do not overlap there is strong evidence that the medians differ (Kassambara, 2019). Statistical tests were carried out using RStudio (R version 4.0.4) (R Core Team, 2021).

3. Results

3.1. Literature reviewed and publication trends

Data were extracted from 148 research articles (Fig. 1). Nearly half (44%) marine macrolitter density data published over the past five years describe stranded litter. Empirical studies of pelagic litter were least abundant (20%). For all compartments, there was a subset of expansive studies which included data from multiple countries and/or ocean basins/marginal seas and which thus constituted multiple data entries in analyses pertaining to geographical trends (Fig. 1). The majority (81%) of data entries on seafloor litter were from the North Atlantic, 65% of them in the Mediterranean (Fig. 2a). The North Atlantic was also the most studied for pelagic litter (61% of entries), followed by the North Pacific (29% of entries) (Fig. 2b). Similarly, 58% of studies on stranded litter took place in the North Atlantic, 45% of them in the Mediterranean. The Caribbean Sea was the second most studied region encompassing 17% of entries in the North Atlantic, although this was due almost exclusively to a single large study reporting data from beaches in several Caribbean nations (Schmuck et al., 2017). The North Pacific was the second most studied (18% of entries on stranded litter), followed by the South Pacific (10%) (Fig. 2c). The full lists of publications from which data were extracted are provided as supplementary materials (Tables S1–S3). The geographical distribution of empirical data on stranded litter corresponds relatively poorly with the estimated geographical differences in annual mismanaged plastic waste (MPW) (Lebreton and Andrady, 2019) (Fig. 3). Western Asia, Europe (excluding Eastern Europe), the Caribbean, North America, and Oceanic countries contribute relatively little MPW, but have been comparatively well studied the past five years. Conversely, Africa, Asia (excluding Western Asia) and Central America were poorly studied although they have high rates of MPW. This suggests a mismatch between MPW and research initiatives documenting the problem.

Over half (57%) of studies on pelagic litter, and the majority (87%) of studies on seafloor litter, took place within 100 km of the shore. Except for two studies (Barnes et al., 2018; Grøsvik et al., 2018), all studies on pelagic litter surveyed the ocean surface only. Most seafloor studies took place on the continental shelf (53%) or the slope (17%), or a combination of the two (14%). A small proportion of studies took place in marine canyons (8%) or deep-sea features, such as seamounts or banks (8%). No studies of macrolitter on abyssal plains were found. All but one study on marine canyons were conducted in the Mediterranean where the continental shelf is narrow and these occur near shore (Tubau et al., 2015). The degree to which the depth of seafloor sampling was reported was highly variable. Only 35% of studies reported the mean depth of sampling, either overall or for individual survey stations, 74% of which took place in waters shallower than 500 m (mean = 472 m, SD = 666 m, median = 241 m). The minimum and maximum depths sampled were reported to some degree for 72% and 78% of studies, respectively. The reported minimum and maximum depths ranged from 0.5–770 m (mean = 80 m, SD = 137 m, median = 32 m) and 5–3000 m (mean = 550 m, SD = 696 m, median = 300 m), respectively. For studies reporting the range of depths sampled (69%), this ranged from 7 to 980 m (mean = 224 m, SD = 259 m, median = 142 m).

The most common reporting units were counts standardised by area as illustrated by the dominance of diamond symbols across all compartments in Fig. 2. Only 8% of studies reported quantities as weight only; 72% of studies reported only counts and 20% reported both counts and weight. Only 8% of studies reported density standardised per linear unit (*e.g.,* km^{-1}); 88% of studies reported density standardised per area unit (*e.g.,* km^{-2}) and an additional 5% of studies reported both. Because of the prevalence of area count data, trends in litter densities were only analysed using this metric ($n\ km^{-2}$).

More than half (58%) of studies on stranded litter took place within a single year. Single-year studies were less common in pelagic and seafloor studies, comprising 37% and 35%, respectively. Following single-year studies, those taking place over 2–3 years were the second most common in all three compartments. Approximately 10% of studies on pelagic and seafloor litter took place over a ten-year period or more, compared to 3% of studies on stranded litter.

3.2. Spatiotemporal trends in macrolitter densities

The large geographic discrepancies in research efforts and publications preclude any extensive analysis of geographic trends. Consequently, only coarse comparisons could be made, and formal statistical analyses were not carried out. The greatest densities of seafloor litter were reported in the North Atlantic (Fig. 4a); however, available data for comparisons in other oceans were rare. Conversely, the highest densities of pelagic litter were reported in the North Pacific (Fig. 5a) with most data collected in the northern Pacific and Atlantic Oceans. For stranded litter, the highest reported densities were in various parts of Asia (Fig. 6a). When extreme hot spots (*i.e.,* outliers) were excluded to compare the remaining data more readily, the second most polluted beaches reported were apparent in Latin America and the Caribbean (Fig. 6b).

There were significant differences among the mean densities reported per study among marine compartments (coastline, seafloor and surface) for both item counts ($\chi^2_2 = 961.4$, $p < .001$) and weight ($\chi^2_2 = 41.9$, $p < .001$). The densities of pelagic litter were consistently the lowest (Fig. 7). For item counts, all extreme values were reported for stranded litter

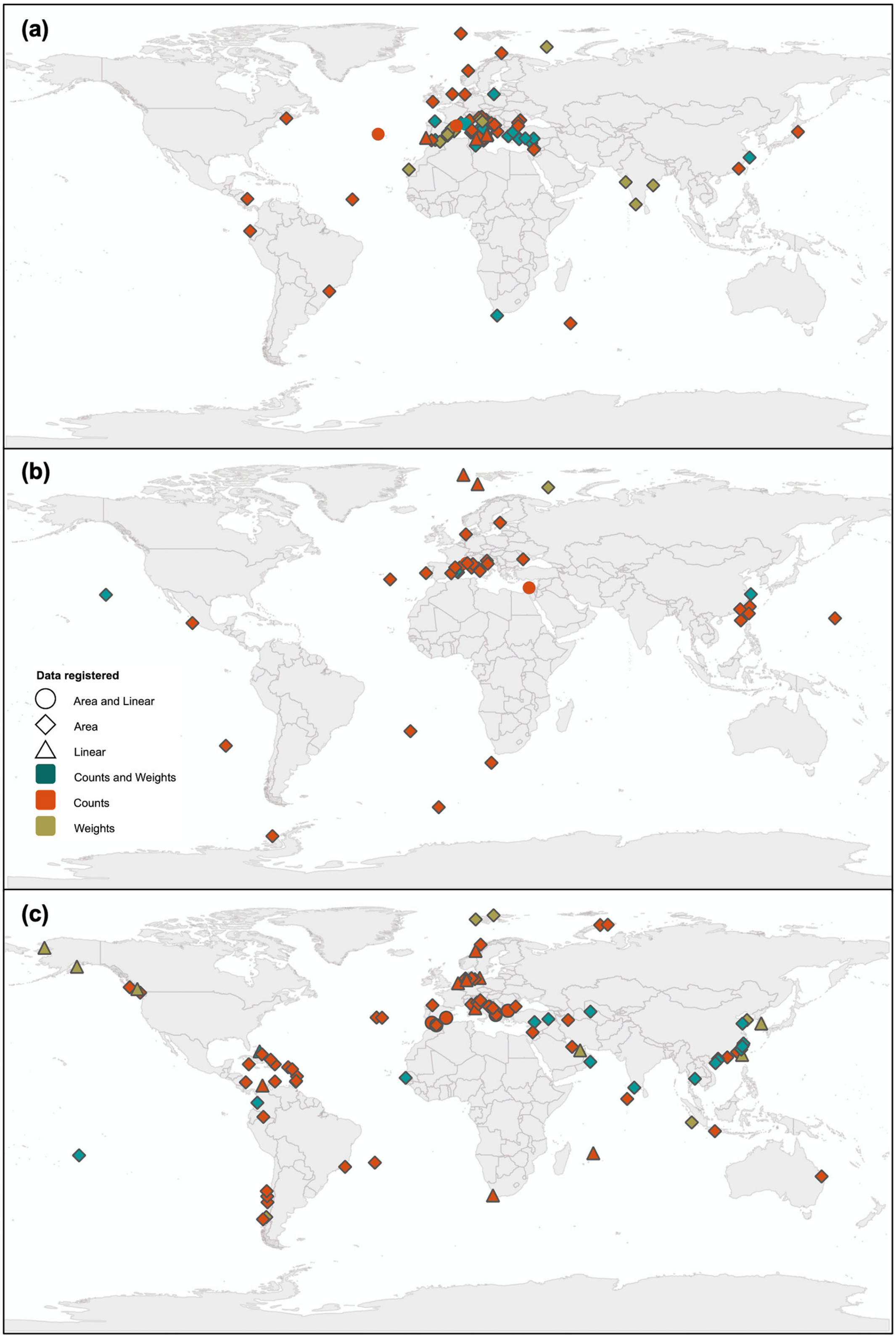

Fig. 2. Maps showing studies retained in the review by country and ocean basin (*i.e.*, "entries") for (a) seafloor, (b) pelagic, and (c) stranded litter.

