



Critical Gaps in Shoreline Plastics Pollution Research

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OPEN ACCESS

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Specialty section:

This article was submitted to
Marine Pollution,
a section of the journal
Frontiers in Marine Science

Received: 31 March 2021

Accepted: 10 June 2021

Published: 07 July 2021

Citation:

Melvin J, Bury M, Ammendolia J,
Mather C and Liboiron M (2021)
Critical Gaps in Shoreline Plastics
Pollution Research.
Front. Mar. Sci. 8:689108.
doi: 10.3389/fmars.2021.689108

Shoreline surveys are an accessible and common method for monitoring plastic pollution in aquatic environments. Their results are critical to well-informed pollution mitigation efforts. Here, we show that three environmental variables: (1) coarse sediment, (2) accumulations of organic material, and (3) snow and ice are dramatically underrepresented by existing shoreline plastic pollution research efforts. We reviewed 361 published shoreline surveys, encompassing 3,284 sample sites, and found that only 4% of sites included coarse sediment, only one study described sampling organic material for plastic, and only 2.5% of sites are sampled in the presence of ice or snow. The relative absence of these environmental variables may stem from the tailoring of shoreline survey guidelines to a narrow range of shoreline environments. These three features influence plastic deposition and retention on shorelines, and their underrepresentation signals a need to recalibrate research efforts towards better methodological reporting, and regional representation and relevance.

Keywords: plastic pollution, marine debris, marine pollution, shoreline, environmental monitoring

INTRODUCTION

As an inexpensive and accessible method of monitoring both micro- and macro-plastic pollution in marine and freshwater environments, shoreline surveys have become a common research method internationally. The widespread use of this research technique, often guided by standard protocols, is illustrated by the breadth of environments that have been examined for plastic debris characterisation and distribution. These environments include: popular tourist beaches (Retama et al., 2016; da Silva et al., 2018), remote islands (Andrades et al., 2018; Hipfner et al., 2018; Rech et al., 2018), mangrove forests (Cordeiro and Costa, 2010; Martin et al., 2019), mudflats (Lo et al., 2018; Phuong et al., 2018), industrial harbours (Abu-Hilal and Al-Najjar, 2004; Muller-Karanassos et al., 2019), and Arctic and Antarctic shorelines (Convey et al., 2002; Eriksson et al., 2013; Bergmann et al., 2017).

Shoreline surveys have some of the longest standing standardised methods in the field of plastic pollution research. As early as 1984, the United Nations Educational, Scientific and Cultural Organisation (UNESCO) released a manual detailing a standard methodology for monitoring tar balls on beaches [IOC (Intergovernmental Oceanographic Commission), 1984]. Following the success of this manual, the United States' National Oceanic and Atmospheric Administration (NOAA) released its first Marine Debris Survey Manual in 1992 (Ribic et al., 1992). In the years since, several intergovernmental and environmental organisations have provided standardised guidelines in an effort to improve comparability of shoreline debris data and allow for the

compilation of global assessments of plastic distribution and abundance (Cheshire et al., 2009; OSPAR Commission, 2010; Opfer et al., 2012; European Commission, 2013; Lippiatt et al., 2013). Several reviews have made significant progress in collating individual studies from around the world as a way of gaining global insights on the problem of plastic pollution on marine and freshwater shorelines with the ultimate goal of identifying hotspots of pollution and enabling effective mitigation strategies (Hidalgo-Ruz et al., 2012; Ivar do sul and Costa, 2014; Van Cauwenberghe et al., 2015; Horton et al., 2017; Serra-Gonçalves et al., 2019). The challenge of combining the methodologies and results of shoreline surveys from around the world has led most of these authors to call for more rigorous standardisation of techniques for collecting, extracting, and reporting on plastics in environmental samples.

It is amidst these calls for even greater standardisation that this paper aims to make a timely intervention. While standardisation helps to ensure consistently commensurable data across disparate contexts, they are never able to manage all possibilities (Bowker and Star, 1999), or landscapes. New research indicates that landscape features common to shoreline environments may affect how and where plastics accumulate upon deposition. Among these landscape features are: (1) sediment grain size, (2) accumulation of organic material at the tidelines, and (3) the presence of ice and snow. The inclusion of diverse shoreline landscapes in plastic pollution research, therefore, is crucial to our understanding of this ubiquitous pollutant and the ability to manage it. This review asks two questions; first, to what degree are these landscape features represented in shoreline plastic pollution surveys; and second, what are the likely explanations for the significant underrepresentation of sites with coarse sediments, organic material, and winter precipitation?

Recent scholarship reveals the important role diverse landscape features play in shaping the incidence and distribution of shoreline plastics. Researchers have demonstrated that coarse sediment (e.g., pebbles, gravel, cobble, boulders) are more efficient at burying plastic particles than fine sediment (e.g., sand) in the laboratory (Efimova et al., 2018; Chubarenko et al., 2020). Preliminary results from field surveys on rocky shorelines demonstrate that plastic debris can become trapped within coarse sediments in these environments (McWilliams et al., 2018; Weideman et al., 2020). In the laboratory, coarse sediment also generates plastic particles (particularly microplastics) through mechanical fragmentation between 5 and 145 times more effectively than sand (Chubarenko et al., 2020). Large organic material may also function to trap plastics on shorelines, as these often appear together in accumulation zones on shorelines, typically at the tidelines (Hoellein et al., 2014; Corcoran et al., 2017; Lazcano et al., 2020). Microplastics can adhere strongly to the surface of seaweed (Gutow et al., 2016; Sundbæk et al., 2018), such that the removal of plastic and other anthropogenic contaminants has become a standard component of pre-processing procedures in commercial seaweed aquaculture operations (Raikova et al., 2019). While the impact of snow and ice on shoreline plastic accumulation has not yet been fully investigated, both snow and sea ice have been identified as important sinks for microplastics in other contexts (Obbard et al.,

2014; Peeken et al., 2018; Bergmann et al., 2019; Kelly et al., 2020). High concentrations of microplastics found in snow and ice are released seasonally following snow and ice melt, a process that has been observed in surface waters (Ory et al., 2020; Uurasjärvi et al., 2020; Von Friesen et al., 2020). There is a significant body of emerging research confirming the importance of landscape features in shaping shoreline plastic deposition.

