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Arctic marine litter: Composition and sources investigated by citizen scientist "super-users"

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ABSTRACT

Combating the challenge of marine litter requires an understanding of its distribution and accumulation for mitigative measures, and its sources for targeted preventative measures. The latter is generally not well assessed through most beach litter registration protocols available to citizen scientists. Deep Dives were specifically developed to provide management with additional relevant data on the sources of and behaviours leading to littering in the Arctic. In this project, the Deep Dive protocol was used as an add-on to the Norwegian national volunteer beach cleanup registration protocol. Litter was cleaned and registered from 9 locations in the Svalbard archipelago 2022-2023 in collaboration with two groups of citizen scientists: members of the Arctic Research Group and students from Svalbard Folkehøgskole. These were given specialised training as "super-users" to apply this more complex beach litter registration protocol. The experience of the volunteers was generally positive and the data quality good, although some need for additions to the training was highlighted to reliably categorise some challenging items. In the future, citizen scientists could contribute significantly to the collection of management-relevant data on marine litter in the Arctic provided adequate training, resources, and a user-friendly data registration portal.

1. Introduction

Plastic pollution is now so pervasive that quantities rival those of natural organic carbon in some ecosystems (Stubbins et al., 2021). In the Arctic, the presence of anthropogenic litter amplifies the stresses imposed on ecosystems by climate change (Bergmann et al., 2022; Lincoln et al., 2022). Effective preventative measures to limit continued pollution requires an understanding of sources and behaviours leading to littering (Falk-Andersson, 2021). Given the generally sparce population density in Arctic regions combined with ocean currents transporting Atlantic and Pacific water northwards, one might expect marine litter in the Arctic to stem largely from long-range transport and a need for preventative measures to focus primarily on emission reductions at southern latitudes (Bergmann et al., 2022; Cózar et al., 2017). Nevertheless, several recent studies suggest a large portion of Arctic macrolitter stems from local emissions, particularly fisheries and other maritime activities (Bergmann et al., 2022; Haarr et al., 2023; Meyer et al., 2023; Vesman et al., 2020).

There are several challenges to fully mapping the distribution, accumulation, and sources of marine litter in the Arctic. Logistics can be challenging given the remoteness of the region, but even when research and monitoring are conducted, studies are not necessarily comparable as methodologies are often not harmonised, which hinders meta-analyses (AMAP, 2021; Grøsvik et al., 2022). The Svalbard archipelago in the European Arctic is a relatively well-studied region in an Arctic context (Bergmann et al., 2017; Collard et al., 2022; González-Pleiter et al., 2020; Grøsvik et al., 2018; Hallanger et al., 2022; Herzke et al., 2021; Jaskólski et al., 2018; Meyer et al., 2023; Tekman et al., 2017; Weslawski and Kotwicki, 2018); although even here, spatiotemporal patterns in beach litter mass and abundance are not well documented.

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Citizen scientists frequently participate in marine litter cleanups, research and monitoring, particularly of macrolitter (>2.5 cm) on beaches (Catarino et al., 2023; Chen et al., 2020; Nelms et al., 2020; Popa et al., 2022). Citizen scientists can enable large-scale data collection that is challenging, if not impossible, for professional researchers to match alone (Popa et al., 2022). For participants, engaging in citizen science can help raise awareness, although it remains uncertain whether this translates to enduring behavioural changes (Popa et al., 2022). Citizen science has been used successfully in marine litter research in the Arctic on several occasions, proving the applicability of the approach also in challenging environments with more complex logistics and safety concerns than most other regions (Bergmann et al., 2017; Ershova et al., 2021; Meyer et al., 2023).

There are numerous litter registration protocols available for citizen scientists. For some studies, custom protocols are developed (*e.g.,* Meyer et al., 2023), while others utilise more widely adopted protocols. In Norway, the majority use an Ocean Conservancy based national protocol for volunteer beach cleaners; a platform initially hosted by Keep Norway Beautiful and later moved to be co-hosted by the Norwegian Environment Agency's Centre Against Marine Litter (www.ryddenorge.no). This protocol has been used by hundreds of thousands of volunteers and is thus well tested.

Most available protocols for the registration of beach macrolitter, however, including extensive ones such as the OSPAR protocol, fail to provide data suitable for answering questions regarding specific sources and behaviours leading to littering, thus still leaving managers and key stakeholders needing this information to identify mitigative actions even when data are collected (Falk-Andersson, 2021). At the same time,