(Fig. 7a), while for weight extreme values were reported for both stranded and seafloor litter, and particularly the latter (Fig. 7b). Median densities for both counts and weights were clearly highest for stranded litter (Fig. 7c–d). When this comparison was limited to the Mediterranean, where the most data were available from all three compartments (Fig. 2), count densities were the highest for stranded litter and the lowest for pelagic litter (Fig. 7e and g). Weight densities, however, where generally highest on the seafloor (Fig. 7f and h).

Seafloor litter densities (n km^{-2}) were generally reported to be highest within the first 100 m from shore, followed by areas 1–100 km from shore (Fig. 4b). However, a full comparison of density values by distance categories was not possible due to very few entries in the remaining categories

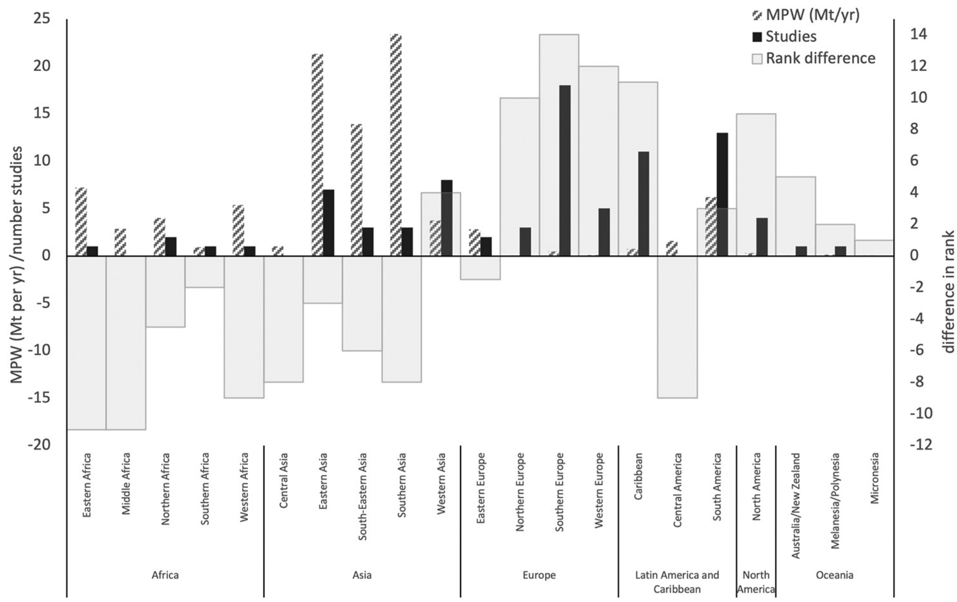

Fig. 3. Bar graph highlighting the discrepancy between regional differences in the expected contribution to marine litter and the amount of research conducted on stranded litter densities by geographic regions: (1) Estimated midpoint Mt. of mismanaged plastic waste (MPW) generated annually within each region (2020 estimates from Table S2 of Lebreton and Andrady, 2019). (2) Number of studies within each region 2015–2020. Studies were counted per country; publications including data from more than one country were counted multiple times. (3) Each region was ranked in descending order first according to annual MPW production and then to number of studies; the studies rank was then subtracted from the MPW rank of each region to show the rank difference. A positive difference indicates a region contributes little MPW but was relatively well studied in the past five years and *vice versa*.

(Fig. 4c). For pelagic litter, there was a significant association between litter density (n km^{-2}) and distance from shore category, with the greatest density reported within a km of shore ($\chi^2_3 = 8.3$, p = .039) (Fig. 5b).

The nature of temporal trends, as well as the reported rate, varied among studies with a time series of data spanning ≥5 years. For stranded litter, all but one reported statistical analyses of temporal trends, which included non-significant results (n = 2), negative trends (n = 2), positive trends (n = 1), and significant interannual variations without trend (n = 3). For studies on pelagic and seafloor litter, half of those with a time series spanning ≥5 years did not report analyses of temporal trends or interannual variation. The studies which did reported a mixture of non-significant (n = 4), positive (n = 4), and negative trends (n = 1), and interannual variation without trend (n = 3). Consequently, studies from the past five years provide no unified signal regarding temporal trends.

3.3. Trends in study design and sampling methodologies

For seafloor litter, trawl surveys were the dominant sampling method (52%), followed by remote sensing (36%), and diver-based visual surveys (13%). Studies conducted within 1 km of shore were exclusively carried out through scuba diving surveys, trawl surveys dominated within moderate distances from shore, and remote sensing techniques were the sole method utilised furthest from shore (Fig. 4c). Pelagic litter was surveyed by ship-based visual observations in 76% of studies; trawls were conducted in 18% and remote sensing in 6%. Visual surveys dominated beyond 1 km from shore while trawl surveys were most common up to 1 km from shore; no data on pelagic litter within 100 m from shore were found (Fig. 5c). Manual surveys dominated among studies of stranded litter (97%); two studies (3%) utilised remote sensing techniques. Of the manual surveys, 37% utilised census surveys (*i.e.,* the entire beach/location was surveyed). The remaining 63% of studies used some form of sub-sampling technique: quadrat sampling (32%), horizontal transects running parallel to shore (24%), or vertical transects running perpendicular to shore (44%) (Fig. 6c).

The densities reported by different methods often differed; combined with spatial trends in their usage this constitutes a confounding variable when attempting to assess spatial patterns. For seafloor litter, scuba diver surveys reported greater densities than trawl or remote sensing surveys ($\chi^2_2 = 32.7$, p < .001) (Fig. 4d). The highest densities of pelagic litter were reported by trawl surveys ($\chi^2_2 = 12.4$, p = .002) (Fig. 5d). For stranded litter there were no systematic differences in density reported by different sampling designs employed during manual surveys ($\chi^2_3 = 6.0$, p = .11) (Fig. 6d) (remote sensing surveys excluded due to low n). The proportion of surveyed seafloor transects reported to contain litter ranged from 0% to 100% and was generally highest for trawl surveys and lowest for remote sensing (Fig. 4e). There was less of a distinction between methods (trawling *vs* visual observations) for pelagic surveys, although remote sensing surveys were too few and reported this metric too seldom to be included (Fig. 5e). As stranded litter was surveyed almost exclusively by manual observations a comparison between this and remote sensing surveys could not be made.

Most seafloor studies reported the level of replication (*i.e.,* number of transects), although one trawl survey did not and another 14% did not specifically state it, only the annual mean in multi-year surveys. Replication differed significantly among sampling methods ($\chi^2_2 = 10.3$, p = .006). Trawl surveys were generally the best replicated (mean = 507, median = 173). Replication was lower for dive surveys (mean = 102, median = 38) and remote sensing (mean = 593, median = 23), although the latter showed considerable variability in the number of replicates (range: 1–5018) largely connected to whether individual still images or deployment tracks were considered the replicate. Similar patterns were not evident for pelagic surveys ($\chi^2_2 = 0.5$, p = .785), although sample size was highly variable (range: 8–25,000, the latter for a long-term multi-year survey) and the number of surveys other than visual observations likely too low for any meaningful statistical power. Replication in remote sensing surveys was not always clear as both tracks (transects) and individual images (quadrats) are used and their relation (*e.g.,* nested) not specified. For stranded litter, the mean number of sites surveyed ranged from 9 (median = 5, range = 29) for studies utilising horizontal transects to 128 (median = 11, range = 1225) for census surveys, but did not differ significantly among methods ($\chi^2_3 = 6.8$, p = .079). When sub-sampling was conducted, the within-site replication (*i.e.,* plots per site) was greater for quadrat surveys (mean = 19, median = 9, range = 119) than both vertical (mean = 10, median = 4, range = 70) and horizontal (mean = 4, median = 3, range = 8) transects ($\chi^2_2 = 7.2$, p = .027).