The purpose of this paper is to assess the extent to which published shoreline surveys reflect three diverse shoreline landscape features which have a demonstrated impact on the distribution and accumulation of plastic pollutants: (1) coarse sediment, (2) accumulations of organic material, and (3) snow and ice. The results of our analysis point to the need for recalibration of research efforts in the field of marine plastic pollution in a way that further enables our shared goal of highlighting “where the most urgent actions are required to better understand the impacts of marine debris, enabling more effective mitigation policies to be developed.” (Serra-Gonçalves et al., 2019; p. 12159). To this end, we conducted a systematic literature review to examine how the three landscape features identified above are accounted for within the methodologies of published shoreline studies from 1977 to 2019. This analysis of over 350 shoreline studies, spanning over 40 years of research and encompassing over 3,000 individual sample sites around the world, is representative of the state of knowledge in this area.

METHODS

Search Criteria

We conducted a systematic literature review for all English-language shorelines studies published in peer reviewed venues between 1977 and September 2019. We defined a shoreline survey as any original research study that collected count or concentration data in the field for anthropogenic debris, including plastics (of any size), on a marine or freshwater shoreline. Any shoreline influenced by a tide (including estuaries) or characterised by salt water (including enclosed seas) was categorised as a marine sample site. Freshwater shorelines, such as lakeshores and riverbanks, were not tidally influenced, meaning they did not include estuarine river mouths. The search was performed in Web of Science, a publisher-neutral repository that is home to over 170 million records covering over 34,600 journals. The following three searches were run: (1) (“marine plastic” OR “marine debris” OR “plastic pollution” OR litter OR plastics) AND (shoreline OR beach OR snow OR ice), (2) Microplastic, (sediment OR “beach” OR “seaweed” OR “algae” OR “wrack” OR “snow” OR “ice”), and (3) (“Marine plastic” OR “marine debris” OR “plastic pollution” OR litter OR plastics), (seaweed OR wrack OR algae). The results of these searches were initially screened for broad-scale relevance based on title and abstract. Following the initial screening, full text articles were screened based on the following inclusion criteria: (1) original research, (2) shoreline survey area with exposure at low tide, (3) research results included plastic density estimates, (4) not a single-item survey. Throughout the literature review we also noted any shoreline survey articles that were referenced within this literature but not collected by our searches. All

articles included in this review were from the peer reviewed literature, with the exception of one Master's thesis. For full PRISMA flow diagram depicting the literature screening process, see **Supplementary Figure 1**.

For each publication, we extracted the coordinates for each available sample site and information relevant to the following categories: (1) type of shoreline survey, (2) sediment type, (3) organic materials, (4) sampling frequency and mentions of snow or ice presence during the survey period. Where individual sample sites within a study could not be extracted, the entire study was treated as a single sample site ($n = 18$ studies).

Sample Site

The constitution of an individual sample site followed delineations provided by the authors for each study. This means that the sample sites referred to in this review ranged in size from a quadrat area of 0.0625 m² to a whole beach. Where no coordinates were provided but a map and/or place names were presented, approximate coordinates were obtained using Google Maps (google.ca/maps/). Where exact GPS coordinates could not be identified, either because no sample site information was provided by the article ($n = 18$), or because the site could not be confidently located based on the descriptors provided ($n = 11$), sites were not included in any visualisations of geographic distribution.

Survey Type

For the purposes of this study, we categorised the reviewed surveys into one or both of two categories: (1) “surface surveys” that quantify plastics sitting on the beach surface, and (2) “buried surveys” that quantify plastics buried beneath the beach surface. Surveys were considered to address buried plastics if researchers described removing, raking, or sieving the sediment to any depth for plastic detection. Plastic size classes included in each survey type were not standardised and were in some cases not explicitly reported. Surface surveys typically investigated plastics to a minimum size of what could be seen by eye from standing height (generally 2–2.5 cm), but the minimum size detected by this survey type ranges from 1 mm to 5 cm. Microplastics (< 5 mm) or plastics not captured by surface surveys (< 2 cm) were the most common target of buried surveys, and the lower limit of plastic detected by these surveys range from 0.2 μm to 5 cm.

Sediment Type

Beach sediment type was classified according to the following categories: (1) sand, (2) coarse sediment, (3) unknown, and (4) other. Sediment type was categorised wherever possible according to the terminology used by the authors of each survey. Any sample sites described as being characterised by sediment coarser than sand (e.g., pebbles, cobbles, gravel, boulders, or bedrock) were classified as “coarse sediment.” Where sediment grain sizes were provided, sample sites were categorised as predominated either by sand (< 2 mm) or coarse sediment (> 2 mm) according to the Udden-Wentworth scale for grain size (Chesworth, 2008). Where sample sites were described as being

a mix of both sand and coarse sediment, they were counted in both of these categories. The “unknown” classification covered all cases where sediment type could not be inferred for individual sample sites in a study. This occurred where: (a) no mention of sediment type was made in the report, or (b) authors indicated that sample sites covered a range of sediment types, but did not describe sediment type per individual sample site, or give any indication of the number of non-sandy sites. In order to account for these cases of coarse sediment sampling, we analysed sediment data not just for sample sites, but for studies as a whole. The “other” category was created to account for non-sedimentary shorelines (i.e., mangroves). Coarse sediment (particularly gravel and pebble) is typically not problematic with existing surface survey protocols, but it does not suit the suggested sieving method promoted in the most commonly cited protocols for buried surveys. We therefore analysed sediment type not only for all sample sites, but also within buried surveys alone in order to determine whether the representation of coarse sediment beaches was influenced by survey type.

