# DEEP DIVES INTO ARCTIC BEACH DEBRIS

## ANALYZING ITS COMPOSITION AND ORIGIN

Bachelor thesis

in Biology

of the Faculty of Mathematics and Natural Sciences
of the Christian-Albrechts-University to Kiel
&

ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR-
UND MEERESFORSCHUNG

submitted by
Anna Natalie Meyer
1137364

June 2022

FIRST EXAMINER: PROF. DR. DIETER PIEPENBURG, CAU

SECONDARY EXAMINER: DR. MELANIE BERGMANN, AWI

## Acknowledgements

A special thanks to Dr. Melanie Bergmann (AWI), for mentoring me throughout my thesis and making the project possible in the first place. And thanks to Prof. Dr. Dieter Piepenburg (CAU) for giving me the freedom to write and submit my thesis under his supervision.

My gratitude goes out to Birgit Lutz and the citizen scientists, the expedition crew and staff for planning and organizing the cleanups as well as collecting the debris. Without them this would not have been possible. I would also like to thank Niklaas Schmidt, Niklas Korfmann and the HIGHSEA class from 2019 for sorting debris and researching origin countries. Bruno Andreas Walther (AWI) instructed me with the FTIR and helped me with statistical analyses. And finally, thanks to Dr. Lars Gutow (AWI) for advice in times of need.

# Contents

# 1 Abstract

## 1.1 English

Plastic waste is ubiquitous in all ecosystems and has even reached locations humans may never reach such as the deep ocean floor and the atmosphere. Recent studies have highlighted that plastic debris is now pervasive in the isolated region of the Arctic. While modelling projections indicated local sources and long-distance transport as causes, empirical data about its origin and sources are scarce. Citizen scientists can increase the scale of observations, especially in those remote regions. Here, I analyze quantitative abundance and composition data of debris collected by citizen scientists on 14 remote Arctic beaches on the Spitsbergen archipelago. In addition, citizen scientists collected three big packs, here composition, sources and origin were determined. A total debris mass of 1,620 kg was collected on about 38,000 $m^2$ (total mean = 41.83 g $m^{-2}$, SEM = ± 31.62). In terms of abundance, 23,000 pieces of debris were collected on 25,500 $m^2$ (total mean = 0.37 items of debris $m^{-2}$, SEM = ± 0.17). Although most items were plastic in both abundance and mass, fisheries waste, such as nets, rope, and large containers, dominated in mass (87%) and general plastics, such as packaging and plastic articles, dominated in abundance (80%). Fisheries waste points to local sea-based sources from vessels operating in the Arctic. General plastics could point to land-based sources, riverine input, and ship waste, as debris is transported to the north via the oceans current. Overall, 1% of the items (206 pieces out of 14,707) collected in two big packs (2017 and 2021), bore imprints or labels allowing an analysis of their origin. Most items stem from nearby Arctic countries (local sources), such as Norway, Russia, Denmark/Greenland (48%) and Atlantic countries, which were mostly European (22%). Only 4% likely originate from more distant sources (USA, Brazil, China, etc.). International measures such as a globally accepted and obeyed plastic treaty with better waste management and upstream measures is urgently needed, to lower the amount of plastic entering our oceans and in turn lifting the pressure on the Arctic region and its sensitive biota.

## 1.2 German

Plastikmüll ist in allen Ökosystemen allgegenwärtig und hat sogar Orte erreicht, die der Mensch vielleicht nie erreichen wird, wie beispielsweise den Grund der Tiefsee und die Atmosphäre. Jüngste Studien haben gezeigt, dass Plastikmüll in der isolierten Region der Arktis mittlerweile allgegenwärtig ist. Während Modellierungsprognosen auf lokale Quellen und den Transport über weite Entfernungen als Ursachen hinweisen, gibt es nur wenige empirische Daten über Ursprung und Quellen. BürgerwissenschaftlerInnen können den Umfang der Beobachtungen erhöhen, insbesondere in diesen abgelegenen Regionen. Hier analysiere ich quantitative Daten zur Häufigkeit und Zusammensetzung von Müll, der von BürgerwissenschaftlerInnen an 14 abgelegenen arktischen Stränden der Inselgruppe Spitzbergen gesammelt wurde. Außerdem sammelten die BürgerwissenschaftlerInnen drei große Müllpakete, deren Zusammensetzung, Quellen und Herkunft bestimmt wurden. Auf etwa 38.000 $m^2$ wurde eine Gesamtmüllmasse von 1.620 kg gesammelt (Gesamtmittelwert = 41,83 g $m^{-2}$, SEM = ± 31,62). Was die Häufigkeit betrifft, wurden 23.000 Müllteile auf 25.500 $m^2$ gesammelt (Gesamtmittelwert = 0,37 Müllteile $m^{-2}$, SEM = ± 0,17). Obwohl die meisten Gegenstände sowohl in Bezug auf die Menge als auch auf die Masse aus Kunststoff bestanden, dominierten Fischereiabfälle wie Netze, Taue und große Behälter in Bezug auf die Masse (87%) und allgemeine Kunststoffe wie Verpackungen und Kunststoffartikel in Bezug auf die Menge (80%). Fischereiabfälle deuten auf lokale, seegestützte Quellen von in der Arktis operierenden Schiffen hin. Allgemeine Kunststoffe könnten auf landgestützte Quellen, Flusseinträge und Schiffsabfälle hinweisen, da die Abfälle über die Meeresströmungen in den Norden transportiert werden. Insgesamt trugen 1% der Gegenstände (206 von 14.707), die in zwei Paketen (2017 und 2021) gesammelt wurden, Aufdrucke oder Etiketten, die eine Analyse ihrer Herkunft ermöglichen. Die meisten Gegenstände stammen aus nahegelegenen arktischen Ländern (lokale Quellen) wie Norwegen, Russland, Dänemark/Grönland (48%) und aus atlantischen Ländern, die meist europäisch sind (22%). Nur 4% stammen wahrscheinlich aus weiter entfernten Quellen (USA, Brasilien, China, usw.). Internationale Maßnahmen wie ein weltweit akzeptiertes und eingehaltenes Plastikabkommen mit besserer Abfallbewirtschaftung und vorgelagerten Maßnahmen sind dringend erforderlich, um die Menge an Plastik, die in unsere Ozeane gelangt, zu verringern und damit den Druck auf die arktische Region und ihre empfindliche Biota zu reduzieren.

# 2 Introduction

Persson et al. (2022) report that the safe operating space of the planetary boundary for novel entities (man-made substances including chemicals and plastics) is exceeded, as production and releases are increasing at a pace that surpasses the global capacity for assessment and monitoring. This corresponds with the consensus that plastic debris is ubiquitous in all global ecosystems and has even reached and remote Arctic beaches (Bergmann *et al.*, 2017b) and isolated locations, most of them will never be reached by humans, such as the atmosphere (Li *et al.*, 2021) and the deep seafloor (Canals *et al.*, 2020). The Arctic is no longer seen as "one of the last unspoiled ecosystems" on planet Earth, but an ecosystem very likely to be a sink for marine anthropogenic debris with tendencies to increase (Parga Martínez *et al.*, 2020) given the predicted annual global plastic production reaching 1.1 billion metric tons by 2050 (Geyer, 2020). Furthermore, the growth of a sixth accumulation area has been predicted in the Nordic Seas (Onink *et al.*, 2019; van Sebille *et al.*, 2012). And with temperatures rising the sea ice extent decreases giving plastic debris the chance to travel further into the Arctic (Bergmann and Klages, 2012). This exasperates the pressure on sensitive Arctic biota, such as polar bears, seals, and seabirds (Bergmann *et al.*, 2017a). The consequences could be serious, as wildlife become entangled in nets or rope or ingest plastic debris (Bergmann *et al.*, 2022; Bergmann *et al.*, 2017b; Collard and Ask, 2021). This is also observed in the Arctic, as most recorded waste is related to the fishing industry, with items getting lost or being disposed of at sea (Bergmann *et al.*, 2017a; Nashoug, 2017). The primary sources of general beach debris are often littering beach-goers and buoyant waste washing ashore (Ryan *et al.*, 2021). However, the population of Svalbard is small and mostly concentrated to Longyearbyen. Therefore, it is very unlikely that the former is the primary conductor of the amount of beach debris found on the numerous remote Arctic beaches analyzed in this study.

Although recent research has shown the presence of plastic debris in some compartments of the Fram Strait such as the water surface, the deep ocean floor, the water column (Bergmann *et al.*, 2015; Grøsvik *et al.*, 2018; Tekman *et al.*, 2017), such observations do not allow definite conclusions as to the provenience of the debris. Modelling patterns indicate that a large part of debris drifts northwards with the Atlantic or originates from local sources (Pogojeva *et al.*, 2021), however empirical evidence is still lacking. Beaches on remote islands intercept prevailing water currents and the debris they carry (Lavers and Bond, 2017), therefore the collection of physical samples for analyzing the origin of the debris may be a good approach.

Citizen science (CS) projects are increasing in the research community as they provide many benefits. With correct preparation and simple strategies CS can obtain a large volume of data at a low cost with a high temporal coverage (Walther *et al.*, 2018). Furthermore, they cover a considerable spatial area (Nelms *et al.*, 2017), this gives researchers the opportunity to obtain samples from sensitive remote ecosystems (Bergmann *et al.*, 2017a) on a local, regional and international scale (Hidalgo-Ruz and Thiel, 2015). In times of the Covid-19 Pandemic, where travel was limited and a surge of production, consumption and disposal of single use plastics occurred the importance of citizen science became even more apparent (Ammendolia and Walker, 2022). In addition, science and research is brought to citizens in an easy and comprehensive manner. This can have educational value, as it raises awareness of environmental issues and can lead to positive changes in behaviors (Nelms *et al.*, 2017).

I analyze debris data from 17 Arctic beaches, including three big packs filled with Arctic beach debris collected by citizen scientists on Svalbard. I quantify the composition of collected debris to determine the debris mass and abundance per $m^2$, to define how polluted Arctic beaches are. I analyze the differences and similarities between the beaches and collected debris, to determine if different factors, such as marine region, exposure and beach type (substrate) cause dissimilarities in quantities or composition. Also, do the transect area size and the number of observers cause differences in quantities and composition? I am particularly interested in defining the provenience of the debris to determine if items come from local or distant sources. Furthermore, I inspect debris items for date imprints to assess their age and estimate the approximate time of pollution. In addition, I analyze if items can be assigned to a certain sector and in connection with that, what the debris entry points into the ocean could be: land-based or sea-based sources, possibly ship waste? Knowledge of quantities, composition, and sources will tailor adequate solutions to reduce plastic in the Arctic, especially with sensitive Arctic biota in mind. Also, it highlights how important it is to not only instill better waste management but create upstream measures such as a global plastic treaty, with production caps enabling a circular economy. This would help lower the amount of plastic entering our oceans and washing ashore (Borrelle *et al.*, 2020; Lau *et al.*, 2020) and in turn would lift the pressure on all ecosystems, especially the Arctic region and its wildlife, as it already experiences stress due to climate change and global warming (Bergmann *et al.*, 2022).

# 3 Material and methods

## 3.1 Study sites

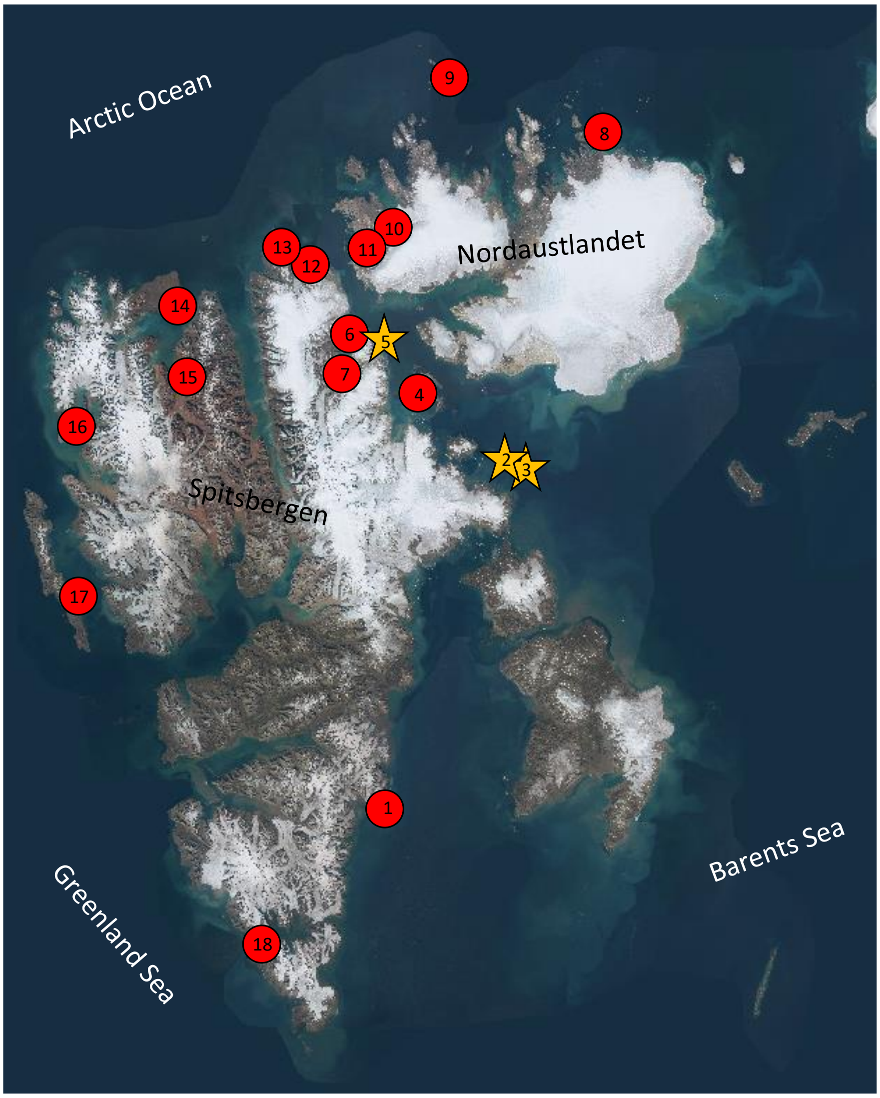



*Figure 1. Red dots represent 15 beach locations around Svalbard, that were monitored by citizen scientists, numbered in order of surrounding Svalbard. Stars mark the locations where big packs were collected. (Map © Norwegian Polar Institute).*

All sampling campaigns were organized by the expedition guide Brigit Lutz during tourist cruises to Spitzbergen archipelago in the Arctic. Citizen scientists carried out the surveys, which took place between 2016 and 2021. Due to the pandemic, cruises had to be paused in 2020. Seventeen transects were monitored in total on various islands and beaches on Svalbard (Fig. 1). Beach selection depended on cruise schedule, weather, and sea conditions. Most beaches were located on the two largest islands of Svalbard: Spitsbergen and Nordaustlandet. Though beaches on smaller islands were surveyed as well, such as Brucebukta on Prince Karls Foreland (beach 17).

With surveys taking place on different beaches, come various factors that could affect the quantity or composition of the collected debris. The effects of six factors were distinguished with different category levels. The four categorical factors included “Marine region” (Arctic, Barents Sea, Greenland Sea), “Substrate” (sand, pebble, rock, mix), “Exposure” (bay, fjord, strait, open ocean) and “Wood frequency” (none, medium, high). Driftwood from the Siberian forestry can affect the amount of debris as it gets washed ashore on Arctic beaches and traps significant amounts of debris behind it. The two numerical factors were “Transect area size” and “Observer number”. A list of all beaches surveyed is provided in Tab. 1.

*Table 1. Geographically sorted surveyed beaches. Numbers correspond with those used in Fig. 1.*

| # | Beach |
|---|---|
| **1** | Boltodden |
| **2** | **Kiepertøya 1** |
| **3** | **Kiepertøya 2** |
| **4** | Wijkanderøyane |
| **5** | **Tommelen** |
| **6** | Lomfjord 1 |
| **7** | Lomfjord 2 |
| **8** | Alpiniøya |
| **9** | Isflakbukta |
| **10** | Sørvika 1 |
| **11** | Sørvika 2 |
| **12** | Crozierpynten |
| **13** | Sorgfjord |
| **14** | Reindiersodden |
| **15** | Wigdehlpynten |
| **16** | Krossfjord |
| **17** | Brucebukta |
| **18** | Gåshamna |

A way of how debris reaches the Arctic is through the oceans current (Huserbråten *et al.*, 2022), when its origin is south of Svalbard. One of the main currents effecting Svalbard is the Atlantic domain, it runs Atlantic water counter-clockwise along the Eurasian continental shelf, streaming along western Svalbard and then parting in the north, down the coast of Greenland and along the Nansen Basin (Huserbråten *et al.*, 2022). Furthermore, the currents surrounding Svalbard are the Transpolar Drift, which streams from the East Siberian continental shelf through the North Pole to East Greenland and the Beauford Gyre, in the north of Alaska (Aliani *et al.*, 2020).

### 3.1.1 Provenience study sites

In three of the transects, located in Hinlopen Strait (Fig. 1) the debris was collected and sent to AWI in Bremerhaven for a more thorough investigation, which is not possible under harsh Arctic conditions. Those big pack beaches were located on smaller islands in the Hinlopen strait, the waterway that separates Spitsbergen and Nordaustlandet. It is ca. 150 km long, between 10 and 60 km wide and more than 400 m deep. Its current shows a linear NW-SE feature (Pfirman and Milliman, 1987).

## 3.2 Survey and sampling design


*Figure 2. Photos taken during surveys. A: measuring of transect area, C: items needed while on isolated Arctic beaches (including rifle and measuring tape), B & D: citizen scientists collecting debris. (All pictures © B. Lutz).*

All transect areas were laid out before taking samples, using a hand-held GPS device (Garmin eTrex 30 x) the geographic position of the corners of the transects, as well as their length and width were determined. The citizen scientists combed through those areas and collected all anthropogenic items larger than 0.2 cm (Fig. 2). All items were sorted into different categories of debris, weight and abundance were determined and noted on monitoring forms along with beach properties and other metadata. The weight was measured with a spring scale provided to the citizen scientists (KERN 285-052: ≤ 5 kg and 285-502; ≤ 50 kg; ± 0.3% accuracy; Fig. 3).

Photographs were taken for a plausibility check. Polar bear watches were present during all sampling events.