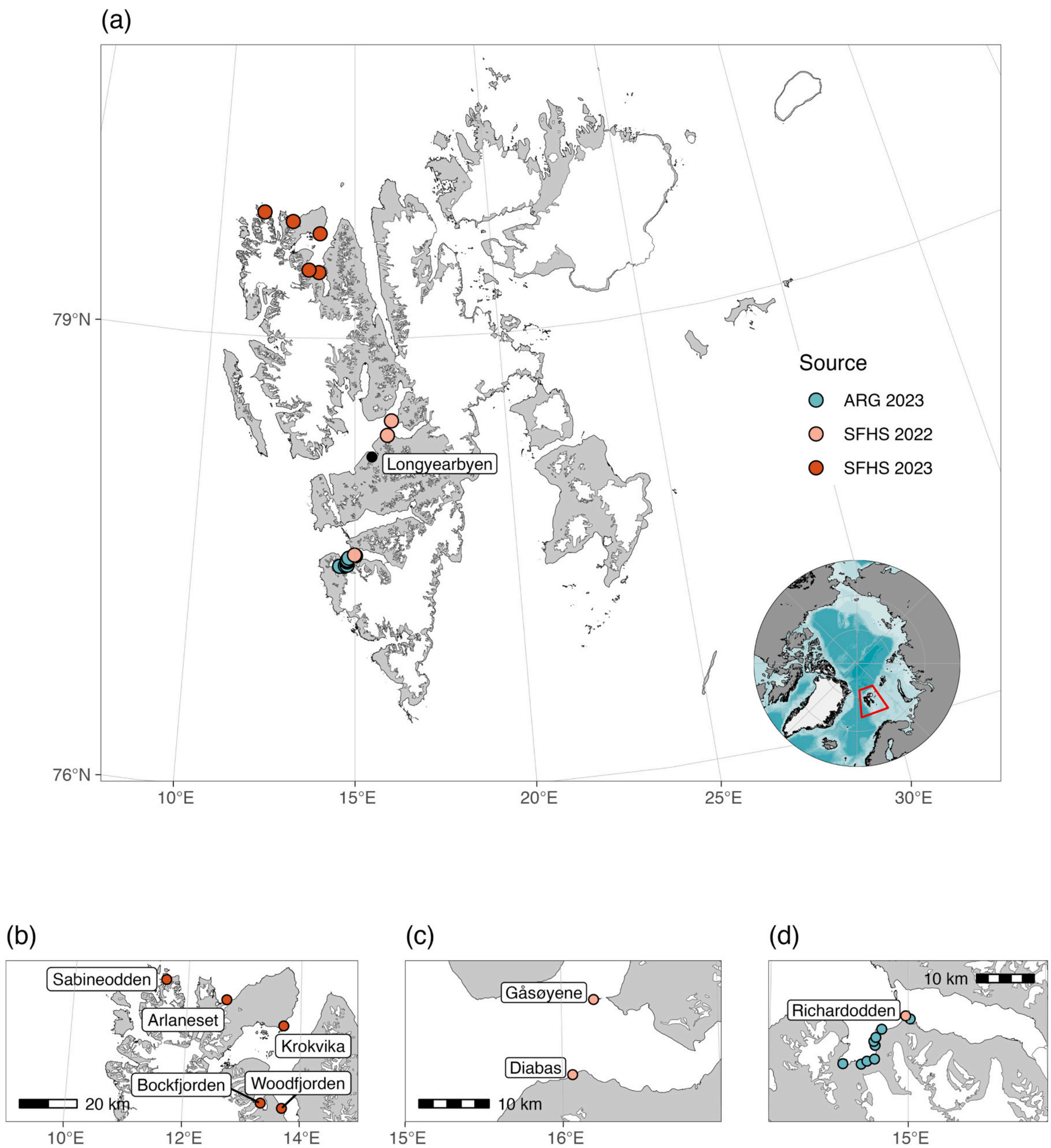

Fig. 1. Map of study area and sites which litter was analysed. Colour coding in panel a indicates the volunteers conducting the litter analyses. Arlaneset and Krokvika (panel b) were cleaned by professional cleanup crews and not SFHS (Svalbard Folkehøgskole) (see text). In panel d, only the site cleaned by SFHS is named (indicated in orange). The green circles indicate landing sites where three 100 m stretches were sampled by ARG (Arctic Research Group) in 2023 and all data pooled for analyses. Maps drawn using ggOceanMaps (Vihtakari, 2022). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

collecting more in-depth data can be challenging and subject to observer bias (Falk-Andersson et al., 2021) and not necessarily compatible with citizen science where protocols are advised to be simple and clear to ensure both motivation and data quality (Kosmala et al., 2016; Nelms et al., 2022). Nevertheless, especially motivated groups of citizens may find more advanced data collection protocols suitable.

The primary objective of this study was to test the training and implementation of such particularly motivated groups, or "super-users", in recording beach macrolitter data according to the Norwegian national volunteer protocol ("Rydde") with a Deep Dive extension protocol for further source identification. Deep Dives were developed particularly for marine litter in the Arctic (see https://deepdive.grida.no for details), although in this study we adapted the protocol to be harmonised with the "Rydde" protocol and function as an extension to it. Fisheries-related litter and packaging were recorded in detail to assess associated behaviours behind littering and provenance and age of items when possible. The study was conducted in collaboration with citizen scientists from Svalbard Folkehøgskole, a folk high school/college located in Longyearbyen (Svalbard), and the UK-based charity Arctic Research Group. The harmonisation of the two protocols was initiated by SFHS students and thus directly by volunteers themselves.

2. Methods

2.1. Litter collection

Svalbard Folkehøgskole (SFHS) students and staff collected and analysed litter in 2022 and 2023. In 2022, groups of 10 cleaned two locations in Isfjorden close to Longyearbyen and one in Van Keulenfjorden in late August and early September (Fig. 1). In 2023, SFHS and two staff from the Norwegian Centre Against Marine Litter conducted an expedition to northern Spitsbergen in mid-September; litter was collected from three sites by groups of 12–15 persons. All groups consisted of beach cleaners, a group leader doubling as polar bear guard, and an additional polar bear guard for safety. In addition, litter from two locations (Arlaneset and Krokvika; Fig. 1) cleaned by Fjordane Friluftsråd and PolarX through the professional cleanup program "Cleanup Norway in Time" in August 2023 was handed over to SFHS for registration. These sites were cleaned by crews of 6 or 12 people accompanied by a polar bear guard and a group leader. A total of 7.9 km of coastline was cleaned.

Sites were selected based on a combination of expected litter load (given the primary goal of cleanup) and accessibility. The likelihood of significant litter accumulation was estimated using satellite or aerial photos to locate driftwood accumulations, and information was gathered from guides, tourist companies, the Governor of Svalbard, and locals who had observed litter. Lastly, the national marine litter databases for professionals and volunteers ("Rent Hav" and "Rydde", respectively) were checked for reported accumulation areas. Accessibility to beaches varies with wind conditions; selected locations were required to have several access options depending on the weather. All visible macrolitter >2.5 cm was collected, although for two locations cleaned by SFHS in 2023 (Sabineodden and Woodfjorden) 1–4 cm fresh snow reduced detectability of small items <20 cm. Beach length and width were dictated by litter dispersal, natural features, and time available.

Members of the Arctic Research Group (ARG) collected litter during a 4-week expedition to Rechecherfjorden (located within Van Keulenfjorden) in August 2023. This ten-person expedition contributed both to this and unrelated research. Litter was collected from nine haphazardly chosen landing sites in proximity to their basecamp (Fig. 1d). At each landing, three locations were surveyed 200–500 m apart. All visible meso- and macrolitter (>0.5 cm) was collected. Beach length was standardized to 100 m and beach width dictated by the vertical distribution of litter. A total of 2.7 km of coastline was cleaned. An overview of all sites and their characteristics are given in Table 1.

2.2. Litter registration

Litter was registered through a harmonisation of the Deep Dive protocol developed for beach litter source identification in the Arctic, and the protocol of the Norwegian national citizen science database "Rydde" (Fig. 2). SFHS analysed litter indoors at a waste management facility in Longyearbyen. One instructor and 7 (2022) or 13 (2023) students participated. ARG registered litter *in situ* in the field, either directly on the beach or at their basecamp and also photographed every item, enabling some further investigations to take place after the expedition was complete.

The "Rydde" protocol lists 78 litter types within five categories: "personal use and domestic", "hygiene and sanitary", "fisheries and aquaculture", "industry and commercial", and "other". For cleaning products, beverage bottles and cans volunteers are asked to note whether these are Norwegian, foreign, or of unknown provenance. Item categories do include unidentified plastic pieces (</> 50 cm), but there is no post for tallying items not described by any of the categories except as free text under comments. Registrations using this protocol do therefore not include all litter cleaned from a beach. Items are counted and a total weight for all litter provided, although weight may be estimated based on the assumption that one full garbage bag (~100 L) weighs on average 10 kg; reference data for this assumption are not available.