Organic Material

Organic material was defined as any biological material of natural origin. In the marine environment, this material most often took the form of stranded seaweed or kelp detritus, or driftwood. In the freshwater environment, organic material included algae, leaves, feathers or grass. Information regarding organic materials was most often provided within sampling and sample processing protocols, and was therefore not site-specific. As a result, information on organic material was collected per study rather than sample site. Documenting stranded organic materials present during surveys was done using the following organic procedures categories: (1) explicit targeting of a tideline, (2) organic material on shoreline, (3) organics removal, (4) organic material in sediment samples, and (5) samples of stranded organic materials. Details on how surveys were classified into these categories are provided in **Table 1**. The term “tideline” refers to any reference to a natural accumulation zone of organic material on a shoreline, encompassing “wrackline,” “strandline” and other interchangeable terms, as well as accumulation zones in environments that are not tidally influenced (e.g., lakes and rivers).

Survey Frequency

The following survey frequency categories were considered: (1) single survey, (2) daily, (3) weekly to bimonthly, (4) seasonal, (5) annual, and (6) other repeated. Sites that were revisited anywhere from 1 week later to 2 months later were classified as “weekly to bimonthly.” Surveys were considered seasonal if they covered more than one season. Each sample site classified as “seasonal” was given a ranking (0.5, 0.75, or 1) based on the seasonal regime of its region. For example, a survey that crossed two seasons would be assigned a value of 1 (100% of seasons covered) if it took place in a region that experiences only two seasons (such as wet and dry). Whereas, a similar survey crossing two seasons would be assigned a value of 0.5 (50% of seasons covered) if it occurred in a region that experiences four temperate seasons (such as spring, summer, fall and winter). The “other

TABLE 1 | Details of methodology, procedure, and objectives for each organic procedure category.

Organic procedures category	Qualifying methodology	Handling of organic material	Research objective
Tideline targeted	Surface surveys: A tideline is referred to being present within the survey transect Buried surveys: At least one sample quadrat is placed purposefully on a tideline	None. All marine/estuarine shorelines have a tideline, regardless of the presence or absence of stranded organic material	Inclusion of a known plastic accumulation zone in the sample area
Natural debris	Surface and buried surveys: Reporting the presence of organic material such as seaweed, wrack or woody debris in the site description or sample collection protocols	Organic material is confirmed to be present in survey area	Site or sample area characterisation
Organics removal	Surface surveys: Excluding areas of large quantities of stranded organic material from sample area Buried surveys: Removal of large pieces of organic material from sample quadrats prior to sediment sample collection	Removal. Organic material is reported as being excluded from the analysis	Exclude substrates which cannot be reliably investigated by the available protocols
Sediment processing	Buried surveys: small organic materials are mentioned in processing procedures for sediment samples collected from sample quadrats	Small particles of organic material are removed (often by acid digestion) from sediment samples during processing	Eliminate organic materials from sediment samples in order to isolate microplastic particles and reveal the density of microplastics buried in shoreline sediment
Organics processing	Buried surveys: investigation of plastics buried within organic deposits on the shoreline	Organic material is included as a substrate for buried plastics	Reveal the density of plastics buried in shoreline organic deposits

repeated” category was used to account for studies that visited a site more than once but did not fit into any of the other frequency categories (i.e., more than 1 year between visits). A survey could qualify for more than one of the above categories. For example, a monthly survey that continued for 2 years would be counted as “weekly to bimonthly,” “seasonal,” “annual,” and “other repeated.” Where a study explicitly described revisiting sample sites from a previously published work already included in this review, the survey frequency classification for those sample sites was determined based on the most recent publication.

RESULTS

Sample Sites

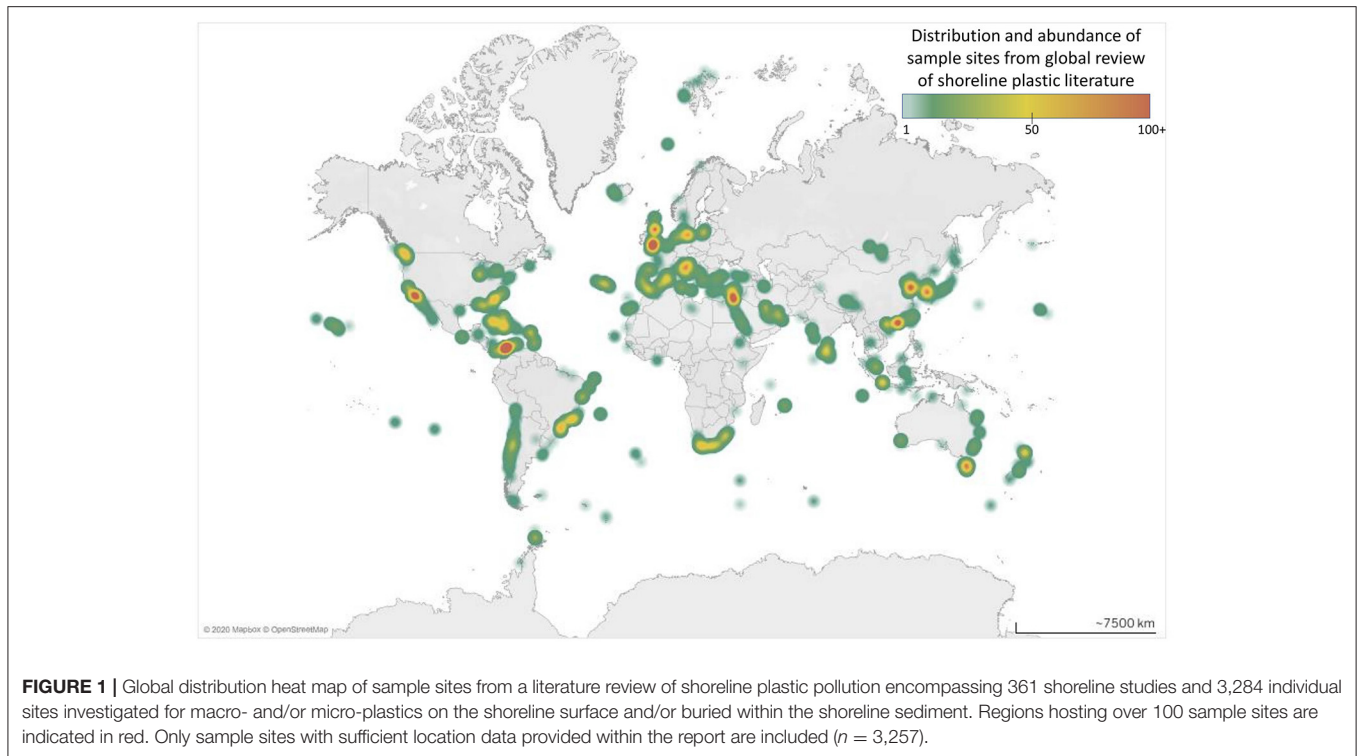
This review captured 361 published shoreline studies from 1977 to 2019, yielding 3,284 individual sample sites (Figure 1). Freshwater sample sites accounted for 3.6% ($n = 118$) of these, stemming from 20 studies (5.5% of studies). Surveys of the shoreline surface were more common (62% of sample sites; $n = 2,047$) than surveys of buried plastics (43% of sample sites; $n = 1,406$). A total of 5% of all sample sites ($n = 167$) were subjected to both survey types.