### 3.2.1 Sampling for provenience

The first big pack was collected on a north-facing beach on Kiepertøya (Beach 2) in 2017, an island located in the south of the Hinlopen Strait. The transect area (79°58.685 N / 021°39.480 E) was calculated after sampling, as it was located around a bay (~200 $\times$ 20 m = 3999 $m^2$). The second one was filled on Tommelen (Beach 5), an island which is part of the small archipelago of Tommeløyane, further north in the Hinlopen Strait. The sack was collected in a transect area of 600 $m^2$ (79°33.200 N / 018°44.940 E). Here the sides of the rectangle measured a = 20 m, b = 30 m, c = 28 m, and d = 8 m. I calculated the area using the “Theorem of Pythagoras”. Debris for the third big pack was once more collected on Kiepertøya (Beach 3). Though a different beach, also facing north, was surveyed. The transect area was laid out at 78°58.655 N / 21°40.081 E and 78°58.580 N / 21°40.343 E. The measuring tool from TopoSvalbard (Norwegian Polar Institute) helped calculate a length of 163 m between the coordinates. The width was determined on site with 15 m from the shoreline (= 2520 $m^2$). In the cases where the citizen scientists sampled for provenience, only pieces that did not fit in the big packs, where then documented on the survey forms and/or photographed.

## 3.3 Categorizing debris

### 3.3.1 Beach monitoring forms

The survey sheets were filled out by the citizen scientists while on site and collecting debris. The forms list various different debris types, such as fishery waste (nets, rope, floats) and other plastics, paper, glass/ceramics, biotic waste, etc. They were co-developed with the expedition leader, aiming for a simple, quick, and feasible design amenable to citizen science under Arctic conditions. Over the years improvements have been made, such as a more distinguished categorization of debris. In addition, the abundance of debris was recorded using a tally chart (Fig. 3) since 2017.

### 3.3.2 Big packs

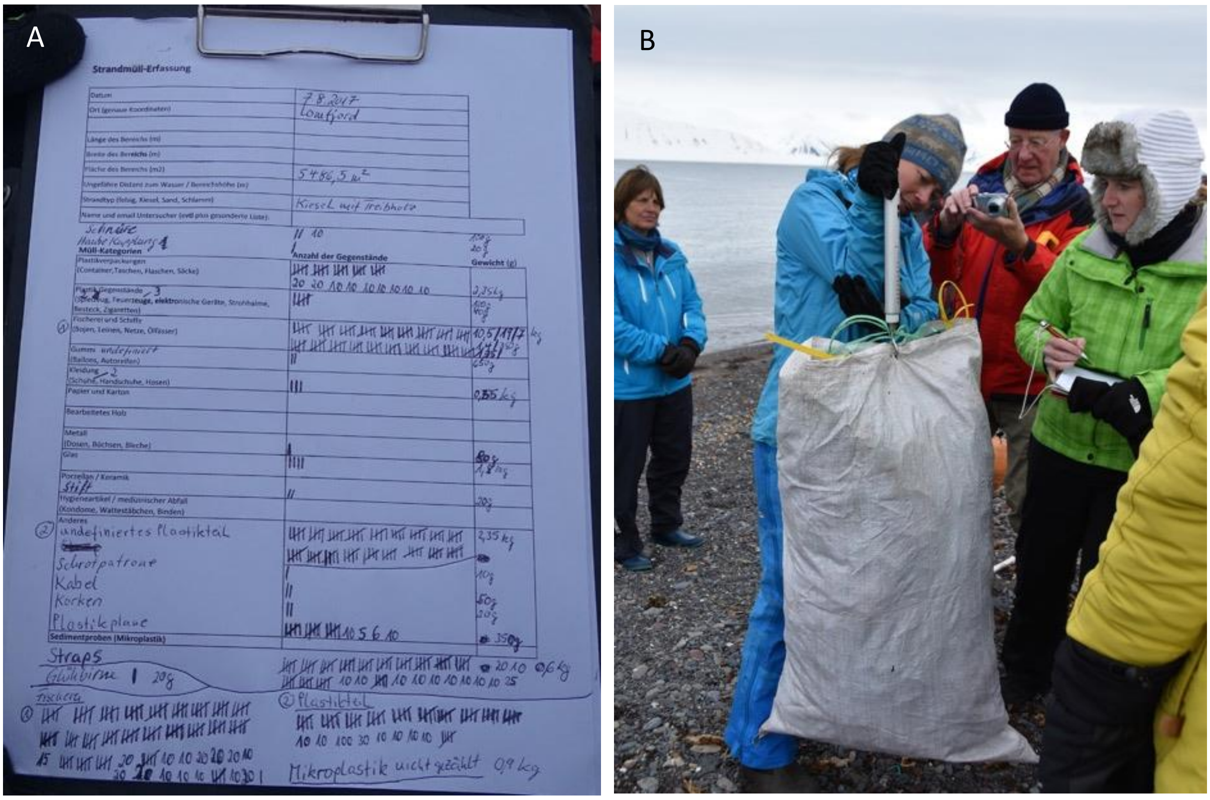



*Figure 3. A: beach monitoring form (© B. Lutz), B: bag of strapping bands being weighed using a spring scale (source: B. Lutz).*

The big packs were sent to the AWI, where they could be analyzed in more detail in the absence of ship constraints and polar bears. Each big pack was inspected by a different group of people, though all done or supervised by Melanie Bergmann (MB). The big pack from 2017 was inspected by MB, Lars Gutow (LG) (AWI) and a student extern, Niklaas Schmidt. The debris from 2019 was categorized by HIGHSEA students at AWI. I inspected the debris collected in 2021, forming the basis for the categorization of different types (Tab. 2). I went over some of the debris items collected in 2019 as well. During the categorization process of all three big packs all items with markings, writing or imprints on them were put aside to analyze closely on their origin country.

*Table 2. Material and categorization of big pack debris, with examples (n.d. = not defined)*

| Material | Category | Examples |
|---|---|---|
| Plastic | Fishery/shipping plastic | Nets, rope, large containers (jerry cans, canisters, etc.), crates, fish boxes, floats |
| | Strapping bands | Plastic straps often used on pallets |
| | Foil | Foil often used to wrap fish |
| | Plastic article | Lighter, bullet casing, tape, canvas, toothbrush, toy, helmet, flashlight |
| | Foam | Styrofoam, other foam |
| | Plastic packaging | Bottles, caps, food containers |
| | Sanitary/medical waste | Syringes |
| | Rubber | Shoes, balloon parts, rubber gloves |
| | Unidentifiable plastics | Not identifiable plastics, fragments |
| Metal | Fishery/shipping metal | metal buoy |
| | Metal | shotgun cartridge, metal ring |
| Glass | Glass | bottle |
| Paper | Paper | cardboard |
| Wood | Manufactured wood | cork, pieces of planks |
| n.d. | Other | material of debris is not defined |

All debris that could be, without any doubt, identified as items from the fishing/shipping industry, were categorized as such, examples include rope and nets, fish boxes and crates. They were not categorized as other plastics, as vessels operating in waters near Svalbard are possible sources for marine debris found on the surveyed beaches. Where there is uncertainty, e.g., with strapping bands and plastic foil, they are listed separately, when possible.

## 3.4 Provenience

All items bearing markings, writing, labels, or imprints, where scrutinized to determine their country of origin (hereafter: provenience). The term “Country of origin” refers to the country that an item was most likely produced in. This process was done for all three big packs. In 2017, MB, LG and Niklaas Schmidt determined the provenience. In 2019, it was determined by HIGHSEA students, FÖJ volunteer Niklas Korfmann under supervision of MB. Items collected in 2021 were analyzed by myself. If necessary, a magnifying glass or binocular was used for a closer examination of items collected in 2019 and 2021.

### 3.4.1 Provenience analysis of items from Kiepertøya (2021)

In order to determine the provenience, all items with writing, markings or imprints were characterized: each individual item was weighed, photographed, writing was copied and, if necessary, translated. In some cases, “Google Lens” was used. By hovering the phone camera over an item, this tool can translate the language, find pictures of similar looking items or identical items online and more. This helped me get an overview of an item or even define what it is or what it was used for. The provenience was determined according to the following methods: (1) geographic information; (2) language (if multiple languages were shown, the language listed first was used); (3) company information (in some cases, inquiries were made regarding production country and date etc.); (4) barcode. In addition, items that are distributed by a global company (e.g., Tetra Pak, Nestlé, Coca Cola) were classed as “Global”. The category “English language” was used for items with English writing, which cannot be assigned to the UK with absolute certainty. Fig. 4 shows examples of items, classification and methods. Once the country of origin was determined, the debris was categorized according to Tab. 2.


*Figure 4. Photographs of items for which the provenience was determined, thus A = Global, B = Germany, C = Norway, D = Russia, E = Italy, F = Global, G = Global, H = Sweden, I = Denmark, J = English language.*

## 3.5 Fourier transform infrared spectroscopy (FTIR)

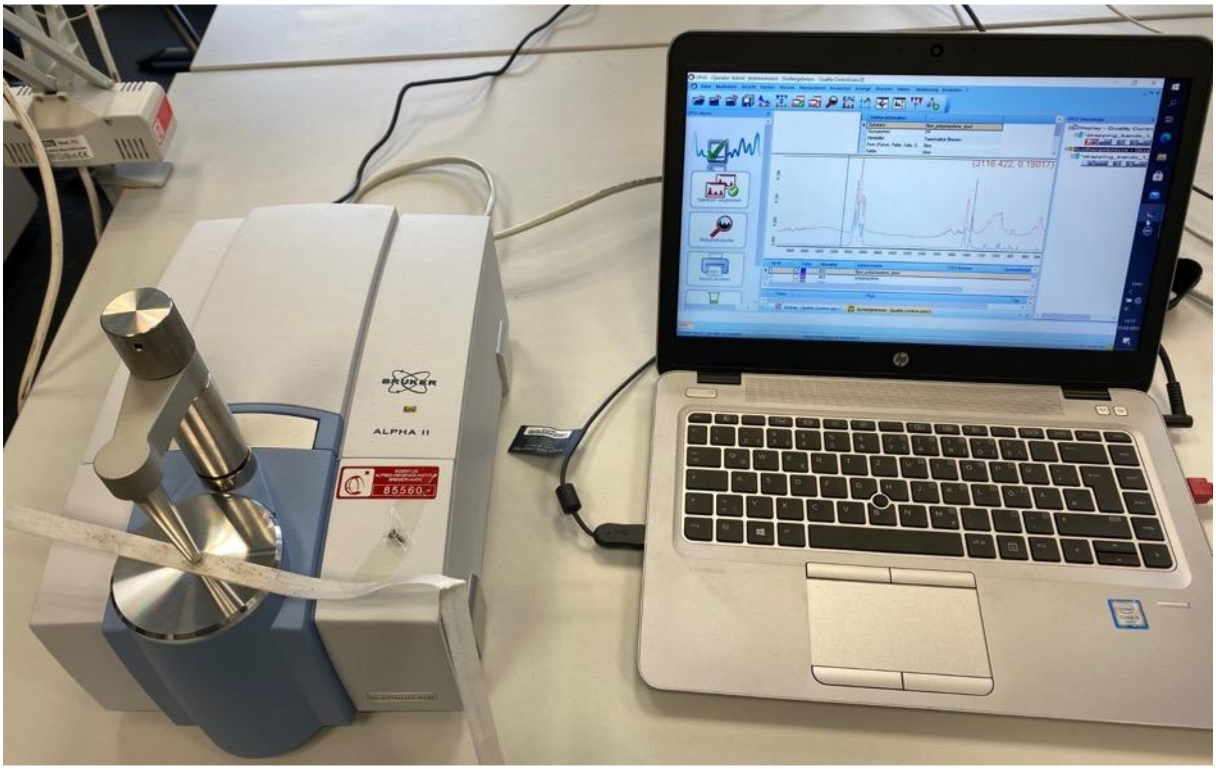



*Figure 5. FTIR in use, measuring the spectrum of a strapping band. Item is screwed in place with the pressure screw, under it lies the crystal. Computer screen shows the OPUS software: spectrum and polymer (Fiber polypropylene dyed).*

The polymers of all items collected in 2019 and 2021, for which the provenience could be determined and a physical item was still available, were determined by attenuated total reflection Fourier transform infrared spectroscopy (ATR-FTIR). In addition, rope and strapping bands were analyzed to confirm their polymer identity. Here, 12.5% of all ropes (82 ropes out of 657 in total) and 1% of all strapping bands (20 out of 1819) were randomly selected.

FTIR measurements were taken by an ALPHA II model (Bruker Optics; Fig. 5). It features a high throughput of zinc-selenium crystal and generates a specific infrared spectrum of absorption/emission of the debris. The item in question is fastened by a pressure screw with the crystal underneath. Using the software OPUS, the spectrum is visualized and can be compared to others in the database, to determine the polymer the debris is made from. Spectra with a hit quality (0-1000) above 700 were deemed satisfactory. For further analyzing and to compare/verify results, I use the open AWI software siMPle (Primpke *et al.*, 2020), which also compares spectra. Here the hit quality range lies between 0.01 and 1 and the threshold of 0.7 is used. This program was used for making the final decisions on the material types, as the hit qualities were higher than OPUS.

## 3.6 Statistical methods

### 3.6.1 Numerical and categorical factors

All survey data were converted to number or weight per square meter to enable comparisons. To analyze the data, I investigated six factors that could influence the abundance, weight, and composition of beach debris (Tab. 3). The factor "Marine regions" was determined with the map shown in Supplementary Figure 1. There are four water masses around Svalbard and three of them acted as a basis for the levels in Tab. 3. as there was no beach surveyed on the fourth region which would be the Norwegian Sea. "Exposure" was determined from the photographs provided and by consulting citizen scientists. "Beach type" (substrate) had been recorded during the surveys and was compared with the photos provided. Driftwood quantities were estimated during surveys and from photos as well. The numerical factors "Transect area size" and "Number of observers" were recorded during landing, although for some transects this had to be determined from photos afterwards.

*Table 3. Categorical factors generated to analyze the collected debris.*

| Factor | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| **Marine region** | Arctic Sea | Barents Sea | Greenland Sea | - | - |
| **Wood** | None | Medium | High | - | - |
| **Exposure** | Fjord | Ocean | Bay | Strait | - |
| **Substrate** | Sand | Pebble | Rock | Sand, Pebble | Sand, Rock |

### 3.6.2 Beached debris

Data analysis was run on data from all beaches, excluding the big pack beaches Kiepertøya 1 and 2 and Tommelen since methods used in the laboratory were not comparable with the beach surveys. An ANOSIM was ran to determine dissimilarity of debris compositions regarding the factors outlined above (Tab. 3), using PRIMER-e. A SIMPER routine of PRIMER-e was performed to determine, which debris categories explained the observed dissimilarity best. The relationship between total mass or abundance and the numerical factors "Transect area size" and "Number of observers", was assessed using the Spearman rank order correlation and the Pearson correlation. To test the categorical factors "Marine regions", "Substrate", "Exposure" and "Wood" on differences regarding "total mass" and "total abundance" and "total mass of plastic" and "total abundance of plastic", an ANOVA including a Tukey Comparison was run. A Kruskal-Wallis Test was used if log- or square root transformed data failed the test for two variances or data were not normally distributed.

# 4 Results

## 4.1 Arctic beach debris surveys


*Figure 6a. Overview of sampled beaches in geographical order.*


*Figure 6b. Overview of sampled beaches in geographical order.*

Figures 6a and 6b give an impression of most sampled beaches, showing the degree of pollution and the metadata. This excludes Boltodden, Kiepertøya 2, Lomfjord 1, Isflakbukta, Wigdehlpynten and Gåshamna as no suitable pictures were taken.

### 4.1.1 Abundance of debris determined during citizen science beach surveys

I pooled the abundance data for all nine beaches (Fig. 7). In total 8,299 pieces were collected on ca. 19,000 m$^2$, resulting in 0.27 pieces of debris m$^{-2}$. However, the mean of all nine beaches was at 0.37 items m$^{-2}$ (± SEM = 0.17). The most common material observed was plastics (99.6%), including both general (76.9%) and fisheries/shipping plastic (22.7%) (Fig. 7).

The highest abundance was recorded at Sørvika and Wigdehlpynten (1.3 items m$^{-2}$) with general plastic dominating (Tab. 4). In contrast, no debris was found in transects on Boltodden and Gåshamna. The only location, where more fisheries/shipping plastic than general plastic was observed is Wijkanderøyane (93% vs. 7%). Tab. 4 summarizes the characteristics, debris quantities and composition of all beaches.

The Spearman rank order correlation between number of debris items and our two numerical factors showed a significant positive correlation for “Transect area size” ($N = 9$, $rho = 0.76$, $p = 0.020$) and “Observer number” ($N = 9$, $rho = 0.86$, $p = 0.003$) indicating that a larger transect area and a higher number of helpers can lead to a higher debris abundance. Multivariate analyses did not show significant dissimilarity between groups for most factors. Only a few factors could be tested, though, because of an uneven spread of the data among categories with less than three replicates for some factors levels (Supplementary Figure 2). There was significant dissimilarity between different types of "exposure" ($N = 9$, $r = 0.611$, $p = 0.016$), especially in the debris composition of fjordic and open ocean beaches ($r = 0.964$, $p = 0.048$), which was primarily caused by plastic (45%). There was also significant dissimilarity between different "substrate" ($N = 9$, $r = 0.665$, $p = 0.015$), especially in the debris composition of beaches characterized by pebble versus sand/pebble ($N = 9$, $r = 0.927$, $p = 0.048$), which is also mostly caused by plastics (43%). For all statistical results see supplementary material 8.2.