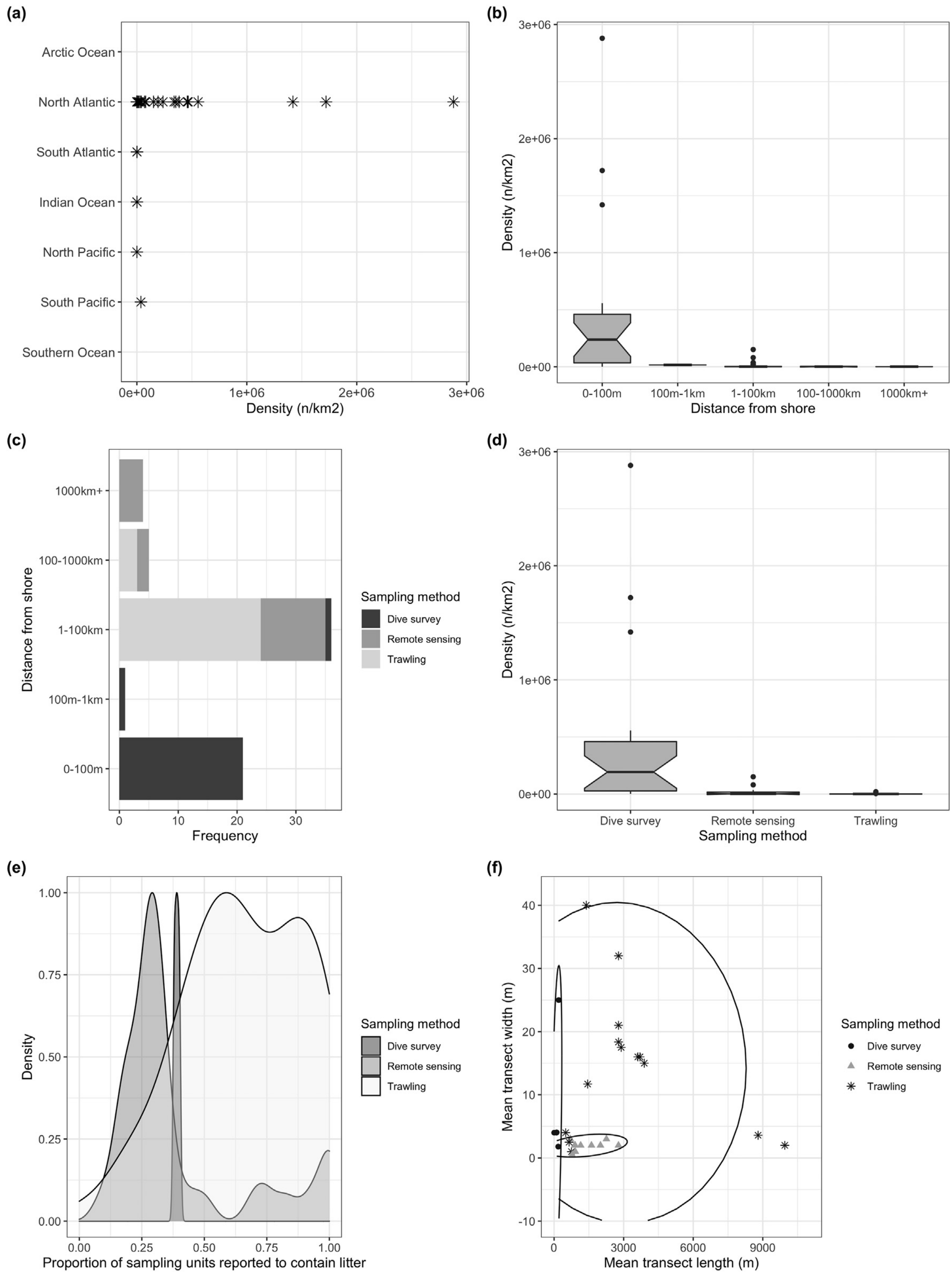

Fig. 4. Summary statistics for publications on seafloor litter. (a) Dotplot showing mean densities reported by studies in different ocean basins. (b) Boxplot of density (n km^{-2}) reported by different categories of distance from shore. (c) Bar graph showing publications by distance from shore category and survey method; note that some studies may be counted in multiple categories. (d) Boxplot of density (n km^{-2}) by survey method; remote sensing covers all video- and image-based surveys using ROVs, towed cameras, *etc.* (e) Density plot of showing the proportion of sampled transects reported as polluted by sampling method. Note that the density curve for dive surveys is very narrow due to few studies. (f) Scatterplot of mean transect length by width used in different studies. Ellipses are normal 95% data ellipses; note that only studies providing both metrics are shown.

For seafloor surveys, remote sensing typically utilises very narrow transects (mean and median = 2 m) (Fig. 4f) due to the restricted field of view of cameras operating closely above the seafloor. Transect length was highly variable depending on whether individual still images or entire deployment tracks were analysed as a unit (mean = 2.6 km, median = 0.9 km, range = 19.7 km). Trawl transects were also long and narrow, although wider than