Sediment Type

Sediment type was not reported for 39% of all sample sites ($n = 1,274$). Of the sample sites for which sediment type was reported ($n = 2,010$), 90% ($n = 1,816$) of these were sandy beaches and only 4% ($n = 89$) were described as coarse sediment beaches (Figure 2A). When the analysis is restricted only to surveys of

buried plastics, sediment type was not reported for 14% ($n = 194$) of sample sites. For those buried plastic surveys that reported sediment type ($n = 1,212$; pattern fill in Figure 2A), 3% ($n = 37$) of sample sites were described as containing any amount of coarse sediment (i.e., including both “coarse” and “mix” sediment sites), 97% were dominated by sand ($n = 1,175$), and 0.2% ($n = 3$) of buried plastic sample sites or samples were described as being dominated by coarse sediment.

Several studies ($n = 17$) sampled at least one coarse sediment shoreline, but did not provide site-specific sediment information and were therefore not included in the analysis of sediment type per survey site. In order to account for these sample sites, the inclusion of coarse sediment sample sites per study was also analysed (Figure 2B), with a finding that 23% ($n = 62$) of studies included at least one sample site containing coarse sediment. When the analysis is restricted only to surveys of buried plastics, sediment type was not referred to in 15% ($n = 25$) of studies. For those buried plastic studies that referenced sediment type ($n = 142$; pattern fill in Figure 2B), 91% ($n = 129$) surveyed exclusively on sandy shorelines, and 9% ($n = 13$) included at least one sample site with some coarse sediment. Coarse sediment was more common in freshwater sample sites than for sample sites in the marine environment (Figure 2C). Among surface surveys, 39% ($n = 7$) of freshwater sites contained coarse sediment, compared to 16% ($n = 117$) of marine sample sites. Among buried surveys, coarse sediment was again better represented on freshwater shorelines (48%; $n = 15$) than in the marine environment (2%; $n = 22$). Relative to sand, coarse sediment is underrepresented in surveys for plastics both on the surface and buried within shorelines, and a failure to report sediment type for



individual sample sites was relatively common, particularly in the case of surface surveys.

Organic Material

Information on the presence of organic material and the methodologies related to it was typically provided per study rather than for individual sample sites. Of the 361 reviewed studies, 48% ($n = 174$) described targeting a tideline, strandline, wrackline, or other accumulation zone of organic material on the shoreline (hereafter referred to as “tideline” inclusively). These descriptions of tideline sampling, where organic accumulations typically occur, were more common for buried surveys (60%; $n = 101$) than for surface surveys (38%; $n = 73$) (Figure 3A). Although targeting natural accumulation zones for organic material (i.e., tidelines) was common in buried surveys, natural debris was mentioned in 25% ($n = 25$) of buried surveys where a tideline was targeted, and only one study described extracting plastics buried within the organic matrix itself. More commonly, microplastics were extracted from sediment samples that contained quantities of organic material small enough (often microscopic) to be dissolved by acid digestion (“Sediment Processing” in Figure 3A). Mentions of an organic accumulation zone in the sample area was more common for marine studies (50%; $n = 169$) than for those that included freshwater sample sites (25%; $n = 5$), but the presence of organic material during site characterisation or sample collection was noted more often in studies that investigated freshwater sample sites (30%; $n = 6$) than in those that strictly sampled marine shorelines (16%; $n = 57$) (Figure 3B). Despite the prevalence of tideline-targeted sampling in both surface and buried plastic survey

methodologies, and the likelihood of encountering both organic material and anthropogenic debris in the area, very few studies mention the presence or nature of the organic debris, and only one study described methods for extracting plastics from organic material.

Seasonality and Snow and Ice

A total of 31% ($n = 1,025$) of all sample sites were subject to repeat sampling in the same location. Most of the repeatedly sampled sites captured more than one season (62% of repeat sample sites; $n = 639$), while 43% ($n = 438$) of revisited sample sites covered the full complement of seasons for their region (Figure 4). None of the freshwater sample sites were monitored across a full complement of seasons for their region. Most seasonally surveyed sample sites are outside of regions of snow accumulation (Figure 4). The presence of snow or ice was mentioned for 0.8% ($n = 26$) of all 3,284 sample sites. Mentions of snow and ice were more common for freshwater sample sites (14%; $n = 16$) than for marine sample sites (0.3%; $n = 10$). All 26 sample sites stemmed from five studies (1% of studies). Three of these studies mentioned snow and ice as a justification for not conducting winter sampling, one study sampled during the winter season but avoided areas of snow cover, and one study sampled during the presence of snow and ice (as evidenced by photos within the publication) but described no protocol adaptations. While many shoreline surveys were designed to capture seasonal variations, very few of these took place in regions frequently subjected to snow and ice precipitation, and none describe protocols for surveying in the presence of snow and ice.