*Table 4. Details of beach surveys undertaken by citizen scientists on Svalbard. All debris abundances are given in number m$^{-2}$. p: plastic, me: metal, n.d.: material not defined; Substrate type: P: pebble, S: sand, R: rock. (*) Area calculation based on GPS corner coordinates.*

| | Boltodden | Wijkanderøyane | Lomfjord 1 | Lomfjord 2 | Sørvika 1 | Sørvika 2 | Wigdehlpynten | Krossfjord | Gåshamna | Total sum | Mean | SEM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Date** | 08.08.21 | Jan 2019 | 07.08.17 | 06.08.18 | 23.08.17 | 11.08.21 | 17.09.17 | 15.08.21 | 07.08.21 | | | |
| **Longitude (°N)** | 77°30.048 | 79°20.391 | 79°32.88 | 79°25.50 | 79°57.334 | 79°56.491 | 79°23.991 | 79°09.452 | 76°56.395 | | | |
| **Latitude (°E)** | 018°12.525 | 019°28.430 | 018°02.10 | 017°46.03 | 018°37.941 | 016°43.378 | 013°58.632 | 011°38.303 | 015°48.593 | | | |
| **Distance to water (m)** | 0 | 0 - 2 | 1 - 30 | 0.5 | 0.5 | 0 | 7 | 0 | 0 | | | |
| **Substrate** | S, P | R | P | P | P | P | S, R | P | S, P | | | |
| **Exposure** | Ocean | Strait | Fjord | Fjord | Strait | Fjord | Fjord | Fjord | Ocean | | | |
| **Marine region** | Barents Sea | Barents Sea | Barents Sea | Barents Sea | Barents Sea | Greenland Sea | Greenland Sea | Greenland Sea | Greenland Sea | | | |
| **Observer number** | 1 | 23 | 20 | 30 | 26 | 1 | 26 | 2 | 1 | | | |
| **Driftwood frequency** | n.a. | None | None | Low | High | Medium | n.a. | Low | n.a. | | | |
| **Survey length × width (m)** | 100 × 10 | 65 × 24 | n.a. | 422 × 5 | n.a. | 112 × 15 | 179 × 15 | 130 × 15 | 50 × 10 | | | |
| **Transect area (m²)** | 1,000 | 1,560 | 5,487* | 2,110 | 2,048* | 1,680 | 2,685 | 1,950 | 500 | 19,020 | 2,113 | 472.52 |
| **Fishery/shipping (p)** | | 0.03 | 0.08 | 0.06 | 0.53 | 0.01 | 0.02 | 0.05 | 0 | 0.79 | 0.09 | 0.06 |
| **Plastic** | | 0.003 | 0.14 | 0.19 | 0.76 | 0.01 | 1.24 | 0.16 | | 2.51 | 0.28 | 0.14 |
| **Clothing/textiles** | | | | | | | 0.001 | | | 0.001 | 0.0002 | 0.0002 |
| **Fishery/shipping (me)** | | | | | 0.0005 | | | | | 0.0005 | 0.0001 | 0.0001 |
| **Metal** | | | 0.0002 | 0.0009 | 0.002 | | 0.0007 | | | 0.003 | 0.0003 | 0.0001 |
| **Glass/ceramics** | | | 0.0009 | | | | 0.001 | 0.001 | | 0.003 | 0.0004 | 0.0002 |
| **Biotic** | | | | 0.0005 | | | | | | 0.0005 | 0.0001 | 0.0001 |
| **Manufactured wood** | | | 0.0007 | 0.0005 | 0.0005 | | | | | 0.002 | 0.0002 | 0.0001 |
| **Other (n.d.)** | | | | | | | | 0.0005 | | 0.001 | 0.0001 | 0.0001 |
| **Total sum** | **0** | **0.04** | **0.22** | **0.26** | **1.29** | **0.02** | **1.26** | **0.22** | **0** | **3.31** | **0.37** | **0.17** |

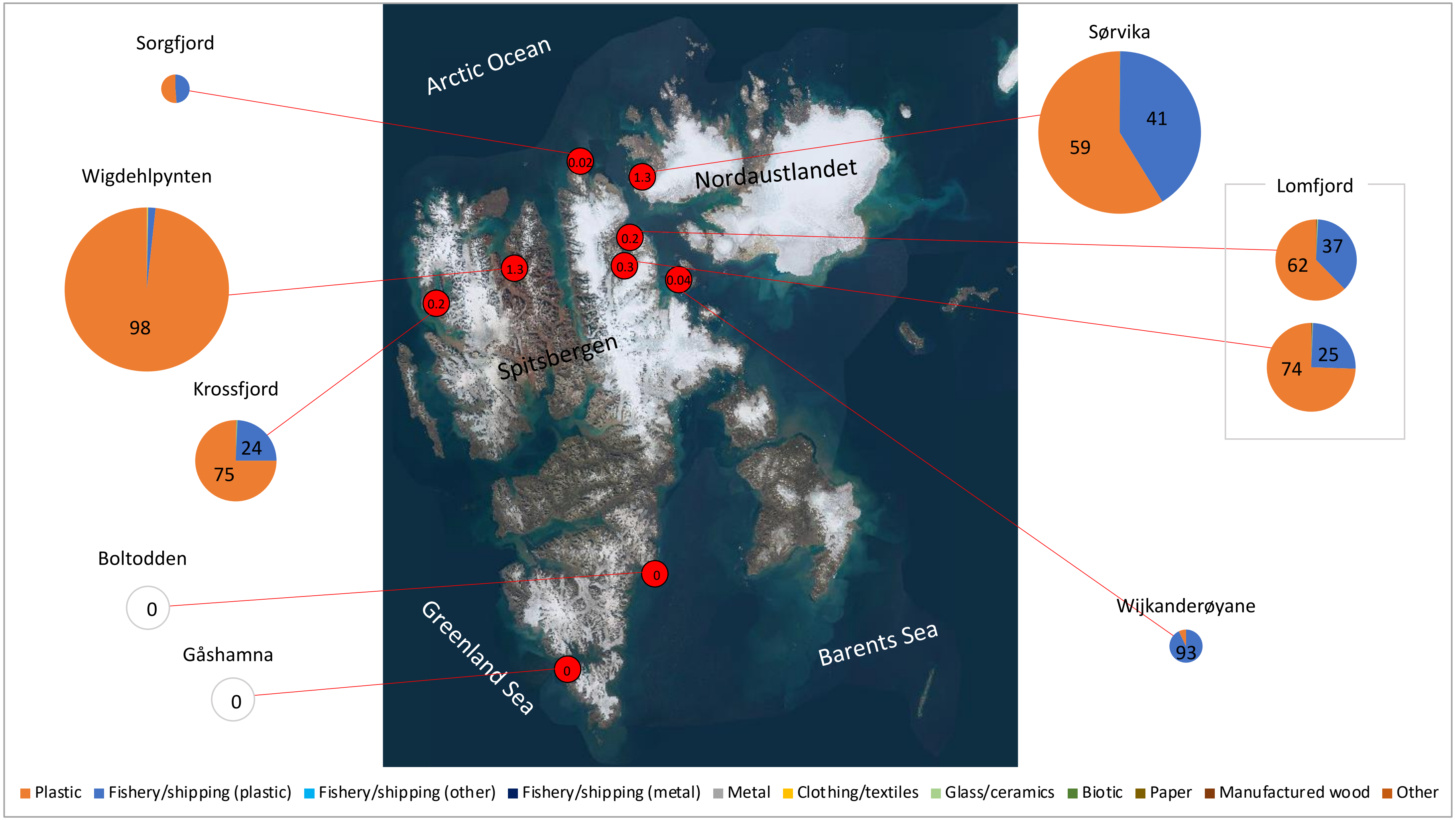



*Figure 7. Map of all locations of beach debris surveys (abundance) represented with red dots, with number of items collected per m$^2$. Which is also represented by the relative size of the respective pie chart showing the rounded proportions of debris categories. The relative size of the pie charts is based on LOG (x+1) transformed abundances, in order to enable a valid representation. (Map © Norwegian Polar Institute).*

### 4.1.2 Mass of debris determined during citizen science beach surveys

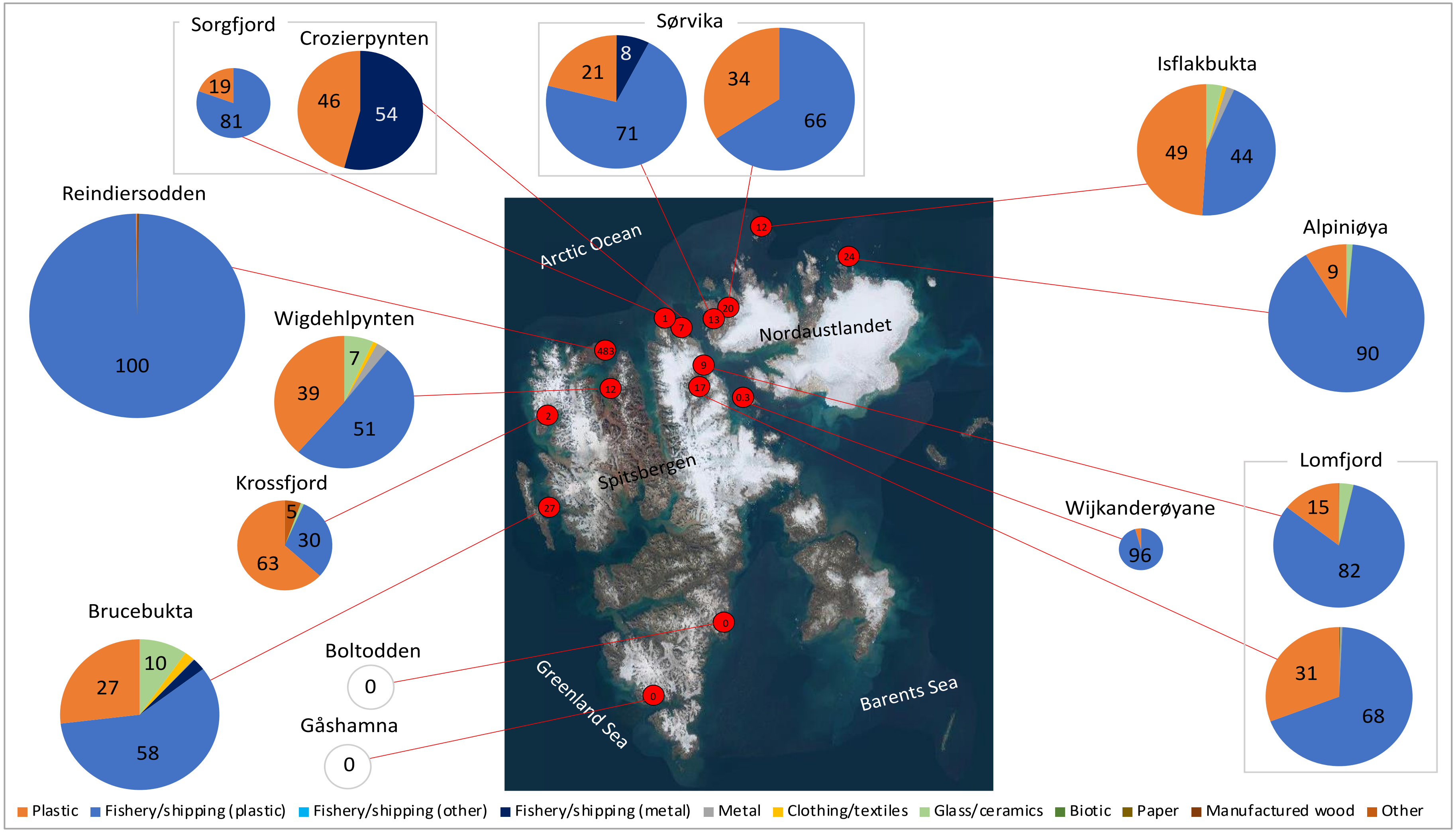



*Figure 8. Map of all locations of beach debris surveys (mass) represented with red dots, with the mass [g] per $m^2$. Which is also represented by the relative size of the respective pie charts showing the rounded proportions of debris categories. The relative size of the pie charts is based on LOG (x+1) transformed abundances, in order to enable a valid representation. (Map © Norwegian Polar Institute).*

The citizen scientists collected 1,147 kg of litter on roughly 30,800 $m^2$ of transect area over the course of this study. This translates to a total of 37 g $m^{-2}$. The mean of the mass recorded on the fifteen beaches was 41.83 g $m^{-2}$ (SEM = 31.62), of which 98% were made of plastic overall. Fisheries-related plastic accounted for 90% of the plastics and general plastic for 8%. The highest mass was collected at Reindiersodden (483 g $m^{-2}$), where a very heavy rope fender dominated the mass and resulted in nearly 100% fishery/shipping plastic (Fig. 6b). The next highest masses were recorded at Brucebukta (27 g $m^{-2}$) and Alpiniøya (24 g $m^{-2}$), again dominated by fisheries-related plastics (58% and 90%, respectively). However, the three beaches where fisheries-related plastic does not dominate are Crozierpynten, Krossfjord and Isflakbukta. At Crozierpynten, in the north, fisheries-related metal dominates (54%). Followed by Krossfjord, in the west, and Isflakbukta in the high north, where general plastic dominates with 63% and 49%, respectively. No debris was recorded at Boltodden and Gåshamna. These two beaches were the only ones that were sampled by one person only and characterized as "open ocean". A summary of all beach characteristics, debris mass and composition are given in Tab. 5.

The Spearman's rank test suggests a significant positive relationship between the mass of debris and observer numbers (N = 15, rho = 0.659, $p = 0.007$), implying that a higher number of observers collects a greater debris mass. There was no significant correlation between debris mass and transect area size (Pearson's correlation). The same applies to the ANOVA and Kruskal-Wallis tests, and to the multivariate analyses (where we ran both scenarios, one which included all data and one without factors, which had less than three samples). For all statistical results see supplementary material 8.3.

*Table 5. Details of beach surveys undertaken by citizen scientists on Svalbard. All debris masses are presented in g m$^{-2}$. p: plastic, me: metal, n.d.: material not defined; Substrate: P: pebble, S: sand, R: rock. Abbreviations: Bol (Boltodden), Wij (Wijkanderøyane), Lom 1 (Lomfjord 1), Lom 2 (Lomfjord 2), Alp (Alpiniøya), Isf (Isflakbukta), Sør 1 (Sørvika 1), Sør 2 (Sørvika 2), Cro (Crozierpynten), Sor (Sorgfjord), Rei (Reindiersodden), Wig (Wigdehlpynten), Kro (Krossfjord), Bru (Brucebukta), Gås (Gåshamna). (*) Area calculation based on GPS corner coordinates.*

| | **Bol** | **Wij** | **Lom 1** | **Lom 2** | **Alp** | **Isf** | **Sør 1** | **Sør 2** | **Cro** | **Sor** | **Rei** | **Wig** | **Kro** | **Bru** | **Gås** | **Total sum** | **Mean** | **SEM** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Date** | 08.08.21 | Jan 2019 | 07.08.17 | 06.08.18 | 22.08.16 | 28.07.16 | 20.06.16 | 23.08.17 | 18.08.16 | 11.08.21 | 08.06.16 | 17.09.17 | 15.08.21 | 31.05.16 | 07.08.21 | | | |
| **Longitude (°N)** | 77°30.048 | 79°20.391 | 79°32.88 | 79°25.50 | 80°20.568 | 80°41.728 | 79°57.334 | 79°57.334 | 79°55.787 | 79°56.491 | 79°44.276 | 79°23.991 | 79°09.452 | 78°26.678 | 76°56.395 | | | |
| **Latitude (°E)** | 018°12.525 | 019°28.430 | 018°02.10 | 017°46.03 | 024°45.537 | 020°54.782 | 018°37.941 | 018°37.941 | 016°54.151 | 016°43.378 | 013°51.042 | 013°58.632 | 011°38.303 | 011°49.231 | 015°48.593 | | | |
| **Distance to water (m)** | 0 | 0 - 2 | 1 - 30 | 0.5 | 5.7 - 7 | 0.5 | 0.5 | 0.5 | 0.5 - 2 | 0 | 0.2 | 7 | 0 | 20 | 0 | | | |
| **Substrate** | S, P | R | P | P | S | R | P | P | S, P | P | S, P | S, R | P | S, P | S, P | | | |
| **Exposure** | Ocean | Strait | Fjord | Fjord | Fjord | Bay | Strait | Strait | Fjord | Fjord | Fjord | Fjord | Fjord | Strait | Ocean | | | |
| **Marine region** | Barents Sea | Barents Sea | Barents Sea | Barents Sea | Arctic Sea | Arctic Sea | Barents Sea | Barents Sea | Greenland Sea | Greenland Sea | Greenland Sea | Greenland Sea | Greenland Sea | Greenland Sea | Green-land Sea | | | |
| **Observer number** | 1 | 23 | 20 | 30 | 30 | 15 | 38 | 26 | 28 | 1 | 18 | 26 | 2 | 26 | 1 | | | |
| **Driftwood frequency** | n.a. | None | None | Low | Medium | High | High | High | Low | Medium | Low | n.a. | Low | Medium | n.a. | | | |
| **Survey length x width (m)** | 100 x 10 | 65 x 24 | n.a. | 422 x 5 | 100 x 52 | 90 x 20 | n.a. | n.a. | 90 x 20.5 | 112 x 15 | 120 x 14 | 179 x 15 | 130 x 15 | 90 x 20 | 50 x 10 | | | |
| **Transect area (m$^2$)** | 1,000 | 1,560 | 5,487* | 2,110 | 2,559 | 1,800 | 2,048* | 2,048* | 1,845 | 1,680 | 1,680 | 2,685 | 1,950 | 1,800 | 500 | 30,752 | 2,050 | 281.76 |
| **Fishery/ shipping (p)** | | 0.29 | 7.22 | 11.40 | 21.65 | 5.22 | 13.13 | 9.15 | | 0.86 | 481.13 | 6.15 | 0.68 | 15.94 | | 572.83 | 38.19 | 31.69 |
| **Plastic** | | 0.01 | 1.28 | 5.13 | 2.08 | 5.78 | 6.84 | 2.71 | 3.21 | 0.21 | 0.83 | 4.67 | 1.43 | 7.33 | | 41.51 | 2.77 | 0.67 |
| **Clothing/ textiles** | | | | | | 0.11 | | | | | | 0.13 | | 0.56 | | 0.80 | 0.05 | 0.04 |
| **Fishery/ shipping (me)** | | | | | | | | 0.98 | 3.79 | | | | | 0.72 | | 5.49 | 0.37 | 0.26 |
| **Metal** | | | 0.01 | 0.08 | 0.00 | 0.22 | | 0.002 | | | | 0.34 | | 0.06 | | 0.70 | 0.05 | 0.03 |
| **Glass/ceramics** | | | 0.30 | | 0.31 | 0.44 | | | | | | 0.82 | 0.03 | 2.67 | | 4.57 | 0.30 | 0.18 |
| **Biotic** | | | | 0.02 | | | | | | | | | | | | 0.02 | 0.00 | 0.00 |
| **Manufactured wood** | | | 0.01 | 0.02 | 0.002 | | | 0.002 | | | 1.43 | | | | | 1.46 | 0.10 | 0.10 |
| **Other (n.d.)** | | | | | | | | | | | | | 0.12 | | | 0.12 | 0.01 | 0.01 |
| **Total sum** | **0** | **0.30** | **8.82** | **16.65** | **24.04** | **11.78** | **19.98** | **12.84** | **7.01** | **1.07** | **483.39** | **12.10** | **2.26** | **27.28** | **0** | **627.51** | **41.83** | **31.62** |

## 4.2 High-resolution composition of three big packs

Since no data on the abundance of big pack 2 (Tommelen) was recorded, only the mass of all three big packs is presented in the following section.

The debris from the three big packs collected on Kiepertøya and Tommelen was examined more thoroughly than is possible on Arctic beaches. Circa 240,000 g of debris were inspected from the first big pack (Kiepertøya, 2017). The second big pack (Tommelen, 2019) weighed ca. 60,000 g and the third (Kiepertøya, 2021) contained ca. 167,000 g of debris (Table 6).

"Plastic" dominated in all three samples (Fig. 9). "Fishery/shipping (plastic)" accounts for the heaviest share of this. However, the big pack from Tommelen had a much lower proportion of fisheries-related plastic (58%) compared to both Kiepertøya campaigns (78 - 92%). Nets and ropes were the most common fisheries-related items, followed by large containers, such as buckets, canisters, and jerry cans.

The two big packs from Kiepertøya showed similar compositions of debris. On Kiepertøya 1, besides fisheries waste, strapping bands (7%), unidentifiable plastics (6%) and plastic articles (3%), were categories that showed a higher proportion compared to others, such as rubber and foam. The second transect area on Kiepertøya, where the highest mass of "Fisheries/shipping (plastic)" was recorded (92%), showed heavier amounts of unidentifiable plastics (3%) and plastic articles (2%). By contrast, the sample from Tommelen was characterized by a large percentage of plastic packaging (20%) and unidentifiable plastics (12%).