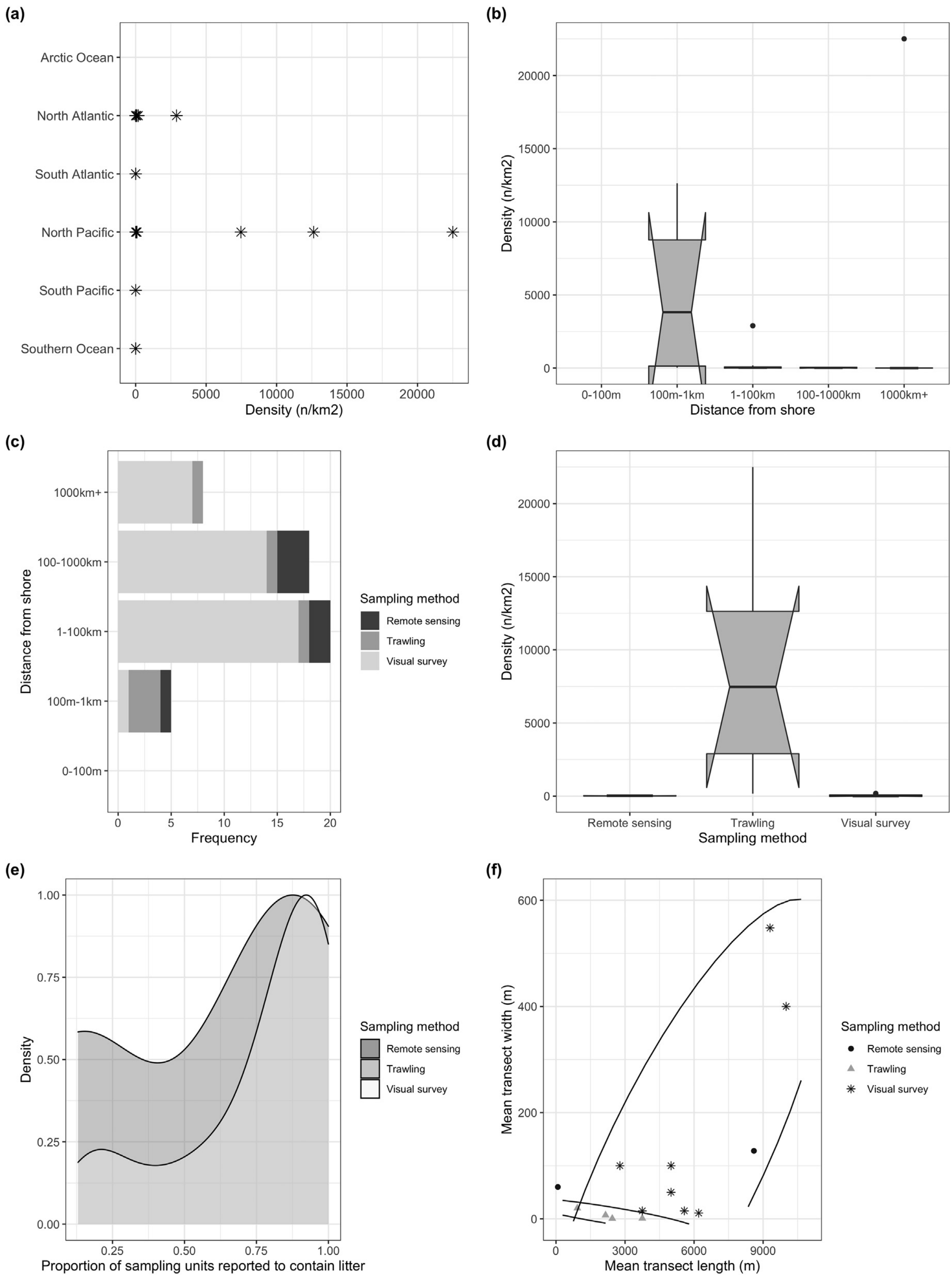

Fig. 5. Summary statistics for publications on floating litter. (a) Dotplot showing mean densities reported by studies in different ocean basins. (b) Boxplot of density (n km^{-2}) reported by different categories of distance from shore. (c) Bar graph showing publications by distance from shore category and survey method; note that some studies may be counted in multiple distances from shore categories. (d) Boxplot of density (n km^{-2}) by survey method; remote sensing covers all image-based surveys. (e) Density plot of showing the proportion of sampled transects reported as polluted by sampling method. Remote sensing surveys are not shown due to few studies and a general lack of reporting of the percentage of polluted sampling units. (f) Scatterplot of mean transect length by width used in different studies. Ellipses are normal 95% data ellipses; note that only studies providing both metrics are shown.

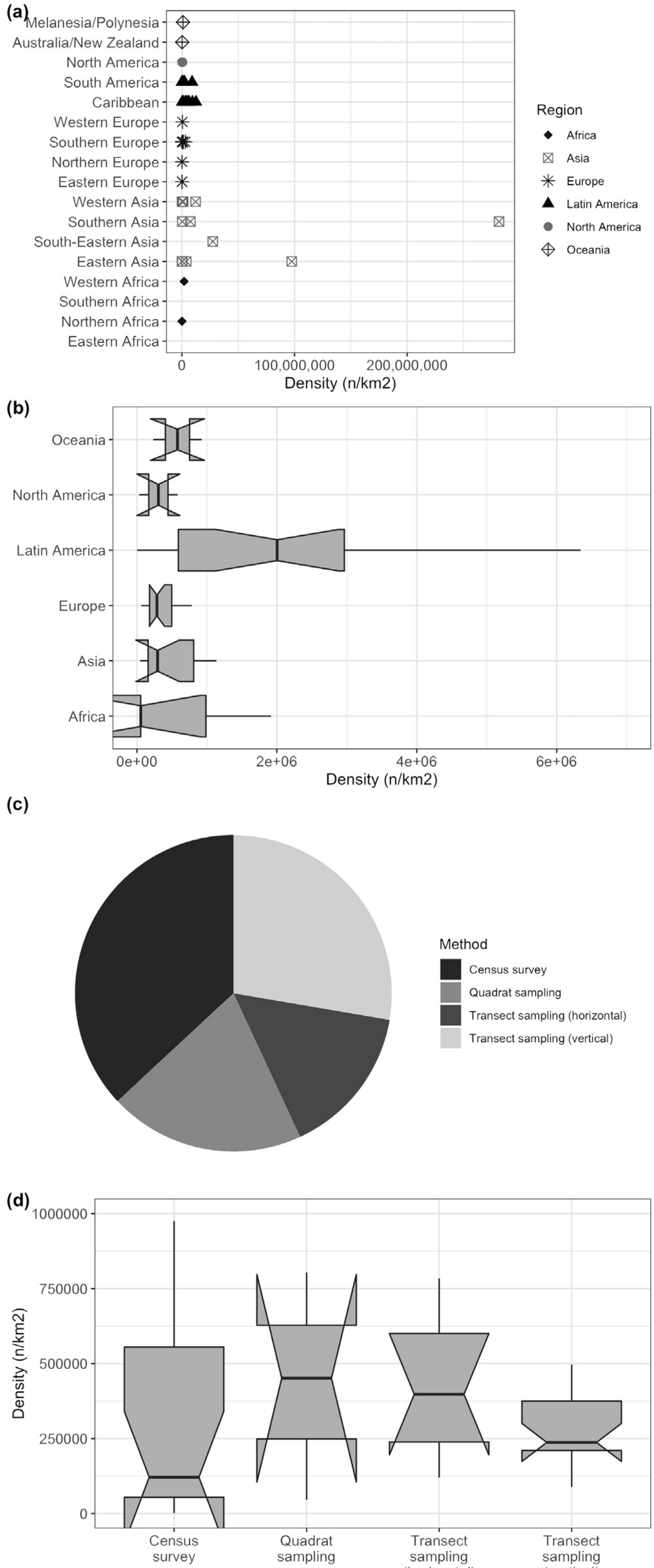

Fig. 6. Summary statistics for publications on stranded litter. (a) Dot plot of density (n km^{-2}) reported in different geographic regions. (b) Bar graph showing the results of panel a grouped by larger regions and excluding outliers. Note that Latin America includes the Caribbean. (c) Proportions of studies using different survey methods for manual beach surveys. (d) Boxplot of density (n km^{-2}) by survey method.

remotely sensed transects. They were also highly variable in dimensions due to a wide range trawl types and sizes and varying haul durations (Fig. 4f). Scuba diving surveys were generally squarer in nature with smaller sweep areas (Fig. 4f). The consistency in transect dimensions, particularly length, varied among methods ($\chi^2_2 = 7.4$, $p = .025$). Scuba diving surveys were generally consistent (range in transect lengths within studies: mean = 36 m, median = 0 m [*i.e.,* fixed plot length]), while remote sensing (mean range = 3976 m, median = 1503 m) and trawl surveys (mean range = 4555 m, median = 1574 m) were more variable. There was a significant positive relationship between the total area surveyed and the number of transects for scuba diving ($F_{1,\ 5} = 55.6$, $p < .001$) and trawl surveys ($F_{1,\ 17} = 13.8$, $p = .002$), but not for remote sensing surveys ($F_{1,\ 10} = 0.2$, $p = .67$).

For visual pelagic surveys, transect length and width were reported in 35% and 65% of studies, respectively; length could be estimated based on mean vessel speed and observation durations in an additional 35% of studies. The number of replicate transects was reported for 58% of visual surveys. The average reported width was 91 m (median = 50 m) but did in some cases exceed 500 m. Average transect length was 135 km (median = 9.8 km) and ranged from 2.8–1100 km. Plot dimensions were the most variable for visual surveys (Fig. 4f), although this is somewhat unsurprising given it was also by far the most commonly used method. Because only very few surveys utilised trawls or remote sensing and not all provide the necessary information, a comparison of transect shapes and sizes was not done among methods.

For stranded litter, plot size was reported more infrequently and was variable when reported. Of beach litter surveys utilising vertical and horizontal transects for sub-sampling, 82% and 36% were of variable length, respectively, stating simply that transects extended to the backshore while specifying few details regarding how this varied among (or within) sites. Relatively low reporting levels of plot size somewhat hinders comparisons among methods. However, of the studies which reported this, plot size was generally largest when utilising horizontal transects (mean = 414 m^2, median = 450 m^2, range = 975 m^2), followed by vertical transects (mean = 100 m^2, median = 100 m^2, range = 0 m^2) and quadrats (mean = 23 m^2, median = 4 m^2, range = 154 m^2) ($\chi^2_2 = 10.3$, $p = .006$).