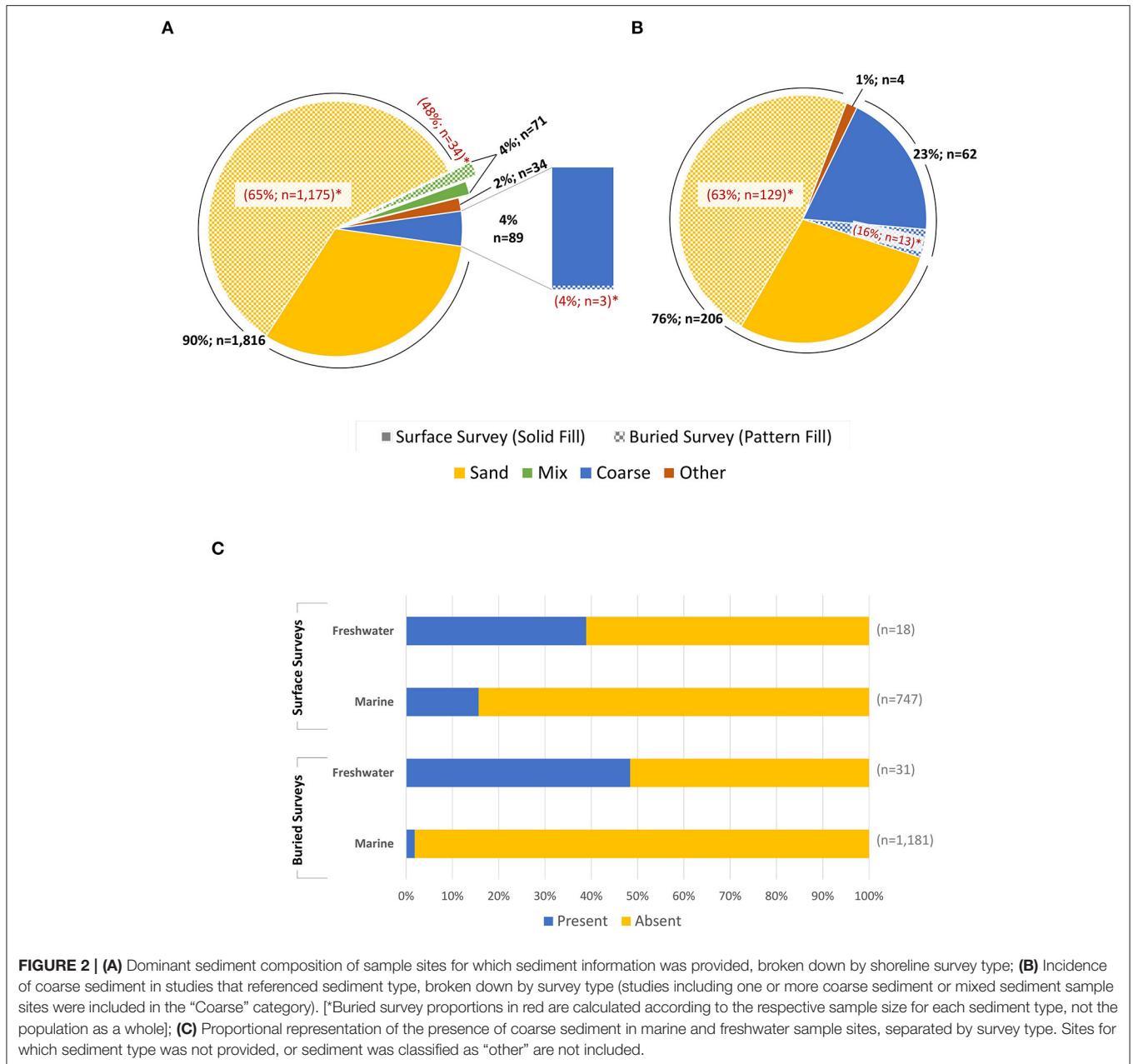


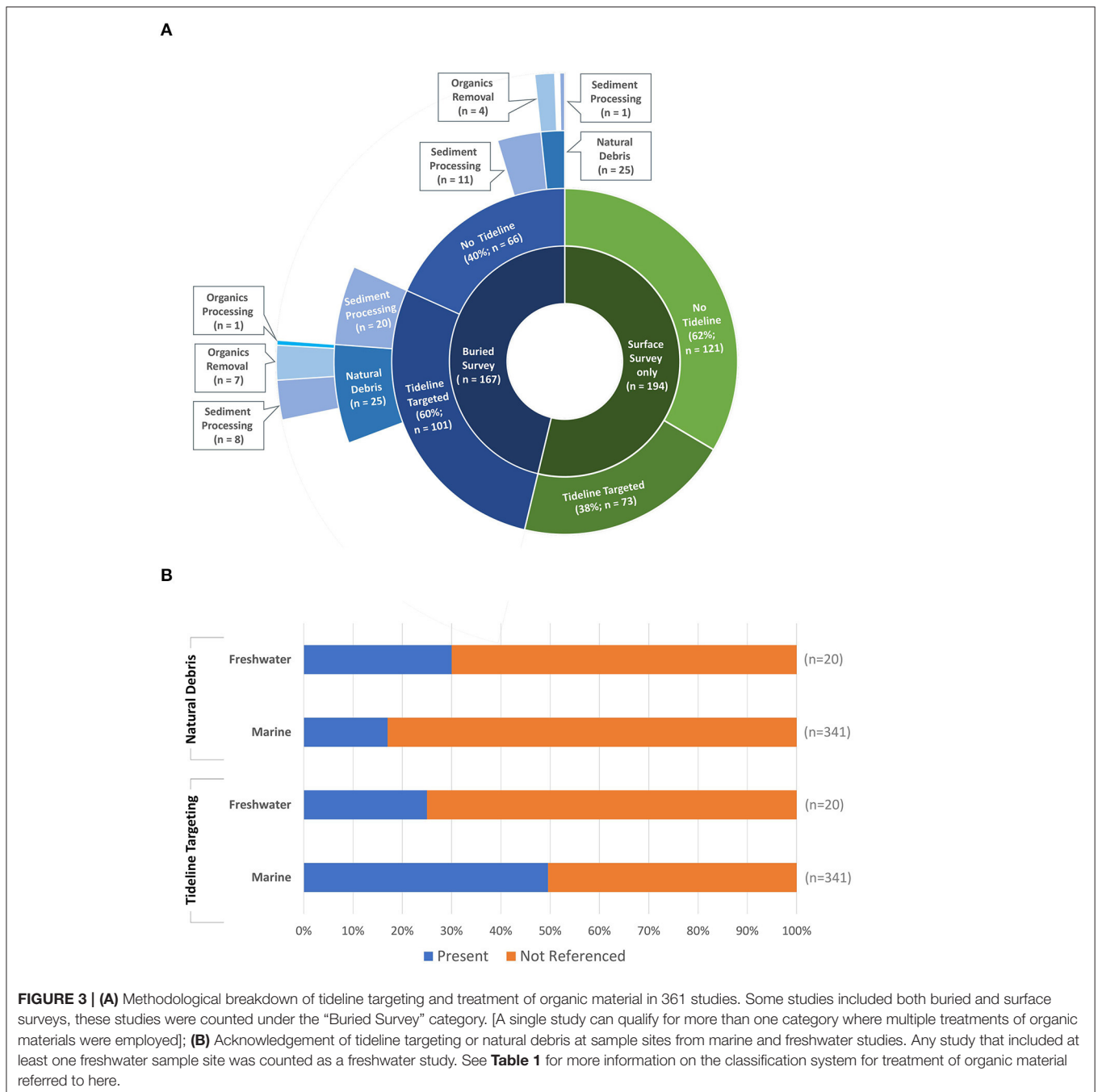
FIGURE 2 | (A) Dominant sediment composition of sample sites for which sediment information was provided, broken down by shoreline survey type; **(B)** Incidence of coarse sediment in studies that referenced sediment type, broken down by survey type (studies including one or more coarse sediment or mixed sediment sample sites were included in the “Coarse” category). [*Buried survey proportions in red are calculated according to the respective sample size for each sediment type, not the population as a whole]; **(C)** Proportional representation of the presence of coarse sediment in marine and freshwater sample sites, separated by survey type. Sites for which sediment type was not provided, or sediment was classified as “other” are not included.