The Deep Dive protocol is also based on the Ocean Conservancy ICC list and is simultaneously of lower and higher resolution than the "Rydde" protocol as its objective is to provide data traditional protocols do not without replicating too much information for the sake of efficiency. There are more categories for fisheries-related items based on workshops with fishers and experts on fisheries technology, particularly related to onboard processing of fish and net mending. The resolution is also higher for packaging where provenance and age are recorded when discernible. Provenance is recorded to the highest resolution possible, which may be by country or a region encompassing individual countries (*e.g.,* Scandinavia includes Norway). Age is recorded as the oldest an item is likely to be (*e.g.,* based on manufacture date when stamped) or the most recent it can be (*e.g.,* the last year a certain logo was in use). The method used to identify provenance and age is recorded, such as text (*e.g.,* language of printed labels), manufacture or expiry dates, logos or brand names (*e.g.,* some brands have a limited distribution), and design (*e.g.,* a brand's ketchup bottle may have changed). Material is also recorded (soft plastic, hard plastic, foam, metal, paper, glass, wood, other identifiable materials, and unknown materials) for packaging and fishing gear. Plastics are considered soft when items can be tied into a knot and crumpled in one's hand. Items other than fisheries-related litter and packaging are counted and weighed in broad collective source categories according to Falk-Andersson et al. (2019).

The two protocols were harmonised to the lowest common denominator and litter recorded according to the protocol with the highest resolution for any given item, along with an "other" category for any items not fitting any categories. Items were also identified through multiple ID columns so that one may choose to summarise data according to only one protocol or the other.

2.3. Volunteer training

Just as SFHS and ARG tested two different models for litter registration (litter transported to a waste management facility and registered indoors at a later date *vs. in situ* litter registrations in the field), two different models for volunteer training were also tested.

With ARG, the training process was highly structured, and only key volunteers were provided training in the litter registration protocol and then themselves passed the training on to others in their team. A 2-day training workshop was held with two ARG team members and two scientists, and both preceded and followed by an online information meeting and Q&A session. The workshop included both theory and

Table 1
List of sampling locations, their characteristics, and the amount of litter removed from each.

Site	Region	Coordinates	Sampling date(s)	Beach cleaned by	Litter analysed by	Length (km)	Characteristics	Min size cleaned	Total litter (n)	Total litter (kg)	Litter density (n km^{-1})	Litter density (kg km^{-1})	Mean item weight (g)
Diabas	Isfjorden	78.3584°N 16.0646°E	Sept. 3rd 2022	Svalbard Folkehøgskole	Svalbard Folkehøgskole	0.92	Rocky beach (mixed grains from pebbles to boulders). Backshore partly a steep cliff Some vegetation.	2.5 cm	1550	142	1695	155	92
Gåseøyene	Isfjorden	78.4542°N 16.2069°E	Aug. 30th 2022	Svalbard Folkehøgskole	Svalbard Folkehøgskole	2.54	Mixed substrate (sand, pebbles to boulders, bedrock). A lagoon and small cliff present. Mostly flat.	2.5 cm	1994	92	785	36	46
Richardodden	Van Keulenfjorden	77.5653°N 14.9812°E	Sept. 9th 2022	Svalbard Folkehøgskole	Svalbard Folkehøgskole	1.18	Primarily pebbles, but some bedrock and sand. Gently sloping upwards to the backshore.	2.5 cm	3209	18	2719	16	6
Recherche-fjorden	Van Keulenfjorden	77.5170°N 14.7498°E	Aug. 8th – 14th 2023	Arctic Research Group	Arctic Research Group	2.70	Primarily cobbles and sand. Mixture of long gently sloping sections and short steep ones.	0.5 cm	197	12	73	4	61
Arlaneset	Northern Spitsbergen	79.7733°N 12.6895°E	Aug. 21st 2023	Fjorande Friluftsråd / PolarX	Svalbard Folkehøgskole	0.39	Rocky beach (mixture of grain sizes from pebbles to boulders) with a lagoon present. Gently sloping upwards to the backshore.	2.5 cm	5630	56	14,436	142	10
Krokvika	Northern Spitsbergen	79.6970°N 13.7031°E	Aug. 17th 2023	Fjorande Friluftsråd / PolarX	Svalbard Folkehøgskole	0.72	Mixed substrate (sand, pebbles and cobbles), accumulation of driftwood, and a lagoon present.	2.5 cm	7784	50	10,841	69	6
Sabineodden	Northern Spitsbergen	79.8275°N 11.6115°E	Sept. 9th 2023	Svalbard Folkehøgskole	Svalbard Folkehøgskole	0.55	Rocky beach (mixed grains). Flat area above the high-water mark with a shallow lagoon. 1–5 cm fresh snow. Area regularly visited by tourists.	20 cm	278	11	502	20	39
Woodfjorden	Northern Spitsbergen	79.4391°N 13.6935°E	Sept. 13th 2023	Svalbard Folkehøgskole	Svalbard Folkehøgskole	1.12	Rocky beach (mixed grains) Mixture of clay/silt, driftwood, vegetation and a small lagoon above the high-water mark. 1–5 cm fresh snow.	20 cm	1724	190	1539	170	110
Bockfjorden	Northern Spitsbergen	79.4540°N 13.3294°E	Sept. 14th 2023	Svalbard Folkehøgskole	Svalbard Folkehøgskole	0.45	Minimal slope. Mixture of coarse sand and pebbles. Wrack zone with driftwood, partially vegetated above.	2.5 cm	2513	132	5584	293	52
					Sum	11			24,879	702	-	-	
					Mean + SD	1.2 ± 0.9			2764 ± 2490	78 ± 65	2764 ± 3190	87.1 ± 98	