4. Discussion

4.1. Geographic and compartmental biases in research

Research quantifying marine litter the past five years has been highly skewed geographically. Most research has been centred in the North Atlantic, and in the Mediterranean in particular. The Pacific, despite being the world's largest ocean, is strongly underrepresented in empirical data. As are regions generating the most land-based mismanaged plastic waste (MPW) (Jambeck et al., 2015; Lebreton and Andrady, 2019). Southern and Eastern Asia, followed by South-East Asia, are estimated to generate the most MPW (Lebreton and Andrady, 2019), yet these regions comprised only 16% of studies reviewed. A recent review of marine litter research in the Philippines confirms limited research in the region (Galarpe et al., 2021). In contrast, most of, for example, Europe and Oceania are more intensely studied, while estimated to contribute considerably less to MPW (Lebreton and Andrady, 2019). This bias towards high-income countries (HIC) is also evident in research on anthropogenic litter in rivers and other aquatic systems (Blettler et al., 2018; Falk-Andersson et al., 2020b).

Publication rates skewed towards research from HIC is well known in other fields of research, and is an established problem within the global production of scientific knowledge (Culumber et al., 2019; Di Marco et al., 2017; Singh, 2006; Skopec et al., 2020; Yousefi-Nooraie et al., 2006). This skewness is likely the result both of less research financing in low-income countries (LIC), but also publication bias where research stemming from HIC is more likely to be accepted for publication than research stemming from LIC; the latter may also be viewed less favourably once published (Harris et al., 2015; Singh, 2006; Skopec et al., 2020; Yousefi-Nooraie et al., 2006). Geographic biases are readily evident in ecological and conservation research where temperate and less biodiverse geographic

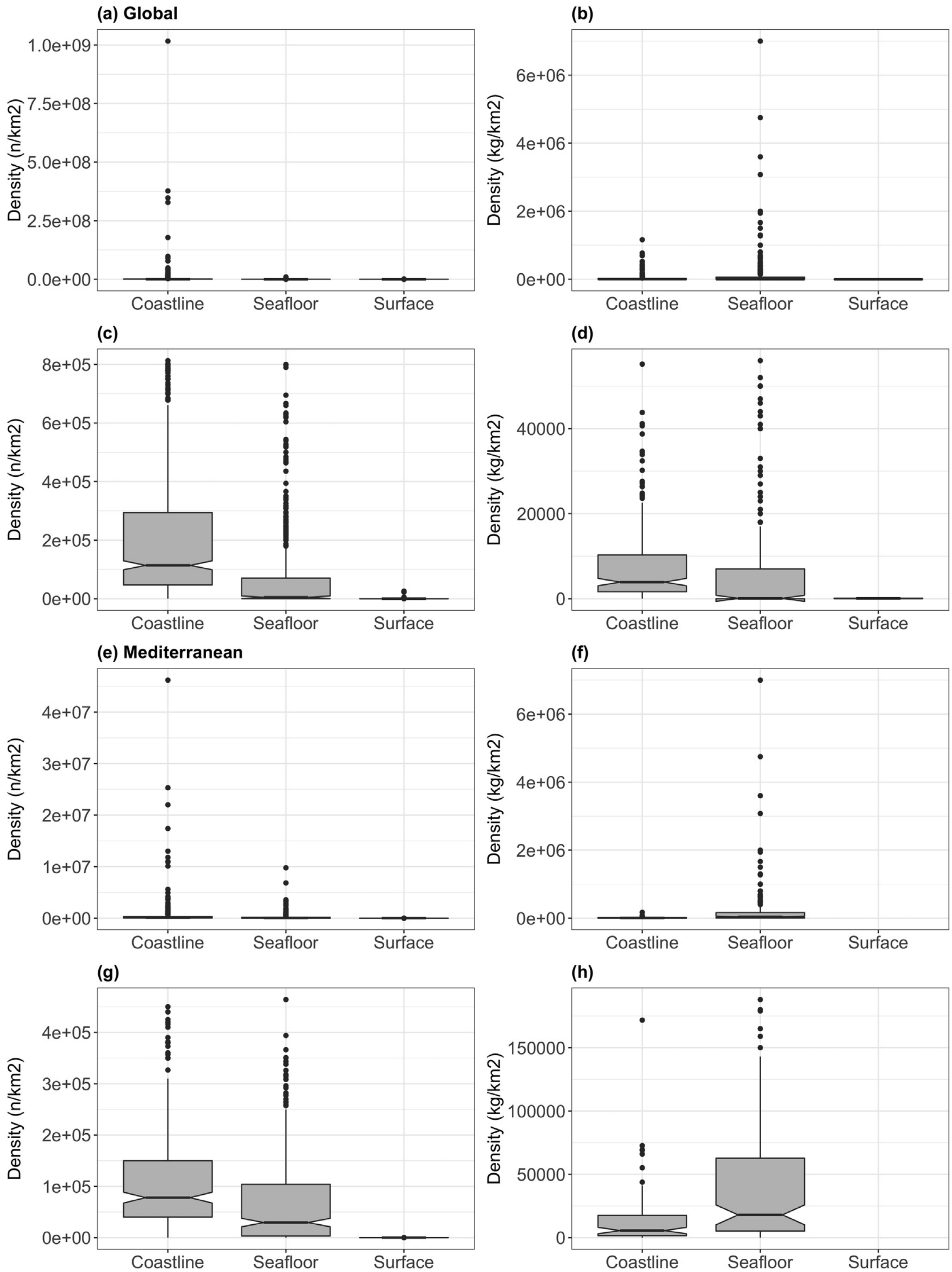

Fig. 7. Boxplots comparing litter densities among compartments (coastline, seafloor and surface). The top row shows raw boxplots of all data compiled for (a) item counts and (b) weight. The second row shows the same data with outliers excluded for (c) item counts and (d) weight. The third row shows data from the Mediterranean only where most data were available for (e) item counts and (f) weight. The fourth row shows the same Mediterranean data with outliers excluded. Notches on the boxplots display confidence intervals around the median. To identify outliers, data were pooled across compartments and values greater than Q3 + 1.5*IQR classified as outliers.

regions have been more studied, and Africa, South America and South-East Asia are heavily underrepresented (Culumber et al., 2019; Di Marco et al., 2017; Donaldson et al., 2017; Hickisch et al., 2019). It is thus unsurprising to see a similar bias in publications quantifying marine litter, but it is nevertheless problematic as it results in a considerable discord between modeling studies and predictions regarding the most significant (geographic) sources of marine litter. An increase in the amount of empirical data would help validate modeling studies and document baselines and spatiotemporal patterns within LIC. Addressing this issue should include an investigation of potential editorial/reviewer bias, but an increase in the quantity and quality of research coming out of LIC is also critical and could be facilitated by increased international collaborations and capacity development (Singh, 2006).

Studies are also skewed towards stranded litter and, for seafloor and pelagic litter, towards nearshore areas. Nearly half the retained publications described stranded litter. Studies on pelagic litter were fewest, and of these only two quantified litter suspended in the water column. This is somewhat in contrast to the findings of Canals et al. (2020) who reported the seafloor as least studied. This difference may be due to ours being a more constricted review focusing specifically on density only and excluding microplastics. Nevertheless, it remains undisputable that the coastline is the best studied. Furthermore, despite our large oceans being several thousands of km across, most data on pelagic and seafloor litter were obtained from within 100 km of the coast, which is likely due in part to logistical challenges and cost. Another reason to increase research on the seafloor and at the surface and in the water column is to improve our understanding of direct emissions from sea-based sources, which are not as well modelled as land-based mismanaged plastic waste, although some regional efforts have been made (*e.g.*, Deshpande et al., 2020). Generally validating model predictions and further confirming the presumed relationship between source points and litter densities in data poor regions and compartments could help enhance our understanding of both the global ubiquity and local variations in macrolitter pollution.