DISCUSSION

In answer to the first question posed by this paper on the degree to which diverse landscapes features are represented in the published literature, our findings reveal that the state of knowledge in shoreline plastic debris research focuses overwhelmingly on shoreline landscapes that are sandy and free of organic material or winter precipitation. Globally, roughly 70% of ice-free shorelines are not sandy (Luijendijk et al., 2018), while within plastic pollution research only 5% of sample sites were characterised by sediment that is coarser than sand. Moreover, although stranded organic debris is an important feature of any shoreline where the coastal waters are

characterised by kelp forests or other macroalgae colonies (Orr et al., 2005; Krumhansl and Scheibling, 2012), only 18% of studies mention its presence and only one study describes any methods for locating plastics buried within stranded organic material. According to the National Snow & Ice Data Centre, snow covers 46 million square kilometres of land annually [NSIDC (National Snow and Ice Data Centre), 2020] mostly in the Northern Hemisphere, yet only 1% of studies make mention of ice or snow, and none include methods for locating plastics in the presence of ice or snow on shorelines, besides avoiding areas of snow/ice cover.

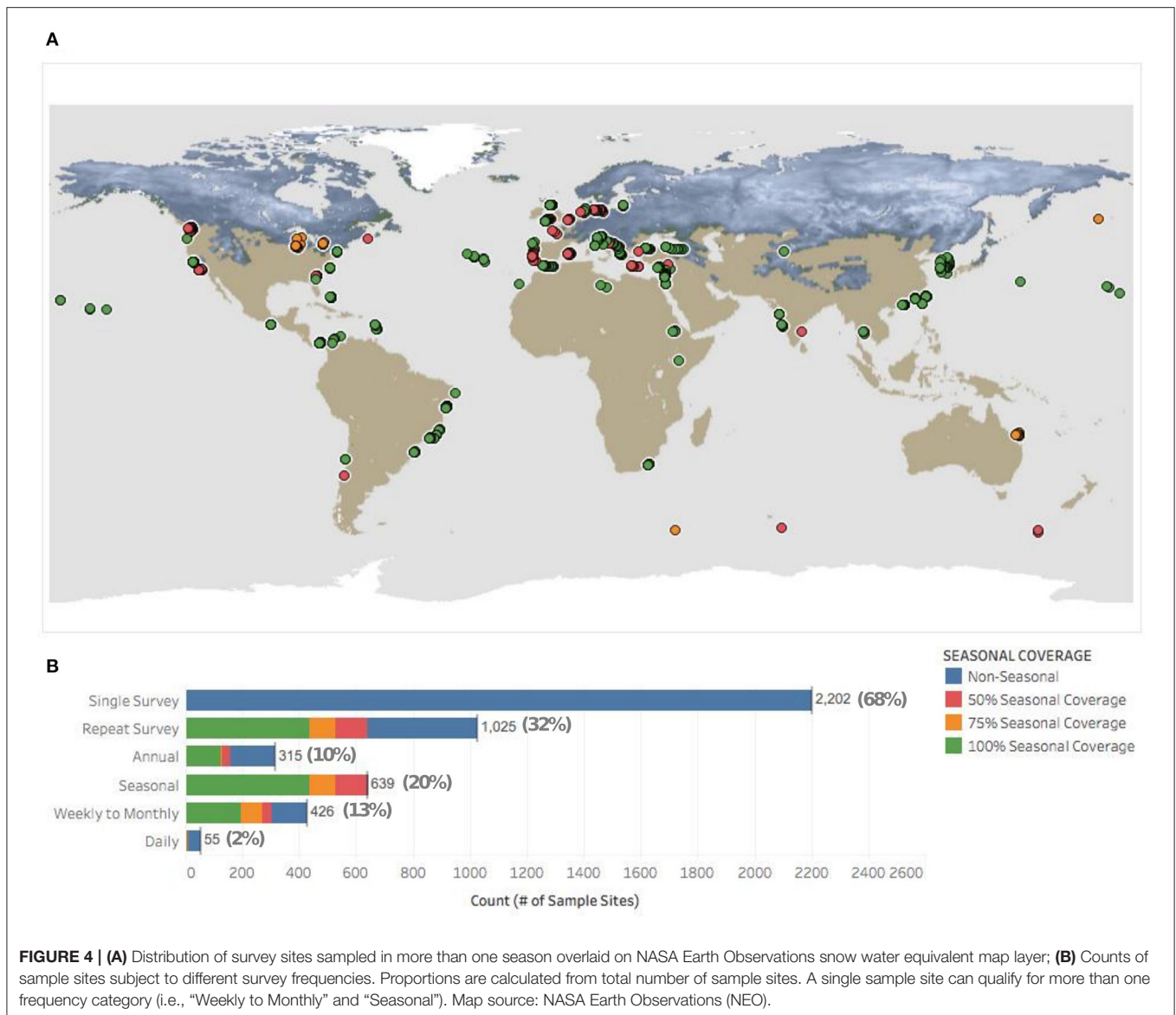
Next, we take up the second question posed by this paper: what are possible explanations for the acute underrepresentation