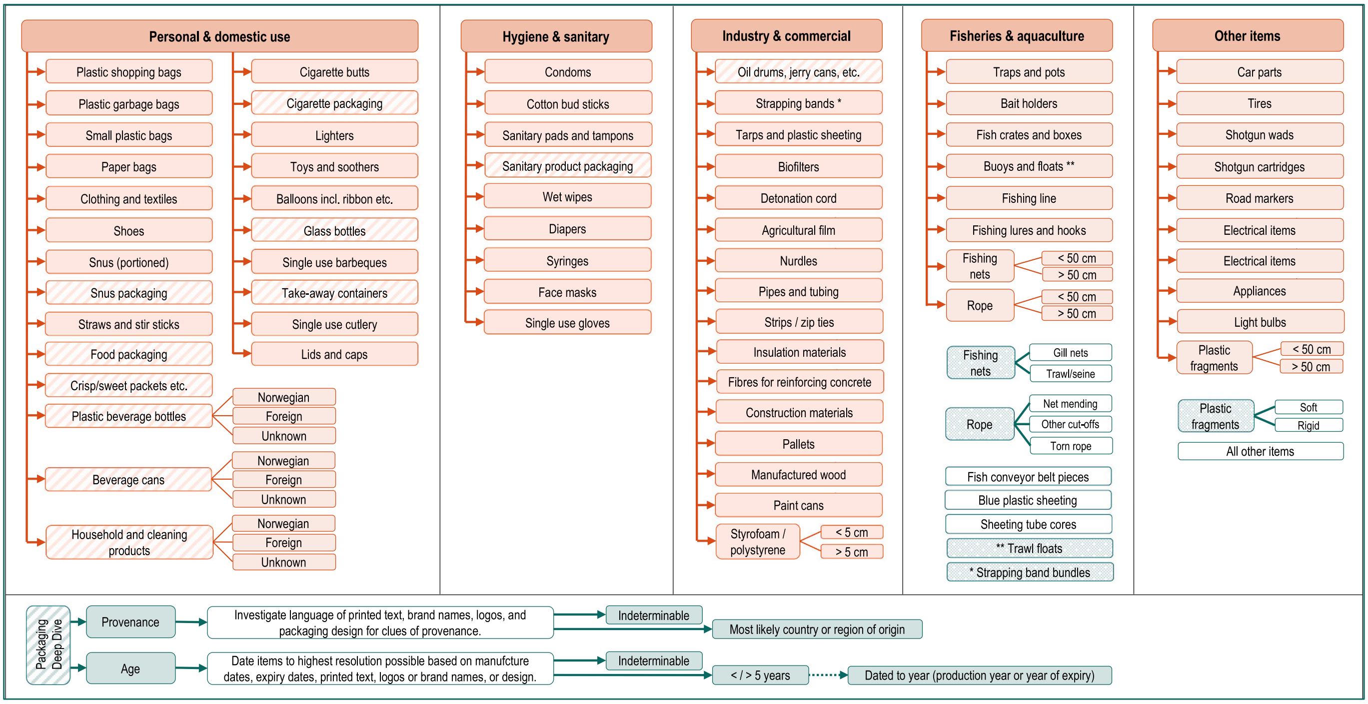

Fig. 2. Illustration of the sampling protocol showing categories registered. Orange indicates the «Rydde» or national citizen science protocol, and the green Deep Dive add-ons. Hatched cells show packaging investigated for provenance and age in the Deep Dive (bottom panel). Within the top panels, stippled green panels show categories subdivided further by Deep Dives while solid shaded panels show additional categories added by Deep Dive. Readers are referred to the online version of the manuscript for a colour rendition of the figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

hands-on litter registration, both on sample litter in the lab and during a beach excursion. The protocol was introduced in the preliminary online meeting. The follow-up online meeting refreshed training by repeating the previous presentation and allow discussion of any additional questions not addressed during the workshop itself or that surfaced upon reflection.

With SFHS, the training process was more flexible and on a by-request basis. Participating students were part of the "Science Sprout" course where the lead instructor is a former researcher holding a PhD in marine biology. Thus, the SFHS participants were more experienced than the average citizen scientist and basic training in litter collection and registration procedures was initiated and conducted in house. Training provided by researchers was primarily to specifically teach the identification of items that are not readily recognised without special training (*e.g.,* rope cut-offs from net mending, pieces of conveyor belt from onboard fish processing). Firstly, the instructor was given hands-on training in the Deep Dives protocol in 2021 by conducting an analysis together with an external researcher. Secondly, both cohorts of students were given a series of guest lectures by researchers both on the challenge of marine litter in general, data value and use, and the protocol itself prior to litter registration. Thirdly, in 2023, two researchers, two staff from the Norwegian Centre Against Marine Litter (a branch of the Environment Agency), and one from Keep Norway Beautiful joined the registration for the first two days. This allowed students to ask questions and discuss different elements of the data collection process and value directly in real time.

2.4. Statistical analyses and qualitative protocol assessment

All statistical analyses, including descriptive statistics, were done primarily on raw litter counts assessing the relative composition of litter registered. Litter density per km coastline cleaned was calculated. However, litter density among sites was not formally compared for two reasons: (1) The cleaning strategy, criteria and conditions differed among cleanup crews, leading to differences in the minimum size of items removed from the beach. Given that litter abundance is known to be sensitive to the minimum observable fragment size (Smith and Turrell, 2021), variability in this among sites creates bias. (2) The site selection process was based entirely on cleanup goals rather than research goals. The sites cannot therefore be considered representative of general litter loadings in the archipelago. The focus of quantitative analyses was therefore on relative composition rather than litter density or abundance.

All analyses were carried out using R version 4.3.1 (2023-06-16) in RStudio Version 2023.06.2 + 561 (R Core Team, 2023). Composition (dis)similarities among sites based on "Rydde" litter categories were compared using nonmetric multidimensional scaling (Kruskal, 1964), carried out using the R package "vegan" (Oksanen et al., 2022). Figures were made using "ggplot2" (Wickham, 2016) along with "ggOceanMaps" for maps (Vihtakari, 2022).

The volunteers' experience utilising the in-depth protocol was assessed qualitatively through a series of discussions following the data collection. For ARG, volunteer feedback on use of the protocol and their experiences with litter collection and registration was given in a two-hours online meeting with the two key volunteers who partook in the training workshop. For SFHS, feedback was given through a series of discussions, both in person while researchers visited the school in 2023 and through several online meetings. Discussions were structured as highly open interviews where the researchers asked the open-ended questions "How was your experience using the litter registration protocol?", "Can you describe any challenges you encountered?", and "What, in your opinion, worked well and what can be improved?". Follow-up questions were asked spontaneously depending on responses, allowing for an open discussion to maximise the input received.

3. Results

3.1. Beach litter

A total of 24,879 litter items weighing 702 kg were registered (Table 1). In addition to documenting litter, volunteers from the Arctic Research Group also documented a case of polar bear faeces containing plastic fragments (Fig. S1). When all litter was pooled, artificial polymers accounted for 95 %, and 69 % by abundance and weight, respectively. Rigid plastic items were most common, constituting half (n = 13,805) of items overall. The presence of soft plastics was variable, ranging from 1 % to 22 % of items by site. The highest percentage of soft plastics was found at Krokvika (20 %) and Bockfjorden (22 %) on northern Spitsbergen. Foam/EPS was rarely present except at the two sites in Isfjorden where it constituted 11 % (n = 175) and 23 % (n = 463) at Diabas and Gåseøyene, respectively. Overall, "unidentified plastic pieces" was the most common litter item (50 % of all items registered, n = 12,380), followed by rope (23 %, n = 6034) and strapping bands (9 %, n = 2313); all were among the top 5 items at each site apart from strapping bands at Gåsøyene. Most sites were dominated by a small number of litter types and the top 5 items generally constituted over 90 % of litter. Despite the recurring dominance of certain item types, the composition of less prevalent items did differ among regions. Multidimensional scaling show a separation of the two Isfjorden sites close to Longyearbyen (Fig. 3).