4.2. Spatial patterns and gradients in macrolitter distribution

A formal analysis of the total amounts of litter present in each compartment is not possible given the large geographic disparities in available data, yet comparisons of reported densities clearly suggest that the density of pelagic litter is considerably lower than that of stranded and seafloor litter. Except for certain seafloor hotspots, densities were generally reported to be the greatest along the coastline. Knowledge of geographic and compartmental patterns in relative litter densities and abundance is crucial to effective mitigation, for example when considering clean-up schemes. Removing litter from the environment is not without negative consequences in terms of bycatch and habitat destruction, as well as economic costs (Cruz et al., 2020; Falk-Andersson et al., 2020b; Zielinski et al., 2019). This review clearly suggests that mitigation efforts for cleaning pelagic litter will entail the lowest catch-per-unit-effort (CPUE). Conversely, CPUE is likely the greatest for stranded litter, which is consistent with a recent suggestion that the backshore is a major sink of marine litter (Olivelli et al., 2020). CPUE is a vital metric to consider optimising clean-up efforts (Falk-Andersson et al., 2020b). In addition to high yields, beach cleanups may also remove litter from circulation in the marine environment and not only from the beach in question given the constant turnover of stranded litter (Bowman et al., 1998; Brennan et al., 2018) and the notion that as much as two-thirds of marine litter will at least temporarily strand during its "lifetime" (Lebreton et al., 2019). Clean-ups of the seafloor may also produce considerable yields, but given limited data from various seafloor habitats, likely high costs, and the generally larger potential negative environmental impacts of cleaning the seafloor (Canals et al., 2020), this is most relevant for targeting identified hotspots.

A good understanding of spatial heterogeneity within compartments is also vital for optimising mitigative measures. The sheer vastness of our oceans and coastlines presents considerable logistical challenges. Consequently, the ability to target the most effective clean-up strategies is imperative. For example, a study of the South Korean coastline suggests that 60% of litter present can be cleaned from only 10% of its coastline (Lee et al., 2019). The finding that macrolitter densities are highest in densely populated areas with high rates of MPW, as well as close to the shore, is in line with the general assumption that litter densities decrease with increasing distance from source points. Spatial gradients where litter density correlates inversely with distance from river mouths, population centers, harbours, shipping lanes and fishing grounds have been reported by several studies (Angiolillo et al., 2015; Buhl-Mortensen and Buhl-Mortensen, 2017; Compa et al., 2020; Critchell et al., 2015; Díaz-Torres et al., 2017; Enrichetti et al., 2020; Fazey and Ryan, 2016; Mordecai et al., 2011; Pedrotti et al., 2016; Rech et al., 2014; Seo and Park, 2020; Watters et al., 2010). In ecological systems the scale of spatial heterogeneity is related to scales in physical processes influencing them, and any given organism may exhibit multiscalar distribution patterns when influenced by multiple factors (Horne and Schneider, 1995; Sale, 1998). The latter is also evident for marine litter with global patterns of hotspot formation, such as of pelagic microlitter in the sub-tropical gyres, but also small-scale variability among transects within a survey area (Eriksen et al., 2014; Goldstein et al., 2013; Haarr et al., 2019; van Sebille et al., 2020).

In addition to proximity to source points, spatial gradients and heterogeneity in litter distribution is driven by the physical characteristics of different types of litter, geomorphology of the shoreline and bathymetry of the seafloor, and redistribution and dispersal by ocean currents and other physical factors. Firstly, the concentration of objects denser than seawater are expected to decrease away from the shore or the point source more rapidly that negatively buoyant objects as the former will sink out and only be available for transportation through bottom processes (Fazey and Ryan, 2016; Morét-Ferguson et al., 2010). Less buoyant items are therefore more common in rivers and near the shore, compared to in the high seas (Crosti et al., 2018; Morét-Ferguson et al., 2010; Ryan, 2015). The windage of objects may influence the distribution of pelagic and stranded litter (Duhec et al., 2015). Secondly, geomorphology and bathymetry affect the retention and accumulation of litter along the coastline and on the seafloor. Litter accumulates in various seafloor depressions, such as submarine canyons, particularly low-density litter (Buhl-Mortensen and Buhl-Mortensen, 2017; Canals et al., 2020; Galgani et al., 2000; Tubau et al., 2015). Highly heterogeneous substrates, such as rocky outcrops, seamounts, and coral, may also trap and thus accumulate litter (*e.g.,* Angiolillo et al., 2015; Enrichetti et al., 2020; Galgani et al., 2018; Watters et al., 2010). For stranded litter, physical features of the coastline, such as beach slope and coastline concavity are apparent drivers in spatial heterogeneity (Brennan et al., 2018; Haarr et al., 2019). Within a beach, higher densities are often found towards the backshore as wind, waves and tides transport litter inshore until it gets trapped by the fore dune or vegetation (Cunningham and Wilson, 2003; Olivelli et al., 2020).

Thirdly, spatial heterogeneity of particularly pelagic litter, but also of stranded litter, is driven by patterns of redistribution and dispersal. Stratification processes, wind and tidal currents affect the residence time and transport of pelagic litter in estuaries (Collignon et al., 2012; Kukulka et al., 2012; Sadri and Thompson, 2014). At sea, large-scale open ocean processes are responsible for the accumulation of pelagic plastics in the ocean gyres (Cózar et al., 2017; Eriksen et al., 2014; Law et al., 2010; van Sebille et al., 2020). However, these accumulations are highly heterogeneous both in space and time, and their borders diffuse (Howell et al., 2012; Lebreton et al., 2018) and plastics are not trapped indefinitely (Egger et al., 2020; van Sebille et al., 2012). The dispersal and distribution of pelagic litter in the open ocean is also influenced by processes such as Stokes drift, internal tides, windage, Langmuir circulation, vertical transport and mixing, and ice formation and melting at various scales (van Sebille et al., 2020). High stochastic variability and inadequate knowledge of other controlling factors may hinder the successful identification of potential spatial gradients linked to circulation dynamics (Barnes and Milner, 2005; Di-Méglio and Campana, 2017). Seafloor litter may also be systematically dispersed by currents; lower litter densities on shelf plains have been explained by bottom currents and sloping terrain transporting litter to deeper waters (Buhl-Mortensen and Buhl-Mortensen, 2017; Pierdomenico et al., 2019; Schlining et al., 2013). Variation in exposure to predominant wind and wave directions can influence the accumulation of stranded litter (*e.g.,* Cunningham and Wilson, 2003).

In addition to systematic spatial heterogeneity, there is considerable stochastic variability, both in space and time. Gradients observed in some locations and instances may break down as competing processes dominate instead. For example, a negative correlation with seafloor litter density and distance from shore is not always evident due to re-distribution by currents (Di-Méglio and Campana, 2017; Schlining et al., 2013) or because commercial fishing may occur offshore, resulting in hot spots of fishing debris there (Angiolillo et al., 2015). Seasonal shifts in transportation processes could also redistribute litter, and seasonal variations in human activities can influence the amount of litter entering rivers and coastal areas throughout the year (Compa et al., 2020; Schlining et al., 2013). The high variability and multitude of influencing factors affecting distribution makes it difficult to identify spatial gradients that consistently apply. Thus, while these general, global trends give some management guidance, the lack of data on plastic density in general, but particularly in areas of high rates of MPW and in the pelagic and the ocean floor compartments, is a limitation for supporting mitigation actions. Furthermore, the large-scale trends are complicated by the many factors affecting the distribution of plastics in time and space. Thus, it is important to improve our understanding of the drivers of spatial heterogeneity in litter distribution through better geographic and compartment coverage of litter studies. This would in turn allow for better design of monitoring strategies to better capture spatial and temporal trends.