of sites with coarse sediments, organic material, and winter precipitation in plastic pollution research? When sediment type was described, 94% of sample sites in this review were composed of sand. This value was even higher among sample sites surveyed for buried plastics, where 99.7% of sample sites were described as containing sandy sediment. Although some widely-used guidelines for surveying marine plastics include gravel and pebble beaches among their recommended site selection criteria (Cheshire et al., 2009; Opfer et al., 2012; Lippiatt et al., 2013), protocols for monitoring microplastics are only

applicable to sandy beaches. For example, protocols require running sand samples through fine mesh sieves to extract plastic particles (impossible when the shoreline comprises sediment coarser than the sieve mesh size) [European Commission, 2013; Lippiatt et al., 2013; GESAMP (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection), 2019].

The emphasis in existing protocols on sandy beaches may explain, in part, why researchers describe seeking out sandy beaches even when these are not representative of the prevailing



landscape in the region. Nachite et al. (2019), for example, selected 14 sandy beaches for their study in Morocco, despite acknowledging that only 20% of beaches in the country are made up of sand. Likewise, Kunz et al. (2016) selected four sandy beaches for their survey in Taiwan, despite the fact that the sampled region in the country “is mostly made up of rocky shores, and sandy beaches occur only in several relatively small and isolated areas” (Kunz et al., 2016, pp. 127–128). Others describe choosing sandy beaches specifically because of an anticipated inability to sample for small or buried plastics on coarse substrate (Ryan, 1987; Slip and Burton, 1992; Davis and Murphy, 2015; Stolte et al., 2015).

The European Commission’s marine debris protocol document states “Sandy beaches are the easiest to survey, but pebbly and rocky beaches can be included in the assessment

programme. However, it must be noted that the results from such beaches will not be comparable to sandy beaches as there will be an underestimation of small items on pebbly beaches and accumulation processes will be different (especially on rocky coastlines)” (European Commission, 2011, p. 13). In the literature examined here, when researchers did attempt to compare shorelines of different sediment types the results were often significant, but mixed. Debris density was sometimes reported to be higher on coarse sediment when compared to sand (Kuo and Huang, 2014; Hardesty et al., 2017; Brennan et al., 2018; Ríos et al., 2018), but the trend was not consistent across coarse sediment categories. For example, Brennan et al. (2018) found the highest debris densities on pebble shorelines, followed by sand, while rock platforms and boulder beaches revealed the lowest densities. In contrast, Hardesty et al. (2017) found

the highest debris densities on boulder shorelines, followed by sand, with lower densities on rock slabs and gravel shorelines. Schmuck et al. (2017) found macro-debris densities to be significantly higher on sandy shorelines than on rocky or mixed sediment shorelines.

More consistently, researchers are finding that debris size and composition varies significantly between sandy and coarse sediment shorelines (Moore et al., 2001; Thiel et al., 2013; Giovacchini et al., 2018; Ríos et al., 2018). These differences could begin to explain the lack of consistency described above. The results of comparative studies of sandy and coarse sediment beaches will be influenced by: (1) the types of anthropogenic debris reported in overall debris densities, since non-plastic debris such as glass and metal have been reported to be more abundant on coarse sediment shorelines (Moore et al., 2001; Thiel et al., 2013; Kuo and Huang, 2014), and (2) the debris size categories under investigation, since large debris is reported to be more common on coarse sediment (Giovacchini et al., 2018; Ríos et al., 2018) and small debris can become buried in the interstitial spaces of these environments (Giovacchini et al., 2018; McWilliams et al., 2018). The potential effect of debris burial is not accounted for by any of the above listed comparative studies, which are all surveys of surface debris.

Clearly, more investigation into the role that coarse sediment shorelines play in accumulating (and/or generating) plastic debris is needed, but the inclusion of coarse sediment beaches in existing assessment programs is easier said than done due to logistical constraints. McWilliams et al. (2018, p. 1) conclude that “standardised protocols for shoreline marine debris studies are not developed for the rocky and icy shores that characterise locations such as Newfoundland, Canada, or indeed, much of the coastline found in high latitudes.” The findings of this review, namely the vast underrepresentation of non-sandy shorelines, likely indicates that researchers around the globe struggle to apply these protocols in their own geographies, and may, as a result, choose to avoid coarse sediment in their surveys.

The same sieving protocol which proves unsuitable for investigating buried plastics in coarse sediment is similarly unsuitable for any organic debris large enough to resist sieving (>5 mm). This is particularly problematic for tideline areas covered in large quantities of stranded seaweed which can become incorporated into the sediment up to 30 cm depth, especially in coarser sediment (Orr et al., 2005). This may, in part, explain why plastic buried or entangled within large organic debris was only investigated at 1% of all sample sites, despite the fact that 60% of buried plastic survey studies reviewed here targeted a tideline for sampling; a sampling strategy which is explicitly recommended in guideline documents [European Commission, 2013; Lippiatt et al., 2013; GESAMP (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection), 2019].