Litter from maritime sources constituted approximately one third of litter by abundance. Based on the "Rydde" protocol, 28 % of litter overall (n = 7022) stemmed from maritime sources. The proportion ranged from 15 % - 40 % among sites, and was the least prevalent at the two sites within Isfjorden. Some items, such as conveyor belt parts (Fig. 4) and packaging film rolls, are not identified in this protocol. Also, strapping bands are classified as being of generalised industrial/commercial origin under the "Rydde" protocol, while these are assumed to be of maritime origin under the Deep Dive protocol. Consequently, the proportion of litter from maritime sources was higher according to the Deep Dive protocol (38 % of all litter, n = 9379). By weight, maritime litter constituted 70 % (479 kg) of litter based on both protocols.

Within the maritime litter category, rope was the most abundant, accounting for 62 % of items overall when strapping bands were considered maritime and 82 % when they were not. Composition was more diverse by weight and relatively unaffected by the inclusion or exclusion of strapping bands as these weighed little (2 % of maritime litter weight when included). Ropes constituted a third (32 %, n = 5821, $\sum$ = 153 kg) of items by weight. Buoys and floats constituted another third (38 %, n = 161, $\sum$ = 178 kg), and trawl/seine nets and fish crates 12 % each. Maritime items not included in the "Rydde" protocol (excl. strapping bands, which are listed under another source category), made up 5 % of maritime litter by abundance (n = 428). In total, 81 % of rope (n = 4714) was identified as cut (36 % from net mending, 45 % unspecified), although the proportions of cut-offs from net mending and other cut-offs was highly variable among sites (Fig. 5). Among strapping bands, 93 % were single and 7 % in bundles, although note that each bundle contained considerable numbers of uncountable individual bands.

Packaging, the primary litter fraction for which it may be possible to determine provenance and age, constituted a small proportion of litter (6 %; n = 1392). Provenance could be determined for 195 items (15 % of packaging). Of these, Norway and Russia accounted for nearly a third each (27 %). The remaining third were primarily from Europe, but also as far as the Americas, Australia and South Africa (Fig. 6a). Only 52 pieces of packaging could be dated; 95 % of packaging was un-dateable. Of the dateable portion, 58 % were older than 5 years (Fig. 6b). Items dateable to year (n = 32) showed a wide range of ages from <1 to 35 years, with manufacture dates generally suggesting older items than expiry dates (Fig. 6c).

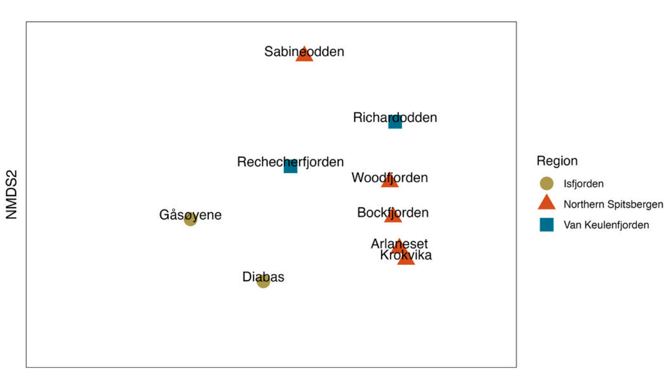

Fig. 3. NMDS plot for litter composition; only the first two dimensions are shown (k = 3, stress = 0.048, distance = Bray-Curtis).

3.2. Volunteer feedback

Overall, the experiences of the volunteers participating in the study were positive. The physical workshop and online training session were positively received by ARG volunteers who were active in asking clarifying questions to secure their understanding of the instructions and reported feeling well prepared for their expedition, both prior to departure and upon their return. SFHS students were inspired by meeting scientists and knowing their results are used. The participation of scientists also furthered the development of the protocol and pedagogical structure of volunteer training. Particular needs during training that were identified included getting a solid overview of different categories litter should be sorted into to optimise workflow, and learning specifically how to distinguish between categories that are similar or difficult to distinguish, such as cut *versus* torn ropes when these are frayed or partly degraded, or unidentified soft plastic *versus* pieces of packing film from fisheries or plastic bags.

Both groups of volunteers reported that their basic setup for registrations functioned reasonably well. ARG volunteers experienced some challenges due to being offline, as expected, but compensated by photographing every single litter item found. They also frequently chose to carry litter back to basecamp to register there with fewer time and logistical constraints than whilst on the beach, although still outdoors and faced with weather-related challenges. SFHS volunteers had better access to resources and fewer constraints working indoors, although the area was not heated. The availability of researchers to supervise SFHS during the initial process, answer questions, and guide the registration in the beginning was considered highly useful when done in 2023.

Volunteers did report challenges distinguishing certain litter items, or these challenges were made apparent later during data analyses and discussions. This pertained especially to different categories of rope and soft plastics. Some volunteers may have recorded all pieces of plastic film that could potentially have been a bag as plastic bags, rather than correctly classifying such pieces as unidentified soft plastic fragments. The motivation and willingness of SFHS students to attempt to determine provenance and age was reported as quite variable, and it was highlighted that clear policy goals and a usage for the data is vital to provides motivation for participants.

A need for more written resources was clearly identified. Numerous volunteers expressed a desire for more in-depth resources both to study in advance of litter registrations and for consultations during. Easy-to use pictorial guides with annotations showing and describing different litter categories and items, highlighting differentiating features, and a concise step-by-step protocol were requested as additional resources beyond a lengthy standard operating procedure document. Such resources were desirable in poster format for hanging on the walls in the facility where registrations take place.

Fig. 4. Pictures of litter items found by the Arctic Research Group (ARG) in and to the east of Rechecherfjorden in July 2023. Top row: Examples of items of potentially maritime origin. (a) Strapping bands. There are assumed to be of maritime origin under the Deep Dive protocol and classified as more general industrial waste under the "Rydde" protocol. (b) Piece of conveyor belt from onboard processing. Classified as maritime litter under the Deep Dive protocol, but classified as "unidentified plastic pieces" under the "Rydde" protocol. (c) Rope cut-offs from net mending. Bottom row: examples of packaging. (d) Chemical container with a date mould stamp. (e) Polish drinkable yoghurt carton. (f) Russian food packaging. Photos: Arctic Research Group.