4.3. Sampling spatially heterogeneous distributions

A meta-analysis of spatiotemporal patterns in litter density is limited not only by the large geographic gaps in available data, but also by varying methodologies which may impact detection probability and the resulting density estimates. The latter was identified as a hindrance to an assessment of global trends in stranded litter in 2015 (Browne et al., 2015), and little has changed in the following years. Optimising sampling methods for patchily distributed organisms has long been an important topic in ecological studies (*e.g.,* Engeman et al., 1994; Fortin et al., 1989; Krebs, 2014a,b; Underwood and Chapman, 1998) yet has received little attention in marine litter research. The optimal plot size, shape, and replicates are determined by several considerations, primarily (1) statistical precision and accuracy, (2) scale relative to the ecological scale of the phenomenon in question, and (3) logistical constraints. The latter is the least scientifically robust criterion, yet commonly dictates design and replication (Canals et al., 2020; Fortin et al., 1989; Krebs, 2014a). The first and second points are rarely discussed in marine litter publications, and surveys appear to be largely designed based on logistical constraints. This is particularly true for seafloor surveys which are often a biproduct of studies with entirely different primary research goals (*e.g.,* fish or habitat surveys), and where the gradient in methods used by distance from shore is readily explained by their logistical strengths and weaknesses (*e.g.,* scuba dive surveys are only possible in shallow water) (Canals et al., 2020).

As all sampling has an inherent spatial structure, it is important to understand the underlying spatial distribution patterns of litter to correctly estimate abundance from density measurements (Krebs, 2014a). Spatial heterogeneity has implications for statistical accuracy, primarily because of a lack of independence among sampling units (Fortin et al., 1989; Legendre, 1993; Wagner and Fortin, 2005). Positive spatial autocorrelation (*i.e.,* aggregation and patchiness) can falsely inflate statistical significance (Dale and Fortin, 2002). Spatial heterogeneity should be reflected in model error terms as random variables (*e.g.,* area, habitat) and there are statistical methods by which to estimate the effective sample size given the presence of autocorrelation, all to ensure that the degrees of freedom are adjusted correctly (Dutilleul, 1993; Griffith, 2005). There are several methods by which to quantify spatial autocorrelation, such as correlograms based on Moran's I or (semi-)variograms, which can be used not only to identify its presence, but also to elucidate the underlying patterns and scale (Fortin et al., 1989; Kraan et al., 2009; Legendre, 1993). However, such methods were not evident among the studies analysed. In an older study, Goldstein et al. (2013) did attempt to elucidate scales of heterogeneity in the density of pelagic litter in the North Pacific, and while the authors did identify variability over both small (10s of km) and large (1000s of km) scales, they were unsuccessful in generating a meaningful variogram, which they attributed to low sample size relative to the variance. There is considerable untapped potential for mapping autocorrelation and spatial heterogeneity within marine litter research. Doing so could help inform best practices with respects to sampling methodologies.

The appropriate plot size depends on the scale of the phenomenon under study (Ambrose, 2001). Particularly remote sensing surveys in which individual images (small quadrats) are sampled, provide potentially good opportunities to assess autocorrelation. Other survey types may also be used, but patterns may be difficult to discern if plots are very long. If the sampling units encompass (*i.e.,* are larger than) the patterns under study, a nugget effect will arise where the mean difference among sampling unit pairs is greater than zero even at the shortest lag distances (Griffith, 2005). Plots of variable sizes, which were common, are unlikely to generate data suitable for assessing spatial autocorrelation and patterns of patchiness given the added error introduced. Variance, and the effects of spatial autocorrelation, will be the greatest when plot size is equivalent to the scale of patchiness, and decrease with increasing plot size until the variance approaches the mean and the distribution appears random; the same occurs when plot size is much smaller than the scale of patchiness (Ambrose, 2001).

The shape of a plot impacts the degree to which it is prone to edge effects, which may lead to counting errors (Krebs, 2014a). As the ratio of length to width of a transect increases, so does the variability of results depend on the inclusion or exclusion of items along the edge (Krebs, 2014a). Edge effects are typically described for transects which are walked manually during which an observer must choose whether to count an organism or object on the edge. While highly relevant for beach, diver, and remote sensing surveys, this may be less of an issue for trawl surveys as no observer needs decide. However, there is the possibility of edge items being knocked either into or out of the path of the trawl, thus still creating an increased edge effect for narrower transects. Particularly low-density litter is likely to be pushed aside by or ahead of a trawl (Canals et al., 2020). Edge effects often cause a positive bias (Krebs, 2014a). There is no direct evidence that this is the case for seafloor surveys as diver-based surveys, which would have smaller edge effects, generally recorded higher litter densities than remote sensing or trawl surveys. However, this finding is confounded with distance from shore, and it is generally hard to quantify bias as it may be habitat- and litter-type specific (Krebs, 2014a). For a single beach survey in Brazil, plot size had no significant impact on litter abundance, but litter composition was found to be significantly more diverse when larger plots were used (de Araújo et al., 2006). The optimal plot size is connected to the variogram range and lag distances over which spatial autocorrelation occurs (Zhang et al., 1994). However, many studies employ unstandardized survey methods where plot size varies among samples. The variable transect lengths frequently documented in remote sensing and trawl surveys are reminiscent of Variable Area Transect (VAT) sampling, but do not share the benefits as transect length is not determined by the time taken to encounter a certain number of litter items (Dobrowski and Murphy, 2006; Engeman et al., 1994); rather, both transect length and the number of items surveyed varies. In ecological studies, mean density when transects are of varying lengths is generally calculated by pooling all transects; calculating the variance when transect lengths are unequal is more complex and requires adapted calculation methods (Krebs, 2014a). Despite variable lengths being common in marine litter surveys, however, these methods are generally not employed.

The size and shape of plots relative to the scale of the spatial patterns under study may impact detection probability and the likelihood of a plot intersecting a patch (Chen et al., 2009). Not only patch radius, but also the distance among items in a patch (*i.e.,* density) is influential in patch detection (Nicholson and Barry, 1996). Generally, detection probability increases with survey effort and plot size (Chen et al., 2009), and of plots with the same area, rectangular ones have a greater chance of crossing a patch than square ones (Krebs, 2014a; Miller and Ambrose, 2000). Smaller patches require greater sampling effort to maintain the same detection probability as larger patches (Nicholson and Barry, 1996). In stranded litter surveys, this was reflected in a mostly greater sub-sampling effort for quadrat compared to transect surveys, yet the increased sample size was quadrats was not generally sufficient to result in a similar total area surveyed as for larger, albeit fewer transects. When plots are rectangular (*i.e.,* transects), their orientation relative to any spatial gradients present will influence accuracy and precision. When sampling intertidal organisms, vertical transects give more accurate estimates of coverage and abundance than horizontal transects (Ambrose, 2001; Miller and Ambrose, 2000). Plots which greatest dimension follows the direction of greatest spatial variance will result in the greatest accuracy (Zhang et al., 1994). Both vertical and horizontal transects were used in beach litter surveys, the former slightly more commonly than the latter, yet the pros and cons of each has not been quantified. For pelagic litter, the higher densities reported for trawl surveys could imply lower detection probability for visual and remote sensing surveys, but also trawl surveys capturing more suspended just below the surface. The apparent lower detection probability of remote sensing over trawl surveys on the seafloor, as seen by a higher proportion of empty transects when utilising the former, is potentially related to very narrow transects. Even if remote sensing surveys are of a similar (or longer) length than trawl surveys, the ability to detect a patch may be reduced given the very narrow interception if the patch density is relatively low. However, as the two types of surveys are of employed in different habitats/substrates (Canals et al., 2020), genuine differences in litter density among substrates cannot be entirely ruled out as the cause.

The variance of data collected will be influenced by the total area surveyed and the number of plots. Generally, a larger total area swept will result in lower variance estimates, but the standard error will be reduced the most if divided over numerous small transects rather than a few larger ones (Krebs, 2014a). A general rule of thumb is that minimum 30 samples are needed to investigate spatial autocorrelation (Fortin et al., 1989). For seafloor litter, remote sensing surveys with high replication did not necessarily survey a larger total area, but rather analysed data by individual images rather than by entire deployment tracks. This may generate density estimates with greater precision, assuming spatial autocorrelation is adequately addressed (Krebs, 2014a). Trawl surveys typically covered the largest total sweep area (generally greater level of replication and larger individual transect sizes), and are thus expected to achieve greater precision than diver-based surveys and most remote sensing surveys (Krebs, 2014a). However, trawl surveys come at greater environmental cost than other types of surveys due to their disturbance (and possible destruction) of substrate and biota, and is not deployable on all substrates (Canals et al., 2020). Further increasing the precision of trawl surveys by conducting shorter hauls may also not be feasible from practical and economic perspectives due to the time and effort involved in deploying a trawl. This is illustrated by the tendency for hauls to be longer in deeper than in shallower waters due to the longer time it takes to release and retrieve a trawl there (*e.g.,* Alomar et al., 2020; Gerigny et al., 2019). While more practical, this results in fewer transects for the same total area surveyed in deeper water and thus decreases precision compared to shallower waters. There are also examples of studies on stranded litter where transect length varied by density with shorter transects in highly polluted areas to save time (*e.g.,* Schmuck et al., 2017).