This highlights unidentifiable plastics, strapping bands, and plastic packaging and articles as important debris categories. Fisheries-related waste still is the largest portion of debris recorded, which includes mostly nets/rope and large containers.

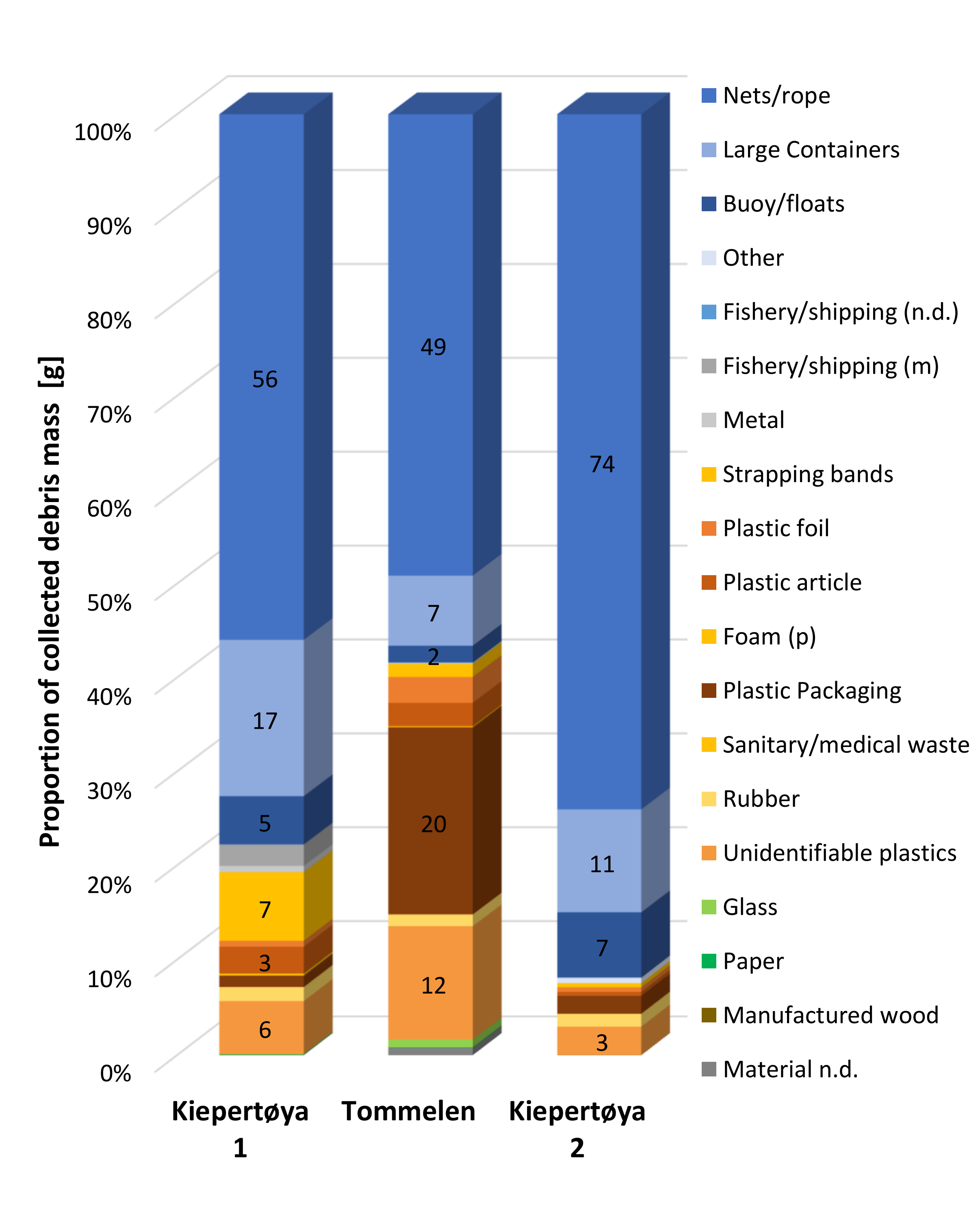



*Figure 9. Detailed composition of beach debris proportions (%) based on mass [g]. (n.d. = not defined, m = metal, p = plastic).*

*Table 6. Summary of results of high-resolution analyses of beach debris in big packs. All debris masses are presented in g m$^{-2}$. p: plastic, me: metal, n.d.: material not defined; Beach type: P: pebble, S: sand; Beach exposure: S: strait; Marine region: B: Barents Sea. (*) Area calculation based on GPS corner positions. (**) length determined with TopoSvalbard measuring tool (Norwegian Polar Institute).*

| | Kiepertøya 1 | Tommelen | Kiepertøya 2 | Total sum | Mean | SEM |
|---|---|---|---|---|---|---|
| **Date** | 23/07/17 | Jan 2019 | 09/08/21 | | | |
| **Longitude (°N)** | 79°58.685 | 79°33.200 | 78°58.655 | | | |
| **Latitude (°E)** | 21°39.480 | 18°44.940 | 21°40.081 | | | |
| **Distance to water (m)** | 0.5 | 1 - 3 | 0 | | | |
| **Substrate** | S, R | P | S, P | | | |
| **Exposure** | Strait | Strait | Strait | | | |
| **Marine region** | Barents Sea | Barents Sea | Barents Sea | | | |
| **Observer number** | 30 | 10 | 13 | | | |
| **Driftwood frequency** | High | High | High | | | |
| **Length × width (m)** | ~200 × 20 | n.a. | 168 × 15** | | | |
| **Transect area (m²)** | 3,999* | 600* | 2,250 | 6,849 | 2,283 | 981 |
| **Nets/ropes** | 138,035 | 28,739 | 123,651 | 290,425 | 96,808 | 34,287 |
| **Large containers** | 41,049 | 4,364 | 18,313 | 63,726 | 21,242 | 10,691 |
| **Buoy/floats** | 12,676 | 1,056 | 11,491 | 25,223 | 8,408 | 3,692 |
| **Other** | | 28 | 951 | 979 | 326 | 312 |
| **Fishery/shipping (n.d.)** | 41 | | | 41 | 14 | 14 |
| **Fishery/shipping (me)** | 5,600 | | | 5,600 | 1,867 | 1,867 |
| **Metal** | 1,623 | 52 | 14 | 1,689 | 563 | 530 |
| **Strapping bands** | 18,012 | 812 | 723 | 19,547 | 6,516 | 5,748 |
| **Plastic foil** | 1,540 | 1,610 | 816 | 3,966 | 1,322 | 254 |
| **Plastic article** | 6,933 | 1,459 | 627 | 9,019 | 3,006 | 1,978 |
| **Foam (p)** | 524 | 70 | 18 | 612 | 204 | 161 |
| **Plastic Packaging** | 2,943 | 11,651 | 3,161 | 17,755 | 5,918 | 2,867 |
| **Sanitary/medical waste** | 7 | | | 7 | 2 | 2 |
| **Rubber** | 3,641 | 732 | 2,261 | 6,634 | 2,211 | 840 |
| **Unidentifiable plastics** | 13,706 | 6,941 | 4,955 | 25,602 | 8,534 | 2,649 |
| **Glass** | 35 | 489 | | 524 | 175 | 158 |
| **Paper** | 190 | 32 | | 222 | 74 | 59 |
| **Manufactured wood** | 13 | | 21 | 34 | 11 | 6 |
| **Material n.d.** | | 442 | | 442 | 147 | 147 |
| **Total sum** | **246,568** | **58,478** | **167,000** | **472,045** | **157,348** | **54,511** |

## 4.3 Provenience of Arctic beach debris

### 4.3.1 Three physical samples

The provenience was determined for 359 pieces from all three big packs. 1% of all items were identified out of the big packs from 2017 and 2021, taking out of consideration the second big pack as there is no abundance data available. Twenty-seven countries were identified in total, excluding the categories “English language” and “Global” (Tab. 7).

*Table 7. Summary of provenience identified (three big packs pooled) in order of proximity to Svalbard and categorized into source regions. Absolute quantity and proportion [%] shown.*

| Sources | Provenience | Quantity | Proportion [%] |
|---|---|---|---|
| **Nearby/local 48%** | Norway | 43 | 12 |
| | Russia | 84 | 23 |
| | Sweden | 7 | 2 |
| | Denmark | 32 | 9 |
| | Finland | 1 | 0.3 |
| | Iceland | 4 | 1 |
| | Faroes | 1 | 0.3 |
| | English language | 31 | 9 |
| **Europe 22%** | UK | 13 | 4 |
| | Germany | 21 | 6 |
| | Lithuania | 1 | 0.3 |
| | Poland | 1 | 0.3 |
| | Netherlands | 7 | 2 |
| | Belgium | 2 | 1 |
| | France | 8 | 2 |
| | Spain | 6 | 2 |
| | Italy | 3 | 1 |
| | Greece | 1 | 0.3 |
| | Bulgaria | 14 | 4 |
| | Turkey | 1 | 0.3 |
| **Distant 3.9%** | Canada | 1 | 0.3 |
| | USA | 4 | 1 |
| | Brazil | 1 | 0.3 |
| | Argentina | 1 | 0.3 |
| | Japan | 1 | 0.3 |
| | Korea | 1 | 0.3 |
| | China | 4 | 1 |
| | Philippines | 1 | 0.3 |
| | Global | 64 | 18 |
| **Total** | | **359** | **100** |

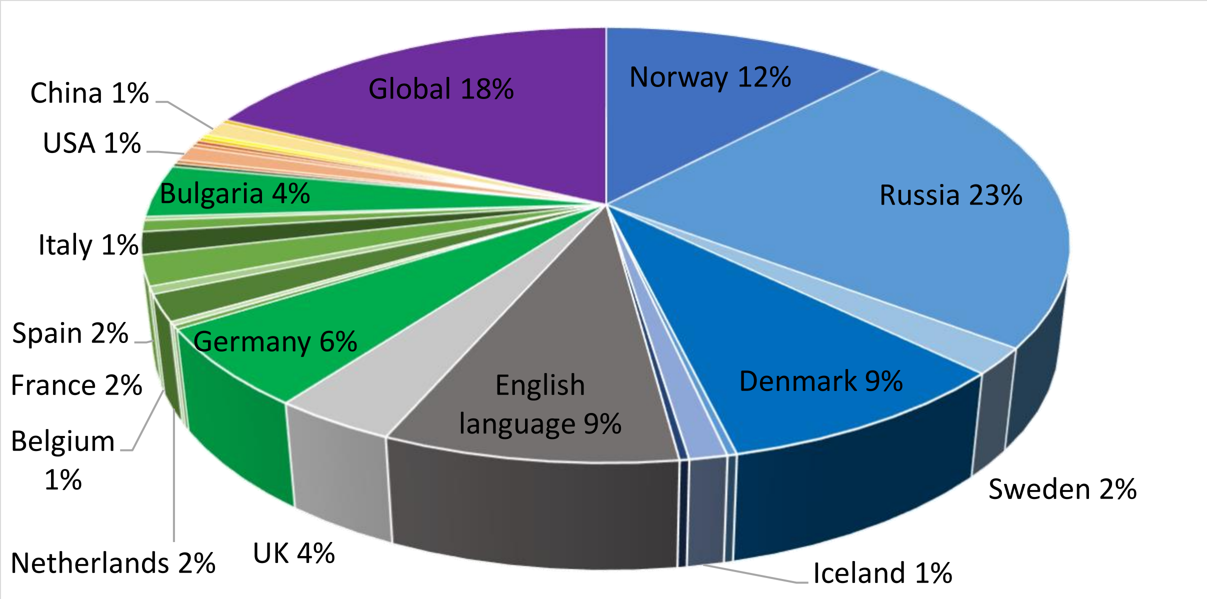



*Figure 10. Pie chart showing the proportion of debris items from different countries. Country and percentage are shown for countries with 1% or more. Local provenience is depicted in shades of blue, European provenience in shades of green and grey, Asian provenience in shades of orange, American provenience in shades of yellow and Global in purple.*

Regarding the pooled data of all big packs (Fig. 10), the countries contributing the most were those located closer to Svalbard (48%) such as Russia (23%), Norway (12%), and Denmark (9%). Note, that Greenland belongs to Denmark and it is not possible to determine which location items originate from. Although Sweden, Iceland and Finland are Arctic states and relatively close to Spitzbergen, their share was lower (< 4%). Other European countries such as Germany (6%), the UK (4%), Spain (2%), and others made up 32% of the debris analyzed. This includes "English language", which is likely of UK provenience (grey) although this is not 100% certain. The category "Global" accounted for 18% and the remainder was of more distant provenience including the American continents (2%) and Southeast Asia (2%). Combined they contribute 14 items to the whole of 359 pieces. Note that the USA and China add four debris pieces each to those two regions. Whereas the other countries classed as American and Asian only contribute one piece each.

### 4.3.2 Provenience of items from three physical samples

The proportion of the category "global" grew every year, from 6% in 2017 to 30% in 2021 (Fig. 11). This could be a sign of globalization. Interestingly, Norway (11-13%) and Denmark (7-13%) remained quite constant throughout the years. While Russia (18-28%) shows a 10% difference from the first year of sampling to the last. All three countries register a slight decline in numbers. The consistency in numbers also applies to Germany and the UK, where the litter quantities differ between 4-9% and 2-5% respectively. While the decline also applies to the UK, it does not apply to Germany, where the numbers vary from sampling to sampling. More distant sources, such as American and Southeast Asian countries had a small share of debris in all three years (<5%). All items pictured in Supplementary Figs 4, 5 and 6.

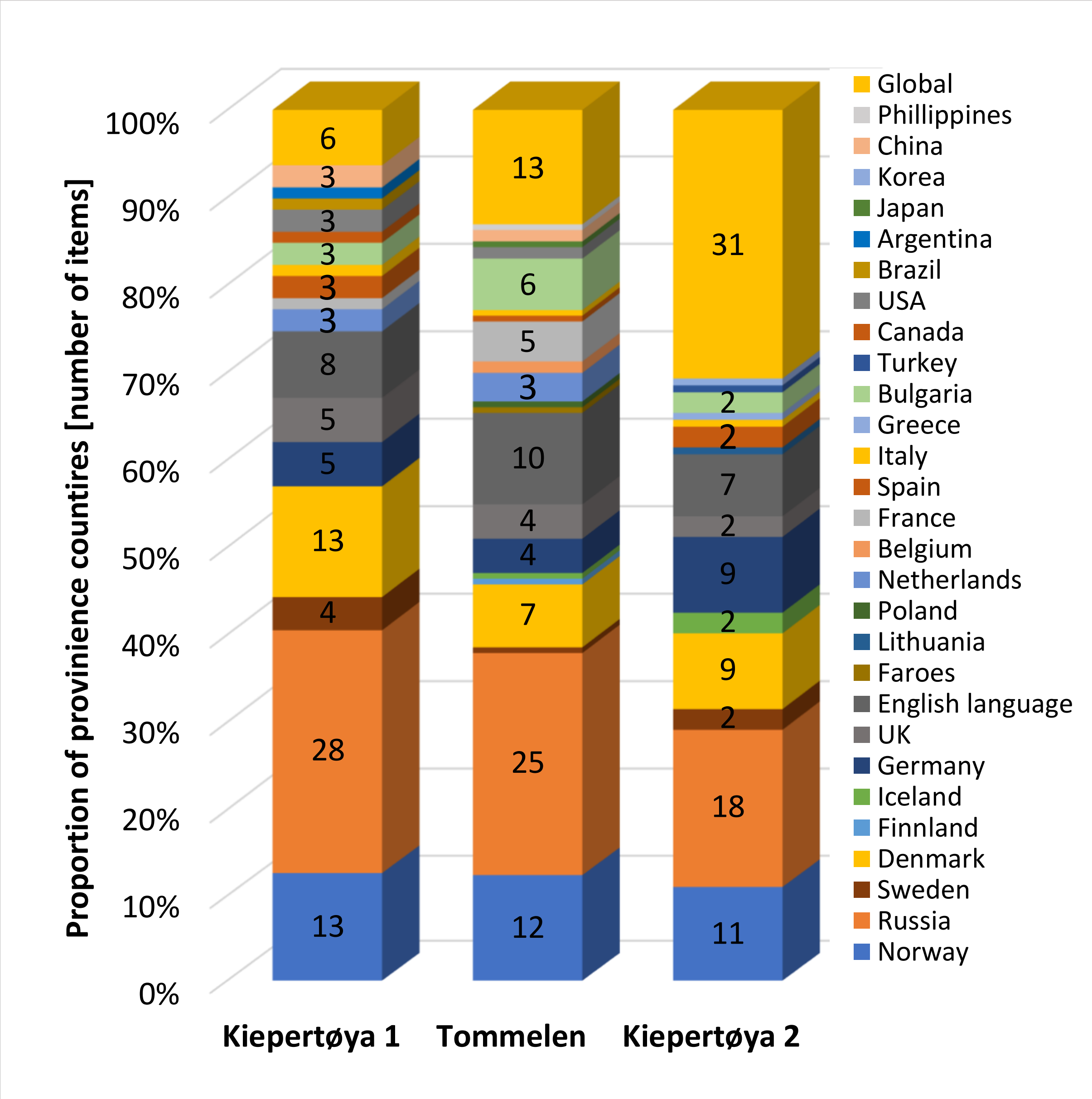



*Figure 11. Proportions of marine debris of different provenience in three samples collected from Kiepertøya (2017), Tommelen (2019) and Kiepertøya (2021) of items that still showed signs of provenience.*

## 4.4 Date prints

I found dates, regarding expiry and/or production on 19 items out of 270 provenience debris pieces, this translates to 7%. The dates range from 1960 to 2013. 53% of items (10 pieces) are from the timeframe between 2000 – 2013. The possibly oldest piece found is a bottle fragment from around 1960. Supplementary Table 3. shows a detailed list regarding all date prints.

## 4.5 Polymer composition

*Table 8. Polymer composition of analyzed debris, showing quantity and proportion [%] of polymers. PE = Polyethylene, PP = Polypropylene.*

| Groups | Polymer | Quantity | Proportion [%] |
|---|---|---|---|
| **PE types 61.4%** | Polyethylene High Density | 112 | 50 |
| | Polyethylene Low Density | 25 | 11 |
| | Polyethylene Chlorinated | 1 | 0.4 |
| **PP types 31%** | Polypropylene | 57 | 25 |
| | Fiber Polypropylene Dyed | 6 | 3 |
| | Fiber Polypropylene | 5 | 2 |
| | Polypropylene Isotactic | 1 | 0.4 |
| | Ethylene Propylene | 1 | 0.4 |
| **Other 7%** | Fiber Polyester | 7 | 3 |
| | Nylon 6_6 | 3 | 1 |
| | Styrene Acrylonitrile | 2 | 1 |
| | Fiber Polyamide 6 | 1 | 0.4 |
| | Polyether urethane | 1 | 0.4 |
| | Poly(diallyl isophthalate) | 1 | 0.4 |
| | Polyurethane | 1 | 0.4 |
| | **Total** | **224** | **100** |

From 224 items for which physical samples from 2019 and 2021 were still available, 15 different polymer types could be identified. Polyethylene (PE) accounted for 61% of the items, 50% of which were high density (HD) and 11% low density (LD) PE. Polypropylene ranked second (31%). Poly(diallyl Isophthalate) (0.4%) and Polyurethane (0.4%) were less common.