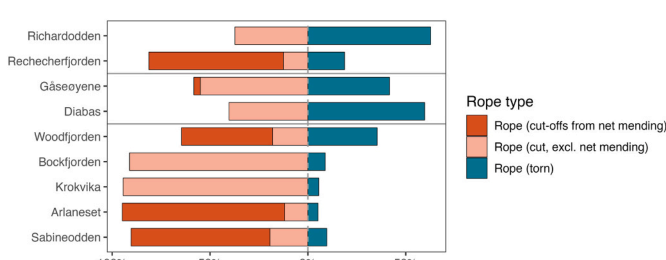

Fig. 5. Composition of rope analysed.

4. Discussion

4.1. Conclusions from the citizen science-generated data

The Atlantic Current transports water from southern parts of the North Atlantic north to the Barents and Greenland Seas, creating a clear potential for long-range transport of marine litter leaked into the environment in Europe or even North America (Cózar et al., 2017; Huserbråten et al., 2022; van Sebille et al., 2012). However, the relative importance of long-range transport *versus* local sources of litter in the Arctic remains uncertain. The observed presence of litter of varying European provenance (this study; Falk-Andersson et al., 2021; Meyer et al., 2023) supports the hypothesis that long-range transport of marine litter to the Arctic in general, and Svalbard in particular, does occur. However, items produced in different European or non-European countries are sold in Longyearbyen as well (*e.g.* milk and chocolate from Netherlands and/or Germany, Asian products in the local Thai-shop, or Russian products from Barentsburg or Pyramiden) or are transported to the archipelago on international cruise ships stocked or restocked at European ports. Currently the number of items for which both provenance and age have been determined is insufficient to decipher whether litter most likely drifted northwards from the North Sea region, were released from vessels or derived from local land-based sources.

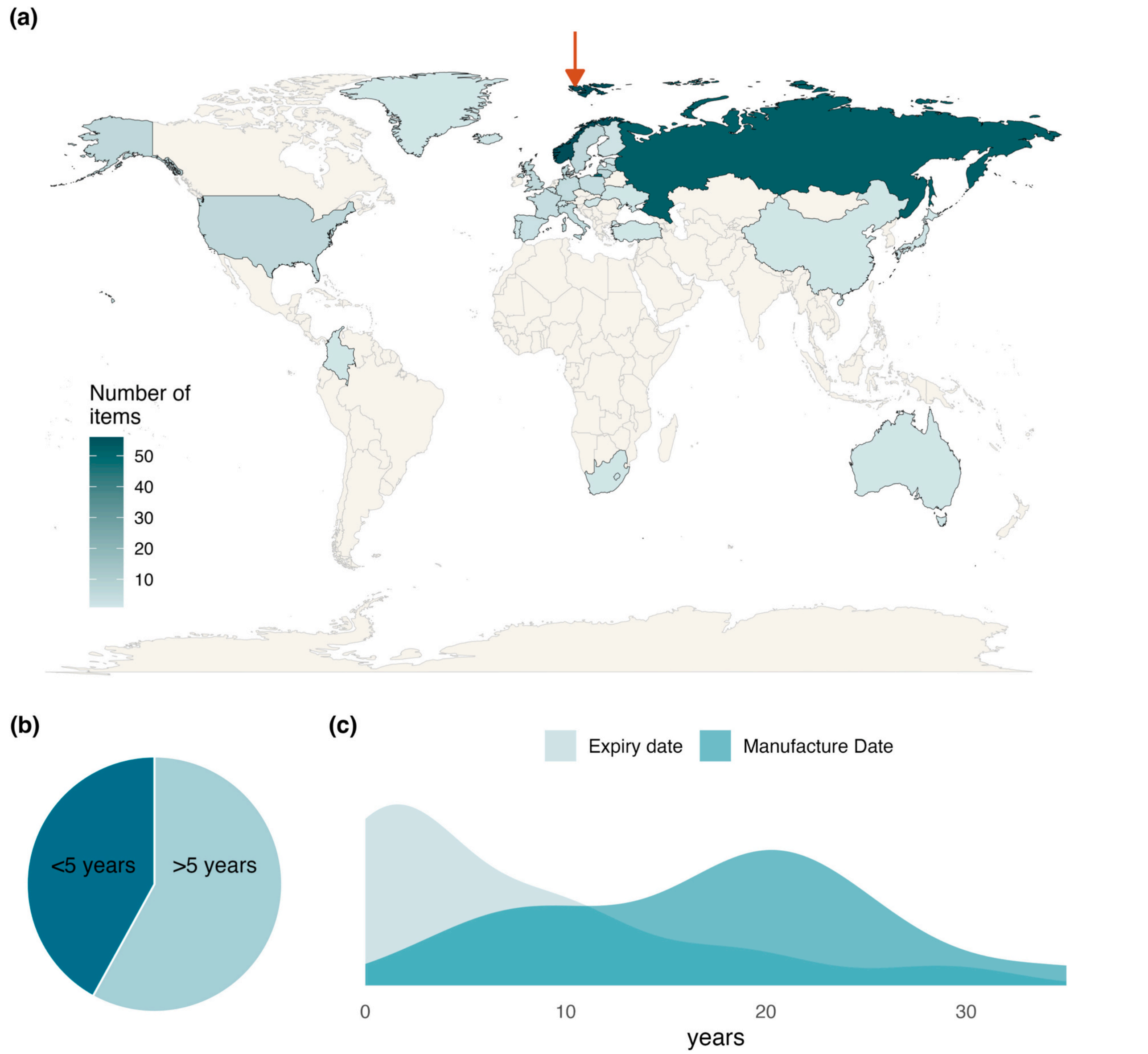

Fig. 6. (a) Map showing packaging provenance for the items for which this could be determine (all sites pooled). The red arrow shows the location of Svalbard. (b) Age distribution of dateable packaging ($n = 52$). Relative prevalence of items younger and older than 5 years. Categorical dateing could have been done based on expiry or manufacture date, design, logos, *etc.* (c) Density plot showing the age distribution of items dated to year using expiry ($n = 17$) or manufacture dates ($n = 15$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

While the amount of long-range transport remains somewhat uncertain, there is evidence of both regional and local litter sources. The predominance of Norwegian and Russian litter among items for which provenance could be determined suggests that significant leakages occur either from land along the borders of Barents Sea, from Svalbard itself, or from vessels from these nationalities, which constitute the key maritime players in the region (Vylegzhanin et al., 2018). Evidence is limited with respects to land-based macroplastics leakages from Svalbard, but the slightly different composition of beach litter observed from the Isfjorden sites in proximity to Longyearbyen compared to the remaining sites (as indicated by the NMDS plot) may reflect a degree of highly local emissions. Plastic waste found at the Hausgarten observatory in the Fram Straight found a correlation between number of tourist and fishing vessels with plastic densities over time, also suggesting local releases (Tekman et al., 2017). The much higher prevalence of expanded polystyrene (EPS/Styrofoam) in Isfjorden is consistent with another observation from the Norwegian Arctic showing disproportionate deposits of EPS close to settlements (Solbakken et al., 2022). Microfiber emissions from Longyearbyen are known to be very high given a lack of wastewater treatment (Herzke et al., 2021).