Randomised surveys perform better than systematic surveys in elucidating spatial structure, presumably because of a greater variance in lag distances among samples (Fortin et al., 1989). For systematic surveys, the spacing of samples relative to the scale of spatial patterns matters more than the level of replication (Fortin et al., 1989). Systematic cluster designs, which are logistically simpler than fully randomised surveys but still ensure a range in lag distances among samples, perform better (Fortin et al., 1989). Despite the potential large influences on representativity and accuracy of results, relatively few studies discuss in depth (or at all) the mechanisms by which study sites and plot locations are chosen. In an older review, only 45% of studies on stranded litter described the reasons for selecting study sites and sites were likely biased in favour of finding debris (Browne et al., 2015). Scuba diving surveys may often suffer from the same positive bias as they can be associated with cleanup efforts, which naturally target hotspots, or done by citizen scientists looking to help by documenting marine litter occurrences (*e.g.,* Consoli et al., 2020). The extent of the study area and the replication within is also of importance. It is common for studies to either sample a large area sparsely on to sample a small area intensely (Kraan et al., 2009). For example, Buhl-Mortensen and Buhl-Mortensen (2017), extrapolated a total sample area of 3.7 km^2 to the entire Norwegian and Barents Seas (approx. 650,000 km^2). Contrastingly, studies quantifying stranded litter are often highly local (Browne et al., 2015). In general terms, the necessary sample size is an inverse function of the homogeneity in the distribution of the phenomenon under study (Fortin et al., 1989).

In addition to the above considerations regarding spatial aspects of survey designs, temporal variation in both marine litter densities and the surveys themselves is a hindrance to large-scale meta-analyses. Surveys are highly variable in the degree to which they consider temporal variation, and space and time are frequently confounded: half the studies reviewed on pelagic and seafloor litter in which the study spanned five years or more did not report analyses of temporal trends or interannual variation. Given the number of studies which did report temporal variation in densities, and the conflicting trends in this variation, temporal variability (both with and without trend) must be given due consideration in survey designs. For studies measuring accumulation of stranded litter, a strong relationship between sampling intervals and the resulting accumulation estimates are well established (*e.g.,* Eriksson et al., 2013; Smith and Markic, 2013).

4.4. Conclusions

There are considerable knowledge gaps regarding spatiotemporal trends in litter density in the different marine compartments across the globe. Data are scarce from many of the regions estimated to mismanage the largest amounts of plastic waste. Such knowledge gaps created by geographic biases should be addressed to identify further research needs and inform policy. Furthermore, when data are available these are typically from coastal areas with few data from open seas and the deep sea. Data on pelagic litter are generally constrained to the sea surface with little or no information about litter deeper in the water column. Even smaller data-rich areas can lack sufficient information to parametrise mass balance models (Harris et al., 2021). Filling these knowledge gaps is not necessary to adopt a precautionary approach to guide policy and mitigative measure but decreasing the gap can aid in shaping and optimising targeted measures, as well as in the monitoring of their effects (Harris et al., 2021).

Our understanding of the relative distribution of litter among ocean compartments is also lacking. There is evidence that considerable amounts of litter sinks to the seafloor, yet as most data are from relatively nearshore areas and there is evidence of negative spatial gradients with distance from shore one cannot readily extrapolate to the entirety of the seafloor. Coastlines constitute a vastly smaller area globally than the seafloor or pelagic realms, yet litter densities are generally high here. Given high densities and turnover of stranded litter, regular beach cleanups appear to provide an efficient way of removing litter from redistribution in the greater marine environment. Easy access and opportunity for using non-damaging removal methods, also votes in favour of beach cleanups.

While the focus of this study was standing stock, future work should give equal consideration to the rate of litter accumulation. Litter accumulation in any given location, irrespective of marine compartment, is a function of the relative relationship between influx and outflux (Bowman et al., 1998). Standing stock will reflect the sum of the two at any given time, but this is not constant as accumulation is “reset” following a clean-up action, for example, or the equilibrium altered by extreme events, such as storms, causing particularly high either influx of outflux (Bowman et al., 1998).

Lastly, there is a lack of standardisation among methods, and uncertainties related to spatial and temporal autocorrelation and the accuracy and precision of baseline data in the face of considerable variability. Marine litter monitoring solutions are mostly still immature from a technology readiness perspective, and clean-up solutions and mitigation strategies even more so (Bellou et al., 2021). Consequently, there is still a great need for methods development and standardisation within the field and some long-established considerations from ecological research may be highly relevant. The review and meta-analysis discussed plot-based survey methods only as these dominated among studies, but some plotless methods have been employed in pelagic litter surveys, notably distance methods (*e.g.,* Sá et al., 2016) and line transects (*i.e.,* transect width not estimated) (*e.g.,* Bergmann et al., 2016). Plotless methods and Variable Area Transects (a combination of plotless and plot-based methods) are frequently used to estimated abundance in ecological studies (Dobrowski and Murphy, 2006; Engeman et al., 2005, 1994; Kalikhman, 2001; Krebs, 2014b), and the appropriateness of their use should also be considered and discussed in marine litter research alongside considerations of meaningful standardisations of plot-based methods. Regardless of the sampling design and methodology used, spatial and temporal autocorrelation and heterogeneity must be given due consideration in studies to improve both the ability to compare studies and to detect patterns and changes during monitoring. These considerations are relevant both when discussing global or regional standardisations of survey design and statistical analyses, as well as for individual and independent studies.

The lack of standardisation in methodology in survey designs, data collection and reporting hinder the improvement of models addressing the connection between litter influx, redistribution and accumulation, as well as the determination of reliable baselines. The latter are important for comparison following management actions to evaluate their efficacy. Independently of how the geographical knowledge gaps are addressed, both ongoing and emerging efforts could benefit from considering the identified gaps and leaning towards standardised or comparable methodologies which could allow building a robust baseline so all efforts count towards an understanding of geographic and compartmental distribution of macrolitter.

CRediT authorship contribution statement

		Haarr, M.L.	Fabres, J.	Falk-Andersson, J.
Conceptualization	Ideas; formulation or evolution of overarching research goals and aims	X		
Methodology	Development or design of methodology; creation of models	X		X
Software	Programming, software development; designing computer programs; implementation of the computer code and supporting algorithms; testing of existing code components			
Validation	Verification, whether as a part of the activity or separate, of the overall replication/reproducibility of results/experiments and other research outputs			
Formal analysis	Application of statistical, mathematical, computational, or other formal techniques to analyze or synthesize study data	X		
Investigation	Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection	X	X	
Resources	Provision of study materials, reagents, materials, patients, laboratory samples, animals, instrumentation, computing resources, or other analysis tools			
Data Curation	Management activities to annotate (produce metadata), scrub data and maintain research data (including software code, where it is necessary for interpreting the data itself) for initial use and later reuse	X		
Writing - Original Draft	Preparation, creation and/or presentation of the published work, specifically writing the initial draft (including substantive translation)	X	X	X
Writing - Review & Editing	Preparation, creation and/or presentation of the published work by those from the original research group, specifically critical review, commentary or revision – including pre-or postpublication stages	X	X	X
Visualization	Preparation, creation and/or presentation of the published work, specifically visualization/data presentation	X		
Supervision	Oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team	X		
Project administration	Management and coordination responsibility for the research activity planning and execution	X		
Funding acquisition	Acquisition of the financial support for the project leading to this publication			

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.

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Appendix A. Supplementary data

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