All nets and ropes analyzed were synthetic (70% Polyethylene, 30% Polypropylene). 95% of the strapping bands were made of polypropylene. The remainder consisted of HDPE.

# 5 Discussion

## 5.1 Assessment of methods

This study relied on citizen scientists (CS) to generate reliable data during clean-ups on Arctic beaches, which increases our knowledge of plastic pollution in remote and under-sampled locations. Citizens are eager to contribute, especially with the environmental topic in mind. It is a way to include the public, which could encourage more citizens to help and leave a lasting effect because of the outreach component (Bergmann *et al.*, 2017a). However, there is uncertainty regarding the data quality since no scientist was present. And the positive correlation between the number of CS taking part in the surveys and the abundance of debris collected per $m^2$ found in this study does highlight this narrative. Therefore, it is important to follow certain steps to ensure reliable data collection. These steps, are (1) preparation of clear protocols, (2) training volunteers, (3) on site supervision and (4) the revision of samples and data (Hidalgo-Ruz and Thiel, 2015). In addition, beach surveys are particularly amenable to citizen scientists who can draw on knowledge from their daily life for the recognition of debris items (>2 cm) requiring very little additional training. Other benefits are the spatial and temporal coverage of under-sampled areas (Nelms *et al.*, 2017), implying that this study would not have reached as many sampling locations without CS. Comparing non-CS data from Kylin, 2020, where 0.0011 items $m^{-2}$ were collected on a beach in the Russian Arctic, to data collected on a comparable beach (Krossfjord, 0.2 items $m^{-2}$) for this study there is a clear difference in numbers. More debris was collected by the CS, surely due to more debris being on site. However, this does imply that this form of accumulating data is reliable, as there are more observers collecting the debris, they can cover a larger area and there is less risk of overlooking items.

Nevertheless, beach clean-ups as such come with uncertainty, such as a lack of information on if and when the beaches had been cleaned prior to the surveys. Therefore, it is uncertain how much debris has accumulated over a certain amount of time, and data from different beaches may not be comparable. However, the beaches visited here are very isolated and some of them most likely have never been cleaned. The oldest item found is a bottle fragment from Norway, its production dating back to the 1960s. While it is unclear when exactly this piece washed ashore, it still gives the indication, that this particular beach had not been cleaned for quite some time.

When it came to sorting and determining the composition of the physical sample from 2021 inconsistencies emerged as the methods applied in 2017 and 2019 differed slightly. For example, as the categorization on survey forms for the citizen scientists was improved over the years, I tried to categorize the big pack accordingly, for consistency. Items such as strapping bands and plastic sheeting were assigned to "fisheries-related plastics" in the first year. While this is likely true (Falk-Andersson, 2021), it is not 100% certain. So, in the following years they were listed separately, also when sorting the physical samples.

## 5.2 Arctic beach debris surveys

This study showed that plastic was present on most of the investigated beaches of Svalbard at a mean mass of 42 ± 32 SEM g debris $m^{-2}$. This is high compared to a Bulgarian beach that harbored 2 g $m^{-2}$ and was located near the third biggest town in Bulgaria (Panayotova *et al.*, 2020). The average weight of large debris collected on Sri Lankan beaches was 175 ± 538 g $m^{-2}$ and the average weight of small pieces was 18.6 ± 21.6 g $m^{-2}$ (Jang *et al.*, 2018). Especially regarding the large items, this is high, compared to our data. Again, Sri Lanka is inhabited and beaches are recreational spots for locals and tourists. This could have an impact on the amount of debris recorded. This also applies to New Zealand, where an overall mean weight of 9.17 ± 2.91 g $m^{-2}$ of marine anthropogenic debris was recorded (van Gool *et al.*, 2021). In addition to that, cleanups organized by the public as well as the government could add to that low amount of debris. Two islands (Henderson Island and Cocos Island), which are comparable to Spitsbergen due to their remoteness and distance from metropolitan areas, were surveyed regarding plastic debris and its correlation with beach sediment temperature extremes. Henderson Island, located in the Pitcairn Islands (5200 km northeast of New Zealand), is very remote and uninhabited. Here the mass density of surface plastic debris was 571 ± 197 g $m^{-2}$. On the Cocos, 2750 km northwest of Perth (Western Australia), 3164 ± 1989 g $m^{-2}$ of surface plastic was recorded (Lavers *et al.*, 2021). While these two beaches are so comparable to Svalbard, they show extremely high numbers of debris compared to our data. A reason for that could be the proximity to the South Pacific Gyre, a known plastic accumulation zone. Though there has been a debris accumulation zone predicted in the Nordic Seas near Svalbard as well (Onink *et al.*, 2019; van Sebille *et al.*, 2012).

On two beaches, Gåshamna and Boltodden, no debris was collected. A possible factor could be that only one person (BL) conducted the surveys. While this factor does have an impact, since we see a positive correlation between the number of observers conducting the clean ups and the abundance of debris collected per $m^2$, I imagine it to be fairly low regarding BL. She has been organizing and supervising the cleanups since 2016 and both beaches in question were sampled in 2021. This timeframe results in her having years of experience and in addition to that I am confident about the sampling technique she carried out. Another factor affecting the number of debris collected could be the location of the beaches. Both of them are located in the south of Svalbard and the currents could drift the debris further north. This theory is supported by the fact that they are the only beaches with exposure to the open ocean, while all the other beaches sampled are not as exposed being located in fjords or around bays. Debris can drift past Gåshamna and Boltodden but stays stuck in fjords or bays where it can't escape and then washes ashore.

A mean debris abundance of 0.37 ± 0.17 SEM items per $m^2$ was found on Svalbard beaches. According to Ansari & Farzadkia (2022) the surveyed beaches would be classified as "low polluted beaches". Slightly higher pollution levels -although surprisingly similar in range- were reported from a beach on Sylt in Germany (0.5 debris items $m^{-2}$) (Haseler *et al.*, 2020), although it is situated in a higher populated location. On the other hand, beaches on Sylt are likely cleaned on a regular, if not daily, basis. Reports from Russian Arctic beaches report pollution levels that were more than a magnitude lower on a mainland beach (0.024 debris items $m^{-2}$) and an island beach (0.011 debris items $m^{-2}$) (Kylin, 2020). A possible reason for the difference between the two beaches could be that the mainland is ice-free for a longer period of time and more exposed to fishing activity, thus more debris can wash ashore (Kylin, 2020). The connection between the declining sea ice extent and increasing vessels operating in the Svalbard region has been made before (Stocker *et al.*, 2020), as has been the link between high fishing activity in areas of low sea ice concentration (Fauchald *et al.*, 2021). It could be argued that an increase of vessels of any kind (fishing, recreational, merchant, tourist or scientific) in turn increases the amount of plastic debris entering the region around Svalbard. This could possibly explain the comparably higher number of debris items found in our surveys. A larger mean mass of debris was found on the more northern sites of Svalbard, though most of our surveys were done in the north, with only two being in the south. A conclusive verdict cannot yet be made since more evenly distributed surveys would be needed. This highlights one disadvantage of the citizen science setup, where site selection cannot be based on scientific principles.

This study reveals that regarding material types, most debris is plastic waste in terms of both abundance (99.6%) and mass (98%), when adding up all beached debris collected on the nine occasions. The dominance of plastic does not come as a surprise as previous studies stated that plastic and artificial polymers form the majority of marine debris as well (Ansari and Farzadkia, 2022; Vesman *et al.*, 2020) and most documented waste in the Arctic reported in previous studies is related to fisheries (Bergmann *et al.*, 2017a; Galgani *et al.*, 2015; Jaskólski *et al.*, 2018; Nashoug, 2017). Our mass percentage of 98% plastics is substantially higher than the global estimate for beaches which is 76% (Tekman *et al.*, 2022). However, 76% is the mean of more than 2600 locations worldwide including urban regions with a potentially higher diversity of debris sources. For example, paper and metal items from distant sources could perish before reaching Arctic destinations. On Svalbard, fisheries plastic accounts for ca. 90% of the plastic weight, which is much higher than the global figure of 6.12% (Tekman *et al.*, 2022). This could be because many study areas were in locations where fewer fishing vessels operate, or because of differences in methodology and reporting. While fisheries-related plastics dominates mass, general plastic is highest in terms of abundance.

The difference between the units also transpires when comparing the debris composition of the 14 Arctic beaches. The heaviest category is items from the fishing industry, which enter the environment at sea, they represent a direct path of entry (local sea-based sources) (Strand *et al.*, 2021). The theory of local sea-based sources in the Arctic is supported by reports of fast-sinking glass debris on the ocean floor (Bergmann *et al.*, 2022). Local debris emissions from increasing shipping activities have also been thought to act as a source for debris and microplastics (Tekman *et al.*, 2017; Tekman *et al.*, 2020). In comparison, the most abundant number of debris recorded, is general plastics (80%), pointing to land-based sources, riverine input, and ship waste. In some cases, the source is determined with a high level of confidence, in others it is not so clear, since debris items can have several potential sources. While it is very likely that strapping bands and plastic foil were used on fishing vessels, we cannot be 100% certain and the same goes for plastic packaging. It is not possible to determine if it was lost or deliberately discarded at sea or possibly entered the ocean via rivers that flow into the Arctic region and was then transported via ocean currents, especially since items such as bottles, food containers, and toothbrushes are used on vessels as well as on land. Larger items, such as food buckets, likely originate from ship galleys (Nashoug, 2017), for example. This theory is also supported by Ryan et al., 2019. They found, according to the date of manufacturing and provenience of bottles, that most bottles collected on a remote beach in the South Atlantic Ocean stem from ships. The report from Topçu et al. (2013) stating two main sources of foreign debris for the SW Black Sea can be applied here as well: (1) debris from terrestrial sources in neighboring countries driven by river currents and (2) maritime originated debris due to international shipping.

But even for debris that has its source in vessels, the circumstance of them entering the ocean is unclear. The theory, that "[…] a clean edge at the end of a rope or part of a trawl net indicates it was cut and likely discarded, either on deck and then to sea, or directly to sea." (Falk-Andersson, 2021; Nashoug, 2017) is interesting, though it does pose uncertainties and leaves room for interpretation. For example, it is difficult to determine a clean edge (Fig. 12), a rope could have a clean edge on one side and an uneven one on the other, or it could have more than one clean edge, it could have been cut off and then processed in a certain way, so that it does not fray. In addition, it is unclear how long items might have been in the water and if an uneven edge is a result of aging and processes.


*Figure 12. Examples of various ropes and their ends. A: clean and sealed edge, B: more than one clean edge, C: rope in rough shape, D & E: one almost clean edge and one uneven edge.*

Plastic debris interacts with Arctic biota via entanglement, ingestion, and colonization by rafting organisms with yet unknown consequences on populations and ecosystems (Bergmann *et al.*, 2022; Collard and Ask, 2021). During citizen science surveys, a reindeer skull was observed, whose antlers were tangled in a net, which causes them not being able to hunt for food or drink water resulting in death (Bergmann *et al.*, 2017a). Numerous items bore bite marks, which could be a result of polar bear's or seal's investigations. In addition, barnacles were found on a fish box fragment. Buoyant plastics can serve as a means of transport for sessile adult and larval biota, resulting in the (re-) introduction of species as observed for the blue mussel on Svalbard (Kotwicki *et al.*, 2021). While one item from Tommelen had also mussels attached to it, most items were free of fouling organisms.

## 5.3 Comparing two physical samples

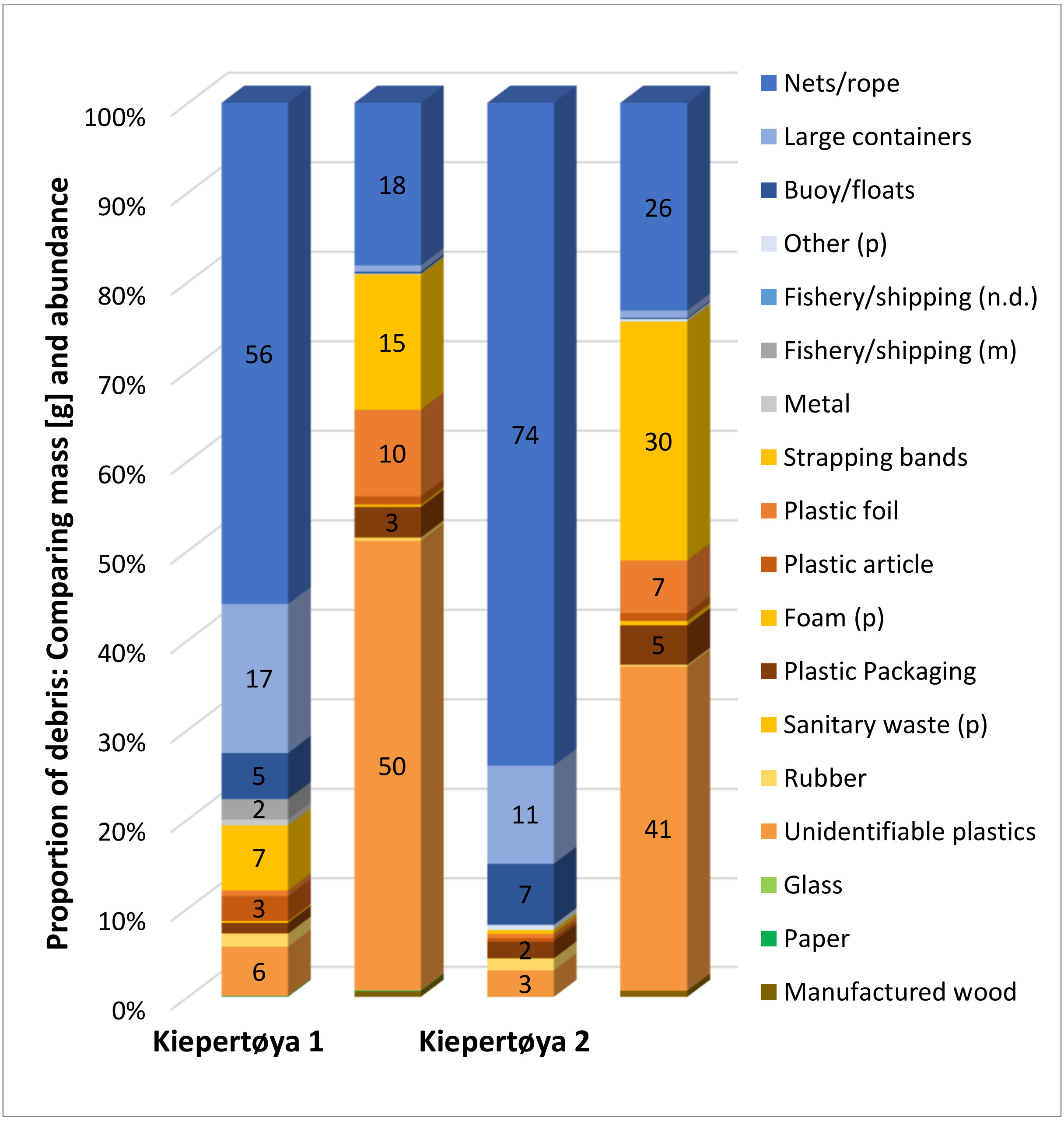



*Figure 13. High resolution proportion of two big packs. Two columns are shown per location: mass (left columns) and abundance (right columns). p = plastic, m = metal, n.d.= not defined.*

The difference between mass and abundance is particularly evident when comparing the compositions of the two physical samples, where mass is dominated by fishery waste (80 – 92%) whereas general plastic dominated in terms of abundance (80 – 85%) (Fig. 13). While the heaviest fishing net found weighed 70 kg it accounted only for one item. This demonstrates why fisheries debris has such a high impact on mass composition. Parallel observations were made in a different study, where a small number of items (macro debris) contributed to the greatest amount of mass (Ryan *et al.*, 2020). Contrarily, "Unidentifiable plastics" dominated in terms of abundance (41 – 50 %), which is not surprising, as this category often comprises a high number of small, nearly mesoplastic-sized debris. Small, unidentifiable plastic debris together with foam particles was also the most abundant debris recorded during surveys on the Turkish Western Black Sea Coast (Topçu *et al.*, 2013). "Unidentifiable plastics" are followed by a high abundance of "Strapping bands" (15 – 30%), which concurs with observations made in the Russian Far east (Jaskólski *et al.*, 2018) and the Siberian Arctic (Vesman *et al.*, 2020). The observation of a high number of small items and a low number of larger items corresponds with the findings that "the number of items increases exponentially with decreasing particle size […]." (Ryan *et al.*, 2020).

## 5.4 Provenience of plastic items

Most debris still bearing signs of origin, seem to be produced in countries in close proximity to Svalbard, such as Arctic states like Norway, Denmark (incl. Greenland) and Russia (48%) and countries bordering the North Sea or the North Atlantic such as Germany, UK, The Netherlands, France and Spain (Fig. 14). This does not come as a surprise since particles tend to drift northwards from the North Sea or Northeast Atlantic towards the Norwegian, Barents and Greenland Seas (Strand *et al.*, 2021). The Atlantic circulation, which feeds the West Spitsbergen Current (Bergmann *et al.*, 2015), transports the debris to the north, where it washes ashore (Nashoug, 2017). Still, some countries such as Sweden and Iceland, which are closer to Svalbard than Germany, for example, have a lower number of items assigned to them. It is arguable that items from Sweden and Iceland do not reach Svalbard, due to hydrography. Also, the percentage of items identified decreased at increasing distance from the study area. Examples include Korea, Greece, Turkey, and Argentina. This was to be expected, as the oceans current carrying items to those regions will take much longer (Strand *et al.*, 2021; van Sebille *et al.*, 2012). This also corroborates the statement, that marine debris in the Norwegian continental shelf and in the Barents Sea is primarily of local provenience and that long distance transport is a less relevant factor (Buhl-Mortensen and Buhl-Mortensen, 2017). One could argue that these items stem from ships, that travel to the Arctic region, such as ships and fishing vessels from which debris enters the ocean and then washes ashore (Ryan *et al.*, 2021). This theory could apply to any packaging or plastic articles found on Arctic shores. The category "Global" has increased every year since doing the surveys, from 6 to 31%. This could be a sign of globalization, as more items are readily available in different countries due to increased import and export. The globalized market makes it difficult to determine whether debris that we categorized as foreign or global has been released in those countries or has possibly entered the ocean via a mobile source, such as vessels. Since foreign products could have been bought in one country and been discarded in another (Falk-Andersson, 2021).