These logistical reasons may be why some researchers document avoiding shoreline areas with large organic deposits (Blumenröder et al., 2017; Edo et al., 2019; Leads and Weinstein, 2019), while others report moving organic material out of the way in order to sample the sand below (Wessel et al., 2016; Abidli et al., 2018; Hansen and Gross, 2019). However, given that high

quantities of recently deposited plastic debris can be expected within these mounds of stranded organic matter (Thornton and Jackson, 1998; Gutow et al., 2016; Rodrigues et al., 2019; Lazcano et al., 2020), their avoidance may result in an underestimation of plastic pollution density particularly given the strong association between deposits of organic material and plastic debris, which has been noted by several researchers within this corpus (Thornton and Jackson, 1998; Velander and Mocogni, 1998; Viehman et al., 2011; Dippo, 2012; Zhou et al., 2018; Rodrigues et al., 2019).

Snow and ice act as sinks, concentrating microplastics until temperatures rise and plastics are released in meltwater (Ory et al., 2020; Uurasjärvi et al., 2020; Von Friesen et al., 2020). Although a full complement of seasons is universally recommended for shoreline monitoring programs in key monitoring guides [European Commission, 2013; Lippiatt et al., 2013; GESAMP (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection), 2019], there are no guidelines for monitoring shorelines in the presence of snow and ice in these same documents. A recent shoreline study highlights this contradiction: “According to protocol, OSPAR beaches are surveyed at 3-month intervals annually (winter, spring, summer and autumn). However, due to harsh winter conditions with ample snow, none of the Norwegian OSPAR beaches are registered more than twice a year” (Falk-Andersson et al., 2019, p.366). This discrepancy in protocols may explain why only 1% of the studies reviewed here mention snow or ice. Since the completion of this review, one recent study in Finland sampled snow, ice, and sediment near freshwater shorelines. The authors, however, note a critical problem: “Regarding snow samples, it was not possible to make any data comparison, as there are no published data on the occurrence of [microplastics] in a snow matrix” (Scopetani et al., 2019, p.14).

The three landscape features we have identified—sediment grain size, organic material and snow/ice—often intersect, compounding the challenges of conducting shoreline surveys where they occur. Coarse sediment beaches are more likely to accumulate large quantities of stranded organic materials like seaweed detritus than their finer sediment counterparts (Orr et al., 2005). Seaweed and kelp colonies are commonly found in the waters adjacent to rocky shorelines (Rodríguez, 2003; Krumhansl and Scheibling, 2012). Most of these colonies require cold, nutrient-rich waters, causing a peak algal biomass to occur between 45° and 60° N latitude (Steneck and Johnson, 2014), a region characterised by northern temperate or subarctic climates with marked seasonality and cold winters that give rise to snow and ice. The avoidance of any one of these environmental features individually may hinder the appearance of the other two in shoreline plastic pollution research. Alternatively, the inclusion of one feature may often lead to the appearance of all three, making it incredibly challenging to apply standard plastics monitoring techniques in these regions.

Here, we have demonstrated that existing plastic pollution research efforts are not addressing diverse shoreline landscapes proportionately. Based on the overall figures presented above, methodological comments made by individual researchers

in published work, and the content of the shoreline survey guidelines themselves, we find that the nature of standardised methods in this field may be contributing to an overrepresentation of those landscape features for which protocols are readily available (i.e., sandy beaches free of organic debris, snow or ice). While standardised methods are critical for the global comparability of data, according to Bowker and Star (1999), they also tend to limit and delegitimize realities and representations thereof to which the standards cannot be applied (see above quote from the European Commission). Global syntheses which do not account for this underrepresentation are likely to generate a very partial view of shoreline plastic pollution. To fulfil the purposes of shoreline pollution research beyond the important goal of comparability (in this case, global synthesis, but also regional policy information, activism, community engagement and countless other place-based outcomes), we must prioritise the creation of knowledge that is representative of the region and landscape about which it speaks in the methods we employ.

In light of the need to balance the diverse and critical goals of plastic pollution research on shorelines, we make the following recommendations. First, in agreement with other reviewers in this field, we recommend more detailed methodological reporting. Site information including GPS coordinates, sediment type, surrounding landscape features and other environmental influences are critical to the comparability and interpretation of data across regions (Cowger et al., 2020). Second, we recommend that more attention is paid to diverse landscapes and the regionally appropriate representation thereof in published shoreline studies. This must necessarily be facilitated by protocol guideline documents that acknowledge variation in plastic accumulation across substrates (including but not limited to coarse sediment, organic deposits and ice and snow) and seek to include more diverse landscapes in the protocols they provide. Finally, we recommend acknowledging and legitimising the outcomes of shoreline surveys beyond comparability and global synthesis to make room for regionally specific and place-based priorities. We do not make this recommendation lightly, but with the confident knowledge that addressing the problem of plastic pollution will require flexibility, creativity and reflexivity.

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DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

JM conducted the original review for this paper and initially noted the central finding of this paper. MB, JM, and JA extracted methodological data per sample site. MB and JM wrote each draught and integrated insight and comments provided by JA, CM, and ML. ML provided critical insight and direction, and assisted JM with data analysis and design of figures and tables. This paper was conceptually a joint effort by all authors.

FUNDING

This work was jointly funded by the Ocean Frontier Institute (OFI), and the Department of Fisheries and Oceans Canada (DFO). Research Portal numbers for these Grants [DFO: RP-20200063 and OFI: RP-20191801].

ACKNOWLEDGEMENTS

We acknowledge that this research was conducted on the unceded, unsundered ancestral Lands of the Mi'Kmaq and Beothuk peoples. We would also like to acknowledge the Inuit of Nunatsiavut and NunatuKavut and the Innu of Nitassinan, and their ancestors, as the original peoples of Labrador. Thank you to France Liboiron, Alexandra Hayward, and Cherish Blackmore, who were with us in the field and in the laboratory when we first identified these gaps, and without whom we never could have overcome the challenges of conducting shoreline research on our own rocky shorelines.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2021.689108/full#supplementary-material>

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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