It is probable that the dominant source of litter on Svalbard are regional fisheries and other maritime activities. The observed proportion of sea-based litter in this, as well as other (Bergmann et al., 2017; Meyer et al., 2023), studies is higher than the global average of 22 % by abundance (Morales-Caselles et al., 2021). Note that this is only counting obviously sea-based items; other litter, such as food packaging and cleaning supplies, are also used on vessels and could have leaked directly from these (Morales-Caselles et al., 2021; Ryan et al., 2019). Furthermore, consumer related items common on beaches globally, such as plastic bags, cotton bud sticks, or cigarette butts (Morales-Caselles et al., 2021; Poeta et al., 2016; Roman et al., 2020) were rare. In general, relatively few items that could not conceivably have originated from onboard a vessel were found. An interesting exception was detonation cord, which although not extremely prevalent, was consistently found. Drift model backtracking of beach litter from the two OSPAR monitoring beaches on northwestern Spitsbergen also suggests litter stranding there originates primarily from within the Barents and Greenland Seas (Strand et al., 2021).

Consequently, the importance of regional fisheries and other maritime operations as a key pathway for litter to Svalbard beaches seems undisputed. Elucidating the exact sources, events and behaviours leading to littering, however, is more complex. For example, rope was common, a considerable portion of which had clearly been cut. While this may not necessarily indicate intentional dumping as cut-offs from net mending and other cut ropes may simply be left on deck or otherwise insufficiently secured and washed overboard, it does point to a behaviour where mitigation solutions can be explored, rather than events beyond the control of the individuals involved. Furthermore, several items linked to onboard processing and trawl activities in the Deep Dive protocol have been linked to intentional discards by stakeholders (Falk-Andersson, 2021). While it has been found that both attitudes and infrastructure affect waste management onboard vessels (Olsen et al., 2020), this is still an area with limited research.

4.2. Survey design considerations

Citizen science is a valuable asset to marine litter research and monitoring as volunteers can aid in collecting data over large geographic areas (McKinley et al., 2017; Popa et al., 2022). At the same time, it is not always clear to citizen scientists how the data they collect actually contribute to policy (Nelms et al., 2022), and authorities and researchers sometimes lack the necessary faith in the quality of citizen science to optimise its use (Vann-Sander et al., 2016) despite evidence that data collected through a well-designed citizen science project is of equal quality to conventional science (McKinley et al., 2017; van der Velde et al., 2017). One aspect of the design of citizen science based marine litter surveys that may limit its uses is the site selection procedure. A key framework behind classical statistical analyses is the probability that all members of a population for which one wishes to make inferences have an equal probability of being selected for sampling. This assumption is often violated in citizen science projects (Brown and Williams, 2019), including the present study. When a key objective is to remove marine litter from the environment, one typically targets polluted locations, resulting in a biased sample. This is the reason litter densities from cleaned beaches in this study were not compared to those reported elsewhere. Incorporating probability-based site selection into citizen science projects like this one would contribute to improve the generalisability of the results.

Working in remote regions of the Arctic, however, poses several challenges to probability-based site selection generally not faced when conducting field work in less remote regions. Travel to study sites can be costly and time consuming given limited to no road access, and requires safe landing spots from sea. Travel times by boat to sampling sites in this study varied from 1 to 30 h (Bockfjorden). Health and safety precautions are also considerably more complex. Extreme weather can restrict or prohibit landings and limit options for intra-annual repeated surveys. Distance from emergency services limits operation in difficult terrain with higher risks of injury, and the risk of polar bear encounters generates a need for active polar bear guards and can restrict landing. Obtaining extensive geographical and temporal replication can therefore be considerably more challenging in the Arctic. Such challenging working conditions also puts extra pressure on volunteers seeking to participate in citizen science, and limits the number of participants as either dedicated expeditions must be undertaken (as in this study) or existing, often exclusive, travel utilised (Bergmann et al., 2017; Meyer et al., 2023). The same limitations also largely apply to professional researchers who may be limited by insufficient funding to overcome the challenges of Arctic field work and obtain adequate sampling effort, further increasing the value of any citizen science participation in the region and the need to ensure well-designed, high quality data when they are collected.

4.3. Citizen scientist training and protocol complexity

An important factor influencing data quality in citizen science projects is the complexity and clarity of protocols used, and the quality and availability of volunteer resources (Brown and Williams, 2019; Kosmala et al., 2016). The “Rydde” protocol was first developed in 2015 (based on the Ocean Conservancy protocol) and modified slightly in 2020 to increase the extent of metadata and litter categories. The protocol has been used by thousands of volunteers since its inception and is thus well tested with various online resources available (see www.ryddenorge.no). There are nevertheless some weaknesses, including the lack of a clearly communicated purpose and use for the collected data (SALT, 2022). The Deep Dive protocol has clearly defined goals to provide necessary knowledge for management and policy makers (Falk-Andersson, 2021) and a web portal with online training resources suitable for citizen scientists has been attempted (see www.deepdive.grida.no) but not extensively tested, and lacks a formal connection to management bodies despite its desired use. Harmonisation of these two protocols aimed to extract the “best of both worlds”.

The added complexity of the Deep Dive protocol puts considerable added demands on volunteers and results can be prone to observer bias. Consequently, the addition of Deep Dive categories, if and when adopted, should be optional and limited to “super users” with above average motivation and training. Volunteers are asked to not only classify litter objects they likely recognise from everyday life, but also much more specific items, such as dolly rope, pieces of conveyor belt, the type of plastic film/sheeting used to package fish and bait during processing, the packaging tube rolls used to deliver this film, and more. While not quantitatively tested, the error rate for classification of these items is likely high among untrained individuals (both volunteers and professionals), despite online tutorials and picture guides being available. Testing of the error rate of super users would give useful insights into measures to maximise data quality.