### 5.4.1 Date prints

Another aspect to finding out the source of debris is to determine when items were disposed of or lost, which is for the most part not possible. What is possible is to interpret the age of a debris item through either their production or expiration date (Sander, 2016). Furthermore, I estimated the age of some items by contacting companies or researching online to find out when they were produced. The time period between production date and date of disposal is still highly variable in these cases (Sander, 2016) but it can give an indication about where an item has been discarded. The age of bottles for example combined with the information of a local or foreign origin can make the distinction between ship debris and long-distance drift (Ryan *et al.*, 2021). A bottle determined as French with the expiration dating back one year could not have drifted from France to the coast of Svalbard in one year (van Sebille *et al.*, 2012). This would indicate it being ship debris opposed to long-distance drift.

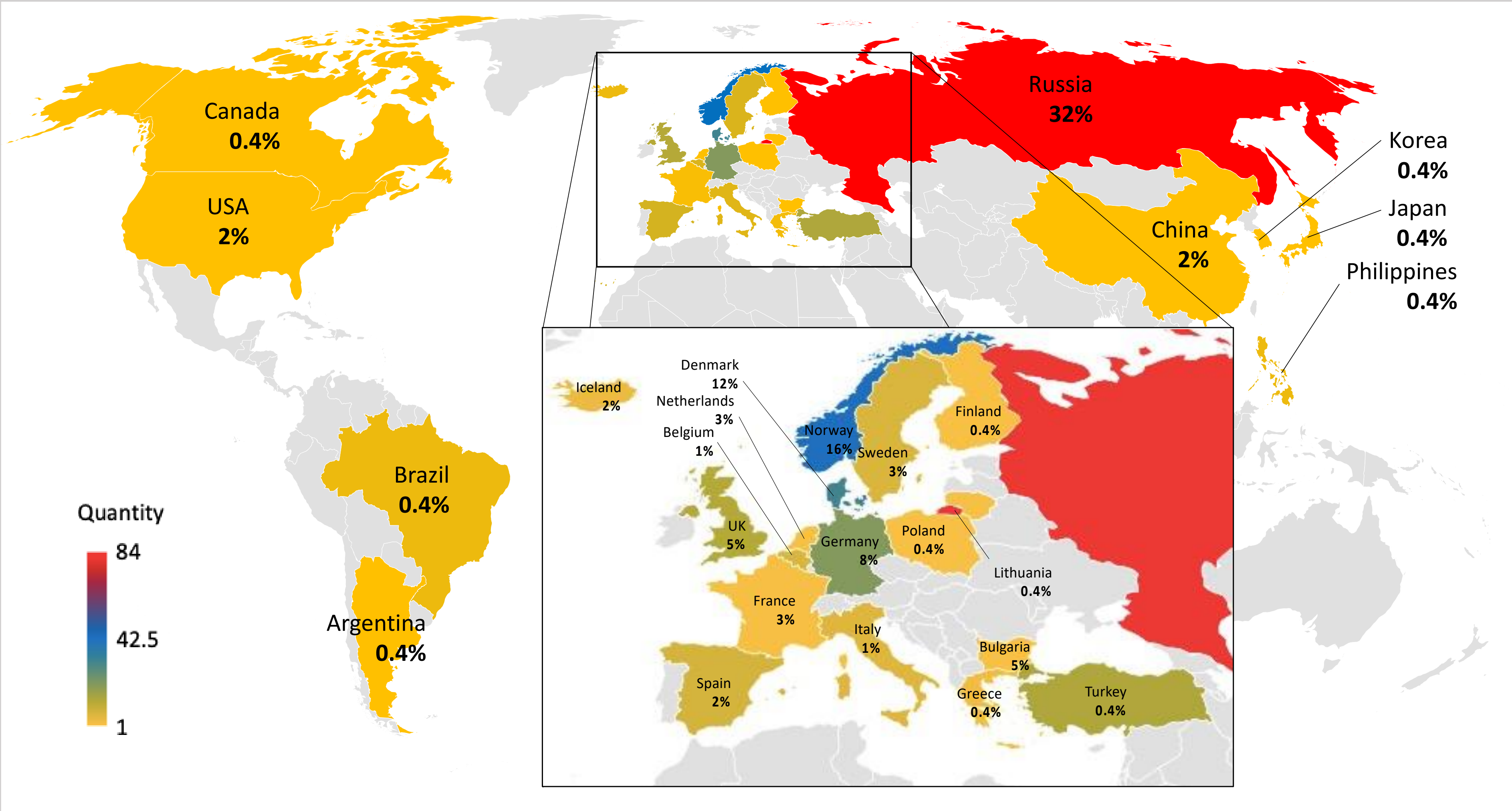



*Figure 14. Origin of items depicted in a map. Countries and proportions marked, color of countries show number of assigned items.*

# 6 Resulting questions and outlook

Further melting of sea ice (Bergmann and Klages, 2012), decrease in ice thickness (Bergmann *et al.*, 2022), and shorter periods of sea ice coverage (Polasek *et al.*, 2017) are all effects of global climate change. They lead to a prolonged period for vessels (fishing, tourism, merchant, expedition, etc.) operating in the Arctic as well as them being able to reach higher latitudes (Bergmann *et al.*, 2022; Stocker *et al.*, 2020). Keeping in mind my research interests it would be interesting to define if fishing activity does affect the composition of beach debris, e.g., do we find more fishery waste on beaches in marine regions with a higher fishing activity? Plastic pollution likely adds to the already out of joint Arctic ecosystems and exasperates the stress on Arctic wildlife. Of course, further cleanups are necessary, to remove existing and future debris that wash ashore. However, useful standardized monitoring schemes for beach debris recordings need to be put in place, to be able to compare results at a meaningful level. Repeated surveys in the same locations would enable us to assess temporal trends and accumulation rates (Panayotova *et al.*, 2020; Weideman *et al.*, 2020). Information is also needed as to how frequently the beaches are cleaned and if that causes differences in the amount of collected debris.

In terms of policy, we need to start at the root of the problem and not just treat the symptoms. Mitigation in form of a globally accepted and obeyed plastic treaty needs to be put in place. Here more upstream measures such as the reduction of global plastic production and a circular economy rather than a linear one should be aimed for. Adding adequate monitored waste management policies regarding fishing vessels and creating public environmental education and awareness is important as well. This in turn would reduce the amount debris entering our oceans and would lift the stress on Arctic wildlife and the Arctic region, which is already threatened by climate change.

## 7 References cited


Aliani, S., Casagrande, G., Catapano, P., Catapano, V., 2020. Polarquest 2018 Expedition: Plastic Debris at 82°07' North. In: Streit-Bianchi, M., Cimadevila, M., Trettnak, W. (Eds.), Mare Plasticum - The Plastic Sea: Combatting Plastic Pollution Through Science and Art. Cham, Springer International Publishing, pp. 89-116.

Ammendolia, J., Walker, T.R., 2022. Citizen science: A way forward in tackling the plastic pollution crisis during and beyond the COVID-19 pandemic. Science of The Total Environment 805.

Ansari, M., Farzadkia, M., 2022. Beach debris quantity and composition around the world: A bibliometric and systematic review. Mar Pollut Bull 178, 113637.

Bergmann, M., Collard, F., Fabres, J., Gabrielsen, G.W., Provencher, J.F., Rochman, C.M., van Sebille, E., Tekman, M.B., 2022. Plastic pollution in the Arctic. Nature Reviews Earth & Environment.

Bergmann, M., Klages, M., 2012. Increase of litter at the Arctic deep-sea observatory HAUSGARTEN. Mar Pollut Bull 64 (12), 2734-2741.

Bergmann, M., Lutz, B., Tekman, M.B., Gutow, L., 2017a. Citizen scientists reveal: Marine litter pollutes Arctic beaches and affects wild life. Mar Pollut Bull 125 (1-2), 535-540.

Bergmann, M., Sandhop, N., Schewe, I., D'Hert, D., 2015. Observations of floating anthropogenic litter in the Barents Sea and Fram Strait, Arctic. Polar Biology 39 (3), 553-560.

Bergmann, M., Tekman, M.B., Gutow, L., 2017b. Marine Litter: sea change for plastic pollution. NatureNature 544, 297.

Borrelle, S.B., Ringma, J., Law, K.L., Monnahan, C.C., Lebreton, L., McGivern, A., Murphy, E., Jambeck, J., Leonard, G.H., Hilleary, M.A., Eriksen, M., Possingham, H.P., De Frond, H., Gerber, L.R., Polidoro, B., Tahir, A., Bernard, M., Mallos, N., Barnes, M., Rochman, C.M., 2020. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. Science 369 (6505), 4.

Buhl-Mortensen, L., Buhl-Mortensen, P., 2017. Marine litter in the Nordic Seas: Distribution composition and abundance. Marine Pollution Bulletin 125 (1), 260-270.

Canals, M., Pham, C.K., Bergmann, M., Gutow, L., Hanke, G., van Sebille, E., Angiolillo, M., Buhl-Mortensen, L., Cau, A., Ioakeimidis, C., Kammann, U., Lundsten, L., Papatheodorou, G., Purser, A., Sanchez-Vidal, A., Schulz, M., Vinci, M., Chiba, S., Galgani, F., Langenkämper, D., Möller, T., Nattkemper, T.W., Ruiz, M., Suikkanen, S., Woodall, L., Fakiris, E., Molina Jack, M.E., Giorgetti, A., 2020. The quest for seafloor macrolitter: a critical review of background knowledge, current methods and future prospects. Environmental Research Letters.

Collard, F., Ask, A., 2021. Plastic ingestion by Arctic fauna: A review. Science of The Total Environment 786.

Falk-Andersson, J., 2021. Beach litter deep dives-A method for improved understanding of sources of and behaviour behind littering. Marine Pollution Bulletin 167, 7.

Fauchald, P., Arneberg, P., Debernard, J.B., Lind, S., Olsen, E., Hausner, V.H., 2021. Poleward shifts in marine fisheries under Arctic warming. Environmental Research Letters 16 (7).

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

Geyer, R., 2020. A Brief History of Plastics. In: Streit-Bianchi, M., Cimadevila, M., Trettnak, W. (Eds.), Mare Plasticum - The Plastic Sea: Combatting Plastic Pollution Through Science and Art. Cham, Springer International Publishing, pp. 31-47.

Grøsvik, B.E., Prokhorova, T., Eriksen, E., Krivosheya, P., Horneland, P.A., Prozorkevich, D., 2018. Assessment of Marine Litter in the Barents Sea, a Part of the Joint Norwegian–Russian Ecosystem Survey. Frontiers in Marine Science 5.
Haseler, M., Balciunas, A., Hauk, R., Sabaliauskaite, V., Chubarenko, I., Ershova, A., Schernewski, G., 2020. Marine Litter Pollution in Baltic Sea Beaches – Application of the Sand Rake Method. Frontiers in Environmental Science 8.
Hidalgo-Ruz, V., Thiel, M., 2015. The Contribution of Citizen Scientists to the Monitoring of Marine Litter. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, Cham, pp. 429-447.
Huserbråten, M.B.O., Hattermann, T., Broms, C., Albretsen, J., 2022. Trans-polar drift-pathways of riverine European microplastic. Scientific Reports 12 (1).
Jang, Y.C., Ranatunga, R., Mok, J.Y., Kim, K.S., Hong, S.Y., Choi, Y.R., Gunasekara, A.J.M., 2018. Composition and abundance of marine debris stranded on the beaches of Sri Lanka: Results from the first island-wide survey. Mar Pollut Bull 128, 126-131.
Jaskólski, M.W., Pawlowski, Ł., Strzelecki, M.C., Zagórski, P., Lane, T.P., 2018. Trash on Arctic beach: Coastal pollution along Calypsostranda, Bellsund, Svalbard. Polish Polar Research 39 (2), 211-224.
Kotwicki, L., Weslawski, J.M., Włodarska-Kowalczuk, M., Mazurkiewicz, M., Wenne, R., Zbawicka, M., Minchin, D., Olenin, S., 2021. The re-appearance of the Mytilus spp. complex in Svalbard, Arctic, during the Holocene: The case for an arrival by anthropogenic flotsam. Global and Planetary Change 202.
Kylin, H., 2020. Marine debris on two Arctic beaches in the Russian Far East. Polar Research 39, 6.
Lau, W.W.Y., Shiran, Y., Bailey, R.M., Cook, E., Stuchtey, M.R., Koskella, J., Velis, C.A., Godfrey, L., Boucher, J., Murphy, M.B., Thompson, R.C., Jankowska, E., Castillo, A.C., Pilditch, T.D., Dixon, B., Koerselman, L., Kosior, E., Favoino, E., Gutberlet, J., Baulch, S., Atreya, M.E., Fischer, D., He, K.K., Petit, M.M., Sumaila, U.R., Neil, E., Bernhofen, M.V., Lawrence, K., Palardy, J.E., 2020. Evaluating scenarios toward zero plastic pollution. Science 369 (6510), 1455-1461.
Lavers, J.L., Bond, A.L., 2017. Exceptional and rapid accumulation of anthropogenic debris on one of the world’s most remote and pristine islands. Proceedings of the National Academy of Sciences 114 (23), 6052-6055.
Lavers, J.L., Rivers-Auty, J., Bond, A.L., 2021. Plastic debris increases circadian temperature extremes in beach sediments. J Hazard Mater 416, 126140.
Li, P., Wang, X., Su, M., Zou, X., Duan, L., Zhang, H., 2021. Characteristics of Plastic Pollution in the Environment: A Review. Bull Environ Contam Toxicol 107 (4), 577-584.
Nashoug, B.F., 2017. Sources of Marine Litter. MARP3, SALT, p. 25.
Nelms, S.E., Coombes, C., Foster, L.C., Galloway, T.S., Godley, B.J., Lindeque, P.K., Witt, M.J., 2017. Marine anthropogenic litter on British beaches: A 10-year nationwide assessment using citizen science data. Science of The Total Environment 579, 1399-1409.
Onink, V., Wichmann, D., Delandmeter, P., van Sebille, E., 2019. The Role of Ekman Currents, Geostrophy, and Stokes Drift in the Accumulation of Floating Microplastic. J Geophys Res Oceans 124 (3), 1474-1490.
Panayotova, M.D., Bekova, R.I., Stefanova, K.B., Todorova, V.R., Gumus, M.R., Slabakova, V.H., Prodanov, B.K., Mihova, S.H., 2020. Seasonal Composition and Density of Marine Litter on Asparuhovo Beach, Varna, Bulgaria. Ecologica Balkanica (3), 85 - 94.
Parga Martínez, K.B., Tekman, M.B., Bergmann, M., 2020. Temporal Trends in Marine Litter at Three Stations of the HAUSGARTEN Observatory in the Arctic Deep Sea. Frontiers in Marine Science 7.

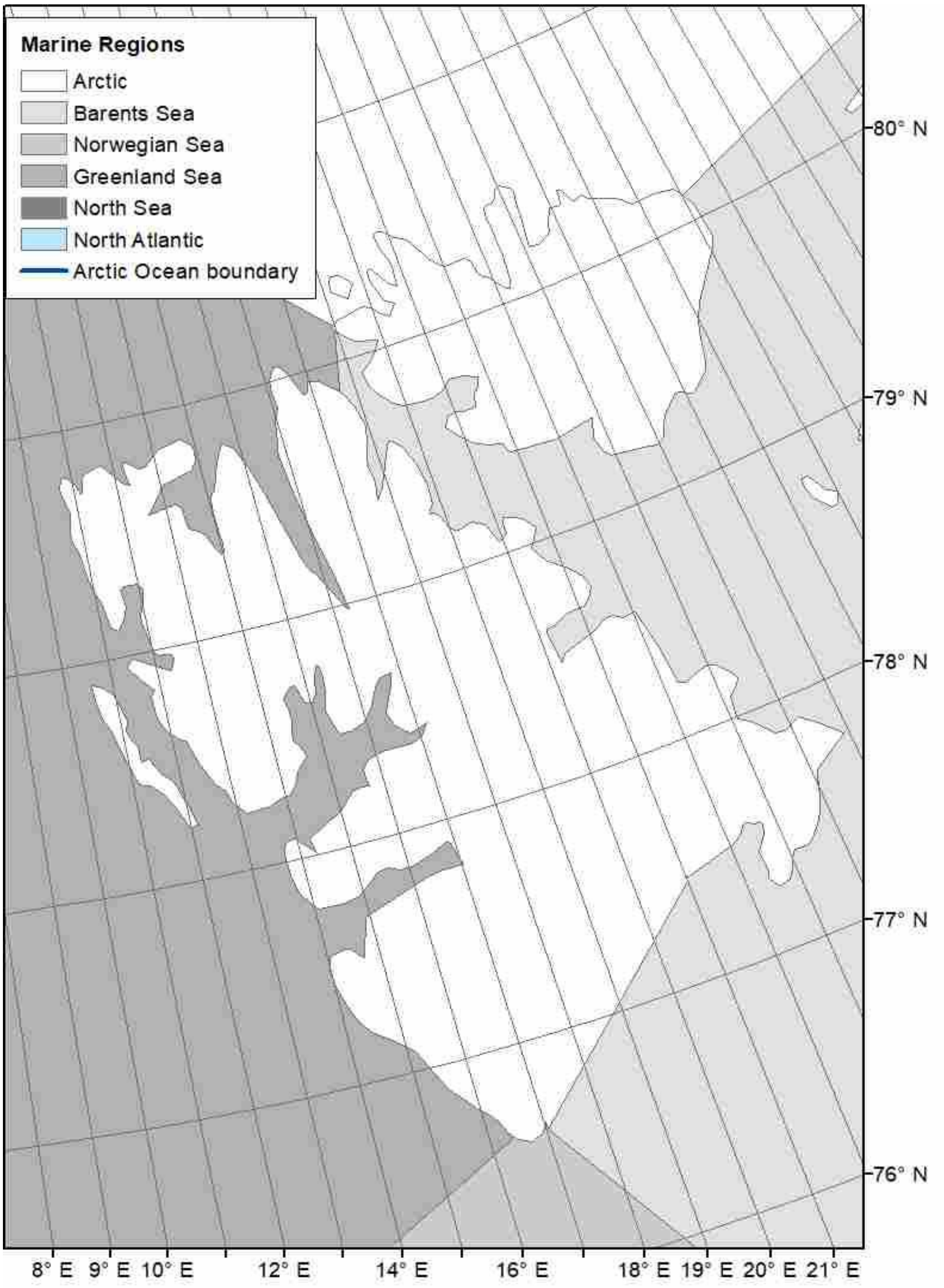
Persson, L., Carney Almroth, B.M., Collins, C.D., Cornell, S., de Wit, C.A., Diamond, M.L., Fantke, P., Hassellov, M., MacLeod, M., Ryberg, M.W., Sogaard Jorgensen, P., Villarrubia-Gomez, P., Wang, Z., Hauschild, M.Z., 2022. Outside the Safe Operating Space of the Planetary Boundary for Novel Entities. Environ Sci Technol 56 (3), 1510-1521.
Pfirman, S., Milliman, J.D., 1987. Morphology, geology and oceanography of the Hinlopen Strait and Trough, Svalbard, Norway. Polar Research 5 (3), 297-298.
Pogojeva, M., Zhdanov, I., Berezina, A., Lapenkov, A., Kosmach, D., Osadchiev, A., Hanke, G., Semiletov, I., Yakushev, E., 2021. Distribution of floating marine macro-litter in relation to oceanographic characteristics in the Russian Arctic Seas. Marine Pollution Bulletin 166, 9.
Polasek, L., Bering, J., Kim, H., Neitlich, P., Pister, B., Terwilliger, M., Nicolato, K., Turner, C., Jones, T., 2017. Marine debris in five national parks in Alaska. Marine Pollution Bulletin 117 (1-2), 371-379.
Primpke, S., Cross, R.K., Mintenig, S.M., Simon, M., Vianello, A., Gerdts, G., Vollertsen, J., 2020. Toward the Systematic Identification of Microplastics in the Environment: Evaluation of a New Independent Software Tool (siMPle) for Spectroscopic Analysis. Appl Spectrosc 74 (9), 1127-1138.
Ryan, P.G., Dilley, B.J., Ronconi, R.A., Connan, M., 2019. Rapid increase in Asian bottles in the South Atlantic Ocean indicates major debris inputs from ships. Proc Natl Acad Sci U S A 116 (42), 20892-20897.
Ryan, P.G., Weideman, E.A., Perold, V., Hofmeyr, G., Connan, M., 2021. Message in a bottle: Assessing the sources and origins of beach litter to tackle marine pollution. Environ Pollut 288, 117729.
Ryan, P.G., Weideman, E.A., Perold, V., Moloney, C.L., 2020. Toward Balancing the Budget: Surface Macro-Plastics Dominate the Mass of Particulate Pollution Stranded on Beaches. Frontiers in Marine Science 7.
Sander, L., 2016. Date-prints on stranded macroplastics: Inferring the timing and extent of overwash deposition on the Skallingen peninsula, Denmark. Mar Pollut Bull 109 (1), 373-377.
Stocker, A.N., Renner, A.H.H., Knol-Kauffman, M., 2020. Sea ice variability and maritime activity around Svalbard in the period 2012-2019. Scientific Reports 10 (1), 12.
Strand, K.O., Huserbraten, M., Dagestad, K.F., Mauritzen, C., Grosvik, B.E., Nogueira, L.A., Melsom, A., Rohrs, J., 2021. Potential sources of marine plastic from survey beaches in the Arctic and Northeast Atlantic. Sci Total Environ 790, 148009.
Tekman, M.B., Gutow, L., Bergmann, M., Peter, C., 2022. Litterbase. https://litterbase.awi.de.
Tekman, M.B., Krumpen, T., Bergmann, M., 2017. Marine litter on deep Arctic seafloor continues to increase and spreads to the North at the HAUSGARTEN observatory. Deep Sea Research Part I: Oceanographic Research Papers 120, 88-99.
Tekman, M.B., Wekerle, C., Lorenz, C., Primpke, S., Hasemann, C., Gerdts, G., Bergmann, M., 2020. Tying up Loose Ends of Microplastic Pollution in the Arctic: Distribution from the Sea Surface through the Water Column to Deep-Sea Sediments at the HAUSGARTEN Observatory. Environ Sci Technol 54 (7), 4079-4090.
Topçu, E.N., Tonay, A.M., Dede, A., Öztürk, A.A., Öztürk, B., 2013. Origin and abundance of marine litter along sandy beaches of the Turkish Western Black Sea Coast. Marine Environmental Research 85, 21-28.
van Gool, E., Campbell, M., Wallace, P., Hewitt, C.L., 2021. Marine Debris on New Zealand Beaches - Baseline Data to Evaluate Regional Variances. Frontiers in Environmental Science 9.
van Sebille, E., England, M.H., Froyland, G., 2012. Origin, dynamics and evolution of ocean garbage patches from observed surface drifters. Environmental Research Letters 7, 1-6.