The large variation among sites in the proportions of cut rope identified as cut-offs from net mending may be linked to the experience of the volunteers. Identifying cut-offs was an integral part of the training workshop with ARG and the proportion of cut ropes they identified as cut-offs was high. This was also the case for sites registered by SFHS when external researchers were present, while almost no cut-offs were registered when students had fewer options for verification of the difference between cut-offs from net mending and other cut rope and generally choosing to err on the side of caution. As litter was not independently registered by professionals beyond partial supervision with SFHS and manual checks of photos taken by ARG it is not possible to fully verify whether this was a real difference among sites or the result of observer bias or inexperience, but it does highlight the necessity of training and possibly oversight when the complexity of the protocol is increased.

The determination of provenance and age is prone to observer bias based on personal experiences with different products and nationalities, particularly when product design, logos and brands are allowed used for determination (Falk-Andersson et al., 2021). The willingness to conduct rigorous detective work, using for example online search tools, to determine age and provenance from available clues is also highly individual and dependent on internet access. Internet and cell phone services are frequently unavailable in remote regions, eliminating the possibility of using translation apps for identifying languages, conducting internet searches for brand distributions, brand and logo histories, and other potentially useful tools, reducing the percentage of items for which provenance and age can be determined when litter registration is done *in situ*. Photographing items can allow for identification at a later stage, but is unlikely to be practical if litter loads are high, particularly as it may be necessary to take multiple photos from different angles. Simplification of the protocol, for example only allowing date and text as indicators of provenance and age, could reduce bias (Falk-Andersson et al., 2021) and make data collection more efficient, yet would also reduce the proportion of items for which provenance and age can be estimated. Irrespective of the choice made, expectations with regards to the effort and tools to be used in determining provenance and age should be clearly specified during volunteer training and in guidance materials for standardisation to reduce observer bias.

The observation of volunteers during data registration provides scientists important insights into how training can be improved. Both observations during this study and of students receiving similar training at a course in Greenland (Haarr et al., 2023) confirmed the need for close observation and guidance when "super-users" conduct their first in-depth analysis. For ARG, all training had to be conducted independently in advance given their month-long expedition and continual *in situ* analyses of litter. Optimal data quality is likely achieved through a combination of solid pre-registration preparation combined with supervision and an opportunity to ask questions when first starting, but the ideal training approach may vary depending on the specific project and its logistics.

4.4. Future directions for citizen science in the Arctic

This study has demonstrated the potential for citizen scientists to contribute in-depth litter registration data relevant to management in the Arctic. To make the most of such efforts in the future, there are certain considerations. Adequate training and user-friendly protocols are key for both data quality and a good experience for the volunteers. As this study was a simple concept test, data sheets were set up in Excel with a series of drop-down menus and designed to be as user-friendly as feasible given available time for development. For broader use in the future this would need be further developed. Ideally an add-on for "super-users" would be established in the national Environment Agency portal (or another base app for use outside of Norway). Additionally, a user manual should be developed, including a detailed picture guide as a resource for consultation, not only of the different item categories, but also showing different methods of determining provenance and age. The latter could include, for example, lists of countries of distribution of different common brands, logo and design histories of common items, bottle return symbols for different countries, and clarification of countries and regions where different scripts are used for when insufficient words are discernable to precisely determine the language, as well as assumptions not to be made (*e.g.,* the English language is too broadly used to assume an origin; Lebreton et al., 2022). In addition to detailed guides, concise overview leaflets or posters with common questions and challenges should be produced and printed on waterproof materials for easy *in situ* access.

Management needs relevant data on litter sources, and answering this question is the reason for the Deep Dive add-on to the regular citizen science protocol. Some items are difficult to allocate to specific sources, however, and further research is needed to optimise data interpretation. Many items are used in multiple settings and identification of an item by experts and stakeholders does not guarantee that the identified source is the only possible one. Workshops with fishermen have revealed that bundles of intertwined strapping bands typically result from jammed machinery during onboard fish processing and subsequent dumping or potentially inadequate waste handling as the machinery is located below deck (Falk-Andersson, 2021). The same applies to tangled masses of (typically blue) film for packaging fish (Falk-Andersson, 2021). Yet this does not necessarily mean that single strapping band or all pieces of similar film stem from fishing vessels as these are items also used in other settings. Fishermen have also identified tubes of a certain diameter and length as the cores inside rolls of film used to package fish (Falk-Andersson, 2021), although note that similar tubes also serve as cores inside rolls of plastic wrap for silage bales used in agriculture (M.L. Haarr, personal observation). As strapping bands in particular are a very common item, and also one with high risk of wildlife entanglement, further research into the relative likelihoods of potential sources, as well as potential geographic differences in these, would greatly improve source allocation of marine litter both in the Arctic and elsewhere.

Analyses of litter age and provenance in combination with drift modeling and documentation of packaging brands and types sold locally (the latter of which also has potential as a citizen science initiative) has been successfully used to untangle the question of whether multiple-use items such as beverage bottles stem from long-range transport, local emissions, or passing vessels in other parts of the world (Ryan, 2020; Ryan et al., 2019). A similar analysis for beach litter on Svalbard would be highly useful, but would require, in addition to drift modeling, a large-scale litter collection effort to obtain an adequate sample size. Note that Meyer et al. (2023) also determined provenance for some items other than packaging (*e.g.,* certain buoys/trawl floats and boots). This should also be considered for Deep Dives. A Canadian lobster tag was found during this study, for example, but not expressly recorded as it did not fit into the protocol to do so.

4.5. Conclusions

Citizen science is a highly valuable addition to research and monitoring of marine litter in the Arctic and can be successful under different models from independent citizen science following training, to workshop-style litter registrations where volunteers also have access to scientists. Given the additional challenges of working in remote and harsh environments the demands on volunteers are higher and the access to them lower than elsewhere, placing added responsibilities on researchers for adequate training and preparation to ensure data quality, and to disseminate results to and engage with volunteers to maintain motivation. The harmonisation of a tried and tested standard composition citizen science protocol with an optional add-on for additional management and policy value for specially trained "super-users" is an effective way to add management relevance to data collected in both remote regions and elsewhere. Further work should be carried to out to ensure seamless harmonisation of these (and other) protocols, including user-friendly methods of data registration to safeguard both data quality and the experience of the volunteers. Volunteers participating in this study also added to the growing body of documentation suggesting that marine macro-litter in Arctic frequently stems from local, and predominantly maritime, sources despite the clear potential for long-range transport with currents.

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CRediT authorship contribution statement

Marthe Larsen Haarr: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Audun Narvestad:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **Jannike Falk-Andersson:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Stephen Staley:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Henry Staley:** Writing – review & editing, Investigation. **Joseph Cox:** Investigation. **Malin Dahl:** Writing – review & editing, Methodology, Investigation. **Helene Svendsen:** Writing – review & editing, Project administration. **Anna Sinisalo:** Writing – review & editing, Funding acquisition, Conceptualization. **Eike Stübner:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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