Vesman, A., Moulin, E., Egorova, A., Zaikov, K., 2020. Marine litter pollution on the Northern Island of the Novaya Zemlya archipelago. Mar Pollut Bull 150, 110671.
Walther, B.A., Kunz, A., Hu, C.-S., 2018. Type and quantity of coastal debris pollution in Taiwan: A 12-year nationwide assessment using citizen science data. Marine Pollution Bulletin 135, 862-872.
Weideman, E.A., Perold, V., Omardien, A., Smyth, L.K., Ryan, P.G., 2020. Quantifying temporal trends in anthropogenic litter in a rocky intertidal habitat. Marine Pollution Bulletin 160, 111543.

# 8 Supplementary material

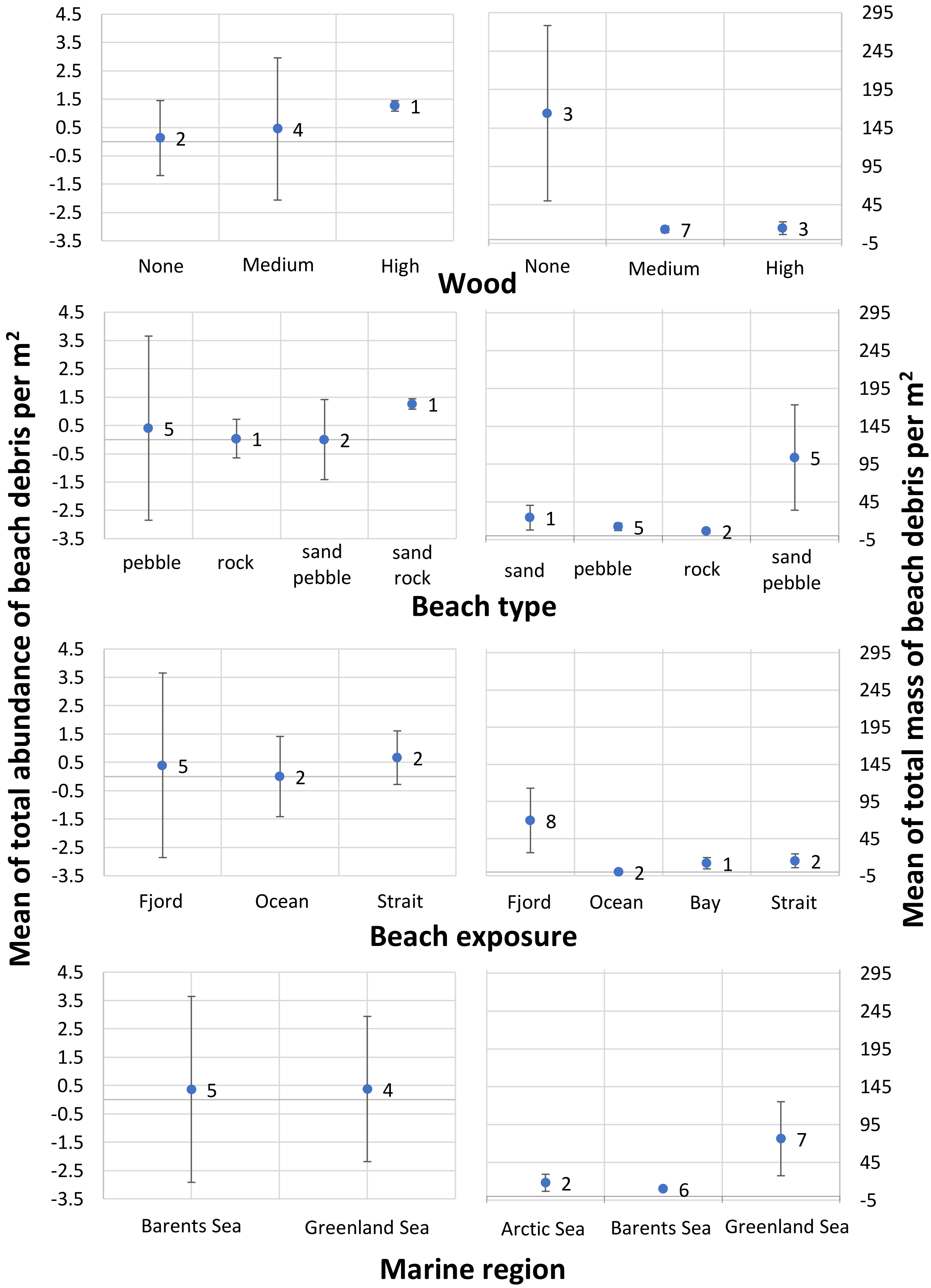
## 8.1 Arctic beach debris statistics

### 8.1.1 Map of marine regions




*Supplementary Figure 1. Map of Svalbard used to determine marine regions of locations. © M. B. Tekman (AWI).*

### 8.1.2 Categorical factors and their classification




*Supplementary Figure 2. The four categorical factors and their classification for the mean of abundance of debris items per m² (N = 9) and the mean of total mass of debris per m²(N = 15), showing the number of beaches assigned to the levels and the custom standard deviation. Visualizing unevenly spread data among categories.*

## 8.2 Abundance statistics

### 8.2.1 Correlation

#### Spearman Rho: Total Abundance; Transect area size

| | |
|---|---|
| Spearman rho | 0.762 |
| P-value | 0.017 |

#### Spearman Rho: Total Abundance; No. Observers

| | |
|---|---|
| Spearman rho | 0.863 |
| P-value | 0.003 |

#### Correlation: Total Abundance; Transect area size

| | |
|---|---|
| Pearson correlation | 0.219 |
| P-value | 0.571 |

#### Correlation: Total Abundance; No. Observers

| | |
|---|---|
| Pearson correlation | 0.596 |
| P-value | 0.091 |

### 8.2.2 Minitab analysis on total abundance of debris vs. categorical factors

Neither the raw nor LOG transformed data show a normal distribution, concluding no ANOVA is possible to run with this data. In the following portion we show the results of the Kruskal-Wallis Tests:

#### Kruskal-Wallis Test: Total Abundance versus Wood

Descriptive Statistics

| Wood | N | Median | Mean Rank | Z-Value |
|---|---|---|---|---|
| 1 | 2 | 0.12713 | 2.5 | -1.16 |
| 2 | 4 | 0.23984 | 4.3 | 0.35 |
| 3 | 1 | 1.25996 | 6.0 | 1.00 |
| Overall | 7 | | 4.0 | |

Test

| | |
|---|---|
| Null hypothesis | $H_0$: All medians are equal |
| Alternative hypothesis | $H_1$: At least one median is different |

| DF | H-Value | P-Value |
|---|---|---|
| 2 | 1.88 | 0.392 |

*The chi-square approximation may not be accurate when some sample sizes are less than 5.*

**Differences between medians are not statistically significant between total abundance of debris and wood, as p-value is greater than significance level (0.05).**

#### Kruskal-Wallis Test: Total Abundance versus Beach Type

### Descriptive Statistics

| Beach Type | N | Median | Mean Rank | Z-Value |
|---|---|---|---|---|
| 2 | 5 | 0.21949 | 6.0 | 1.22 |
| 3 | 1 | 0.03590 | 4.0 | -0.39 |
| 4 | 2 | 0.00000 | 1.5 | -2.05 |
| 5 | 1 | 1.25996 | 8.0 | 1.16 |
| Overall | 9 | | 5.0 | |

### Test

| | |
|---|---|
| Null hypothesis | $H_0$: All medians are equal |
| Alternative hypothesis | $H_1$: At least one median is different |

| Method | DF | H-Value | P-Value |
|---|---|---|---|
| Not adjusted for ties | 3 | 5.27 | 0.153 |
| Adjusted for ties | 3 | 5.31 | 0.150 |

*The chi-square approximation may not be accurate when some sample sizes are less than 5.*

**Differences between medians are not statistically significant between total abundance of debris and beach type, as p-value is greater than significance level (0.05).**

## Kruskal-Wallis Test: Total Abundance versus Beach Exposure

### Descriptive Statistics

| Beach Exposure | N | Median | Mean Rank | Z-Value |
|---|---|---|---|---|
| 1 | 5 | 0.219487 | 5.8 | 0.98 |
| 2 | 2 | 0.000000 | 1.5 | -2.05 |
| 4 | 2 | 0.663812 | 6.5 | 0.88 |
| Overall | 9 | | 5.0 | |

### Test

| | |
|---|---|
| Null hypothesis | $H_0$: All medians are equal |
| Alternative hypothesis | $H_1$: At least one median is different |

| Method | DF | H-Value | P-Value |
|---|---|---|---|
| Not adjusted for ties | 2 | 4.29 | 0.117 |
| Adjusted for ties | 2 | 4.33 | 0.115 |

*The chi-square approximation may not be accurate when some sample sizes are less than 5.*

**Differences between medians are not statistically significant between total abundance of debris and beach exposure, as p-value is greater than significance level (0.05).**

## Kruskal-Wallis Test: Total Abundance versus Marine Regions

### Descriptive Statistics

| Marine Regions | N | Median | Mean Rank | Z-Value |
|---|---|---|---|---|
| 2 | 5 | 0.218354 | 5.3 | 0.37 |
| 3 | 4 | 0.121351 | 4.6 | -0.37 |
| Overall | 9 | | 5.0 | |

### Test

| | |
|---|---|
| Null hypothesis | $H_0$: All medians are equal |
| Alternative hypothesis | $H_1$: At least one median is different |

| Method | DF | H-Value | P-Value |
|---|---|---|---|
| Not adjusted for ties | 1 | 0.13 | 0.713 |
| Adjusted for ties | 1 | 0.14 | 0.712 |

*The chi-square approximation may not be accurate when some sample sizes are less than 5.*

**Differences between medians are not statistically significant between total abundance of debris and marine regions, as p-value is greater than significance level (0.05).**

### 8.2.3 Minitab analysis on total plastic abundance of debris vs. categorical factors

#### Kruskal-Wallis Test: Total Plastic A versus Wood

##### Descriptive Statistics

| Wood | N | Median | Mean Rank | Z-Value |
|---|---|---|---|---|
| 1 | 2 | 0.12621 | 2.5 | -1.16 |
| 2 | 4 | 0.23812 | 4.3 | 0.35 |
| 3 | 1 | 1.25624 | 6.0 | 1.00 |
| Overall | 7 | | 4.0 | |

##### Test

| | |
|---|---|
| Null hypothesis | $H_0$: All medians are equal |
| Alternative hypothesis | $H_1$: At least one median is different |

| DF | H-Value | P-Value |
|---|---|---|
| 2 | 1.88 | 0.392 |

*The chi-square approximation may not be accurate when some sample sizes are less than 5.*

**Differences between medians are not statistically significant between total plastic abundance of debris and wood, as p-value is greater than significance level (0.05).**

#### Kruskal-Wallis Test: Total Plastic A versus Beach Type

##### Descriptive Statistics

| Beach Type | N | Median | Mean Rank | Z-Value |
|---|---|---|---|---|
| 2 | 5 | 0.21795 | 6.0 | 1.22 |
| 3 | 1 | 0.03590 | 4.0 | -0.39 |
| 4 | 2 | 0.00000 | 1.5 | -2.05 |
| 5 | 1 | 1.25624 | 8.0 | 1.16 |
| Overall | 9 | | 5.0 | |

##### Test

| | |
|---|---|
| Null hypothesis | $H_0$: All medians are equal |
| Alternative hypothesis | $H_1$: At least one median is different |

| Method | DF | H-Value | P-Value |
|---|---|---|---|
| Not adjusted for ties | 3 | 5.27 | 0.153 |
| Adjusted for ties | 3 | 5.31 | 0.150 |

*The chi-square approximation may not be accurate when some sample sizes are less than 5.*

**Differences between medians are not statistically significant between total plastic abundance of debris and beach type, as p-value is greater than significance level (0.05).**

### Kruskal-Wallis Test: Total Plastic A versus Beach Exposure

#### Descriptive Statistics

| Beach Exposure | N | Median | Mean Rank | Z-Value |
|---|---|---|---|---|
| 1 | 5 | 0.217949 | 5.8 | 0.98 |
| 2 | 2 | 0.000000 | 1.5 | -2.05 |
| 4 | 2 | 0.662836 | 6.5 | 0.88 |
| Overall | 9 | | 5.0 | |

#### Test

| | |
|---|---|
| Null hypothesis | $H_0$: All medians are equal |
| Alternative hypothesis | $H_1$: At least one median is different |

| Method | DF | H-Value | P-Value |
|---|---|---|---|
| Not adjusted for ties | 2 | 4.29 | 0.117 |
| Adjusted for ties | 2 | 4.33 | 0.115 |

*The chi-square approximation may not be accurate when some sample sizes are less than 5.*

**Differences between medians are not statistically significant between total plastic abundance of debris and beach exposure, as p-value is greater than significance level (0.05).**

### Kruskal-Wallis Test: Total Plastic A versus Marine Regions

#### Descriptive Statistics

| Marine Regions | N | Median | Mean Rank | Z-Value |
|---|---|---|---|---|
| 2 | 5 | 0.216531 | 5.3 | 0.37 |
| 3 | 4 | 0.120582 | 4.6 | -0.37 |
| Overall | 9 | | 5.0 | |

#### Test

| | |
|---|---|
| Null hypothesis | $H_0$: All medians are equal |
| Alternative hypothesis | $H_1$: At least one median is different |

| Method | DF | H-Value | P-Value |
|---|---|---|---|
| Not adjusted for ties | 1 | 0.13 | 0.713 |
| Adjusted for ties | 1 | 0.14 | 0.712 |

*The chi-square approximation may not be accurate when some sample sizes are less than 5.*

**Differences between medians are not statistically significant between total plastic abundance of debris and marine regions, as p-value is greater than significance level (0.05).**

### 8.2.4 Multivariate analysis (PRIMER) – ANOSIM & SIMPER

ANOSIM for Marine Regions:

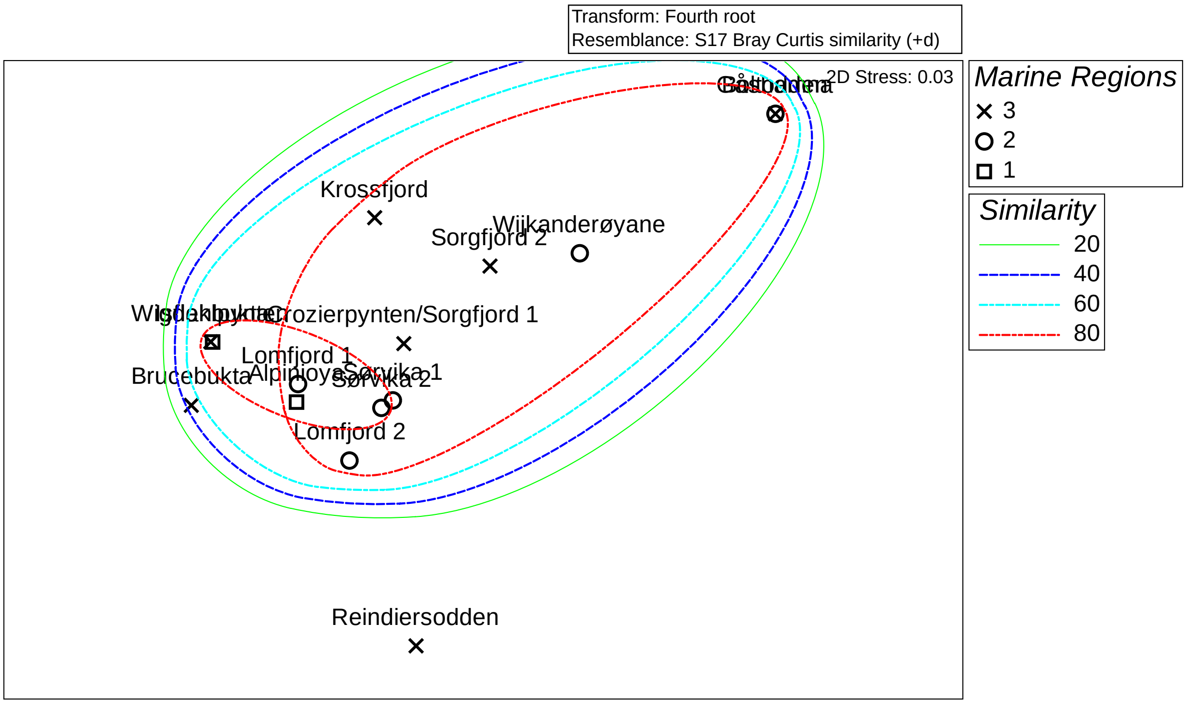
*Factor Values*
Factor: **Marine Regions**
2: Barents Sea
3: Greenland Sea

*Factor Groups*

| Sample | **Marine Regions** |
|---|---|
| Lomfjord 1 | 2 |
| Sørvika 2 | 2 |
| Lomfjord 2 | 2 |
| Wijkanderøyane | 2 |
| Boltodden | 2 |
| Wigdehlpynten | 3 |
| Gåshamna | 3 |
| Sorgfjord 2 | 3 |
| Krossfjord | 3 |

*Global Test*
**Sample statistic (Global R): -0.103**
**Significance level of sample statistic: 65.9%**
Number of permutations: 126 (All possible permutations)
Number of permuted statistics greater than or equal to Global R: 83

**Dissimilarity could be greater within groups, than between, as R-value is below 0. Though p-value of 0.659 suggests this is not statistically significant.**




*Supplementary Figure 3. MDS (Multidimensional scaling) plot for "Marine Regions" showing three levels of regions and similarity. Note: All beaches, excl. big pack beaches, are shown here.*

ANOSIM for Beach Exposure:

*Factor Values*
Factor: **Beach Exposure**
1: Fjord
4: Strait
2: Ocean

*Factor Groups*

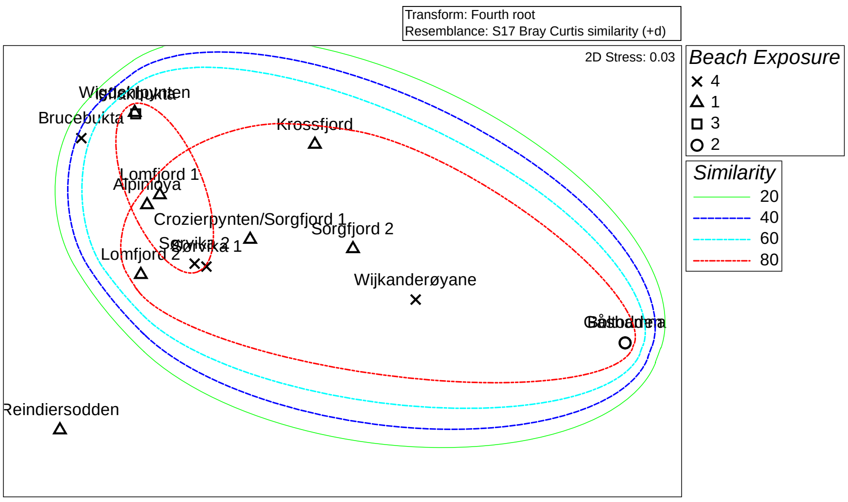
| Sample | Beach Exposure |
|---|---|
| Lomfjord 1 | 1 |
| Wigdehlpynten | 1 |
| Lomfjord 2 | 1 |
| Sorgfjord 2 | 1 |
| Krossfjord | 1 |
| Sørvika 2 | 4 |
| Wijkanderøyane | 4 |
| Gåshamna | 2 |
| Boltodden | 2 |

*Global Test*
**Sample statistic (Global R): 0.611**
**Significance level of sample statistic: 1.6%**
Number of permutations: 378 (All possible permutations)
Number of permuted statistics greater than or equal to Global R: 6

*Pairwise Tests*

| Groups | R Statistic | Significance Level % | Possible Permutations | Actual Permutations | Number >= Observed |
|---|---|---|---|---|---|
| 1, 4 | 0.127 | 23.8 | 21 | 21 | 5 |
| 1, 2 | **0.964** | **4.8** | 21 | 21 | 1 |
| 4, 2 | **0.5** | 33.3 | 3 | 3 | 1 |

**There is a statistically significant (p = 0.016) dissimilarity between groups (R = 0.611). Pariwise test suggests that the groups 1 & 2 (R = 0.964, p = 0.048) are most dissimilar. Note, that the groups do not have enough replicates per factor and results are not 100% valid.**




*Supplementary Figure 4. MDS plot for "Exposure" showing four levels of exposure and the similarity. Note: All beaches, excl. big pack beaches, are shown here.*

## SIMPER for Beach Exposure

*Group 1*
Average **similarity**: 67.42

| Species | Av.Abund | Av.Sim | Sim/SD | Contrib% | Cum.% |
|---|---|---|---|---|---|
| Plastic | 0.66 | 34.13 | 6.42 | 50.62 | 50.62 |
| Fishery/shipping (plastic) | 0.44 | 26.94 | 5.72 | 39.96 | 90.58 |

*Group 4*
Average similarity: 44.78

| Species | Av.Abund | Av.Sim | Sim/SD | Contrib% | Cum.% |
|---|---|---|---|---|---|
| Fishery/shipping (plastic) | 0.64 | 29.33 | ####### | 65.50 | 65.50 |
| Plastic | 0.58 | 15.45 | ####### | 34.50 | 100.00 |

*Group 2*
All the samples in the group are empty

*Groups 1 & 4*
Average **dissimilarity** = 36.98

| Species | Group 1 Av.Abund | Group 4 Av.Abund | Av.Diss | Diss/SD | Contrib% | Cum.% |
|---|---|---|---|---|---|---|
| Plastic | 0.66 | 0.58 | 14.23 | 1.62 | 38.47 | 38.47 |
| Fishery/shipping (plastic) | 0.44 | 0.64 | 7.74 | 1.59 | 20.94 | 59.41 |
| Glass/ceramics | 0.11 | 0.00 | 3.77 | 1.07 | 10.19 | 69.60 |
| Metal | 0.09 | 0.09 | 3.18 | 1.03 | 8.60 | 78.20 |
| Manufactured wood | 0.06 | 0.07 | 2.68 | 0.91 | 7.25 | 85.45 |
| Fishery/shipping (metal) | 0.00 | 0.07 | 2.03 | 0.93 | 5.48 | 90.93 |

***Groups 1 & 2***
Average dissimilarity = 100.00

| Species | Group 1 Av.Abund | Group 2 Av.Abund | Av.Diss | Diss/SD | Contrib% | Cum.% |
|---|---|---|---|---|---|---|
| Plastic | 0.66 | 0.00 | **45.24** | 7.47 | **45.24** | 45.24 |
| Fishery/shipping (plastic) | 0.44 | 0.00 | 33.12 | 3.17 | 33.12 | 78.37 |
| Glass/ceramics | 0.11 | 0.00 | 6.64 | 1.15 | 6.64 | 85.00 |
| Metal | 0.09 | 0.00 | 5.27 | 1.13 | 5.27 | 90.27 |

*Groups 4 & 2*
Average dissimilarity = 100.00

| Species | Group 4 Av.Abund | Group 2 Av.Abund | Av.Diss | Diss/SD | Contrib% | Cum.% |
|---|---|---|---|---|---|---|
| Fishery/shipping (plastic) | 0.64 | 0.00 | 51.62 | 3.22 | 51.62 | 51.62 |
| Plastic | 0.58 | 0.00 | 37.89 | 9.66 | 37.89 | 89.52 |
| Metal | 0.09 | 0.00 | 3.91 | 0.87 | 3.91 | 93.43 |

**The greatest dissimilarity between groups Fjord (1) and Ocean (2) is generated by plastic (45%).**

ANOSIM for Beach Type

*Factor Values*
Factor: **Beach Type**
2: Pebble
5: Sand, Rock
3: Rock
4: Sand, Pebble

*Factor Groups*

| Sample | **Beach Type** |
|---|---|
| Lomfjord 1 | 2 |
| Sørvika 2 | 2 |
| Lomfjord 2 | 2 |
| Sorgfjord 2 | 2 |
| Krossfjord | 2 |
| Wigdehlpynten | 5 |
| Wijkanderøyane | 3 |
| Gåshamna | 4 |
| Boltodden | 4 |

*Global Test*
**Sample statistic (Global R): 0.665**
**Significance level of sample statistic: 1.5%**
Number of permutations: 756 (All possible permutations)
Number of permuted statistics greater than or equal to Global R: 11

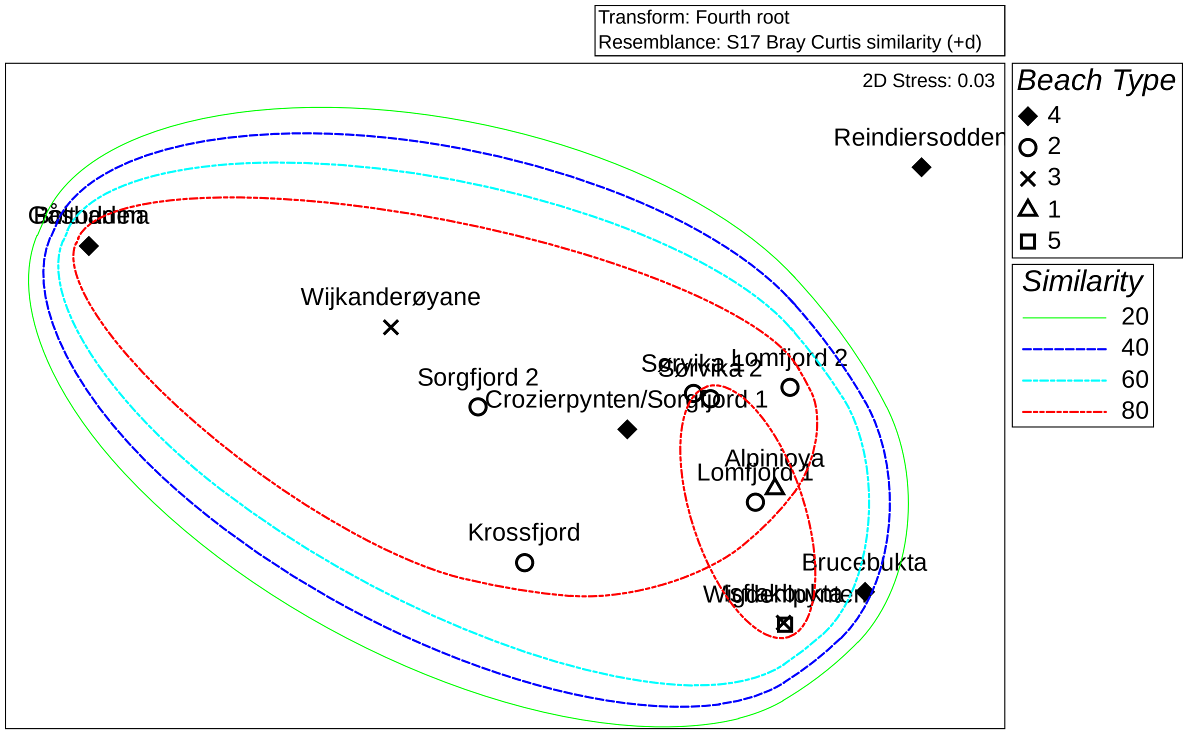
*Pairwise Tests*

| Groups | R Statistic | Significance Level % | Possible Permutations | Actual Permutations | Number >= Observed |
|---|---|---|---|---|---|
| 2, 5 | 0.28 | 33.3 | 6 | 6 | 2 |
| 2, 3 | 0.24 | 33.3 | 6 | 6 | 2 |
| **2, 4** | **0.927** | **4.8** | 21 | 21 | 1 |
| 5, 4 | 1 | 33.3 | 3 | 3 | 1 |
| 3, 4 | 1 | 33.3 | 3 | 3 | 1 |

*Failed Pairwise Tests*

| Groups | Error |
|---|---|
| 5, 3 | At least one level must be larger than 1 in size |

**There is a statistically significant (p = 0.015) dissimilarity between groups (R = 0.665). Pariwise test suggests that the groups 2 & 4 (R = 0.927, p = 0.048) are most dissimilar. Note, that the groups do not have enough replicates per factor and results are not 100% valid.**




*Supplementary Figure 5. MDS plot for "Beach Type" showing five different types and the similarity. Note: All beaches, excl. big pack beaches, are shown here.*

## SIMPER for Beach Type:

*Group 2*
Average similarity: 67.31

| Species | Av.Abund | Av.Sim | Sim/SD | Contrib% | Cum.% |
|---|---|---|---|---|---|
| Plastic | 0.63 | 33.09 | 5.89 | 49.17 | 49.17 |
| Fishery/shipping (plastic) | 0.54 | 28.41 | 9.38 | 42.21 | 91.37 |

*Group 5*
Less than 2 samples in group

*Group 3*
Less than 2 samples in group

*Group 4*
All the samples in the group are empty

*Groups 2 & 5*
Average dissimilarity = 35.02

| Species | Group 2 Av.Abund | Group 5 Av.Abund | Av.Diss | Diss/SD | Contrib% | Cum.% |
|---|---|---|---|---|---|---|
| Plastic | 0.63 | 1.05 | 13.17 | 1.48 | 37.61 | 37.61 |
| Clothing/textiles | 0.00 | 0.20 | 5.75 | 5.54 | 16.41 | 54.02 |
| Fishery/shipping (plastic) | 0.54 | 0.37 | 4.94 | 1.30 | 14.11 | 68.12 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Glass/ceramics | 0.07 | 0.20 | 3.73 | 1.22 | 10.65 | 78.78 |
| Metal | 0.09 | 0.17 | 2.60 | 0.94 | 7.43 | 86.21 |
| Manufactured wood | 0.09 | 0.00 | 2.44 | 1.08 | 6.95 | 93.16 |

*Groups 2 & 3*
Average dissimilarity = 38.76

| | Group 2 | Group 3 | | | | |
|---|---|---|---|---|---|---|
| Species | Av.Abund | Av.Abund | Av.Diss | Diss/SD | Contrib% | Cum.% |
| Plastic | 0.63 | 0.23 | 17.63 | 2.95 | 45.49 | 45.49 |
| Fishery/shipping (plastic) | 0.54 | 0.43 | 6.58 | 1.34 | 16.98 | 62.47 |
| Metal | 0.09 | 0.00 | 3.78 | 1.06 | 9.75 | 72.22 |
| Manufactured wood | 0.09 | 0.00 | 3.77 | 1.07 | 9.73 | 81.96 |
| Glass/ceramics | 0.07 | 0.00 | 3.25 | 0.73 | 8.39 | 90.34 |

*Groups 5 & 3*
Average dissimilarity = 54.99

| | Group 5 | Group 3 | | | | |
|---|---|---|---|---|---|---|
| Species | Av.Abund | Av.Abund | Av.Diss | Diss/SD | Contrib% | Cum.% |
| Plastic | 1.05 | 0.23 | 31.52 | Undefined! | 57.32 | 57.32 |
| Clothing/textiles | 0.20 | 0.00 | 7.46 | Undefined! | 13.57 | 70.89 |
| Glass/ceramics | 0.20 | 0.00 | 7.46 | Undefined! | 13.57 | 84.46 |
| Metal | 0.17 | 0.00 | 6.27 | Undefined! | 11.41 | 95.87 |

***Groups 2 & 4***
Average dissimilarity = 100.00

| | Group 2 | Group 4 | | | | |
|---|---|---|---|---|---|---|
| Species | Av.Abund | Av.Abund | Av.Diss | Diss/SD | Contrib% | Cum.% |
| Plastic | 0.63 | 0.00 | **42.85** | 9.71 | **42.85** | 42.85 |
| Fishery/shipping (plastic) | 0.54 | 0.00 | 36.96 | 5.20 | 36.96 | 79.81 |
| Manufactured wood | 0.09 | 0.00 | 5.18 | 1.12 | 5.18 | 84.99 |
| Metal | 0.09 | 0.00 | 5.16 | 1.12 | 5.16 | 90.15 |

*Groups 5 & 4*
Average dissimilarity = 100.00

| | Group 5 | Group 4 | | | | |
|---|---|---|---|---|---|---|
| Species | Av.Abund | Av.Abund | Av.Diss | Diss/SD | Contrib% | Cum.% |
| Plastic | 1.05 | 0.00 | 53.26 | Undefined! | 53.26 | 53.26 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Fishery/shipping (plastic) | 0.37 | 0.00 | 18.56 | Undefined! | 18.56 | 71.82 |
| Clothing/textiles | 0.20 | 0.00 | 9.92 | Undefined! | 9.92 | 81.74 |
| Glass/ceramics | 0.20 | 0.00 | 9.92 | Undefined! | 9.92 | 91.66 |

*Groups 3 & 4*
Average dissimilarity = 100.00

| | Group 3 | Group 4 | | | | |
|---|---|---|---|---|---|---|
| Species | Av.Abund | Av.Abund | Av.Diss | Diss/SD | Contrib% | Cum.% |
| Fishery/shipping (plastic) | 0.43 | 0.00 | 65.50 | Undefined! | 65.50 | 65.50 |
| Plastic | 0.23 | 0.00 | 34.50 | Undefined! | 34.50 | 100.00 |

**The greatest dissimilarity between groups Pebble (2) and Sand/Pebble (4) is generated by plastic (43%).**

## 8.3 Mass statistics

### 8.3.1 Correlation

#### Spearman Rho: Total Mass; Transect area size

| | |
|---|---|
| Spearman rho | 0.495 |
| P-value | 0.061 |

#### Spearman Rho: Total Mass; No. Observers

| | |
|---|---|
| Spearman rho | 0.659 |
| P-value | 0.007 |

#### Correlation: Total Mass; Transect area size

| | |
|---|---|
| Pearson correlation | -0.075 |
| P-value | 0.791 |

#### Correlation: Total Mass; No. Observers

| | |
|---|---|
| Pearson correlation | 0.032 |
| P-value | 0.910 |

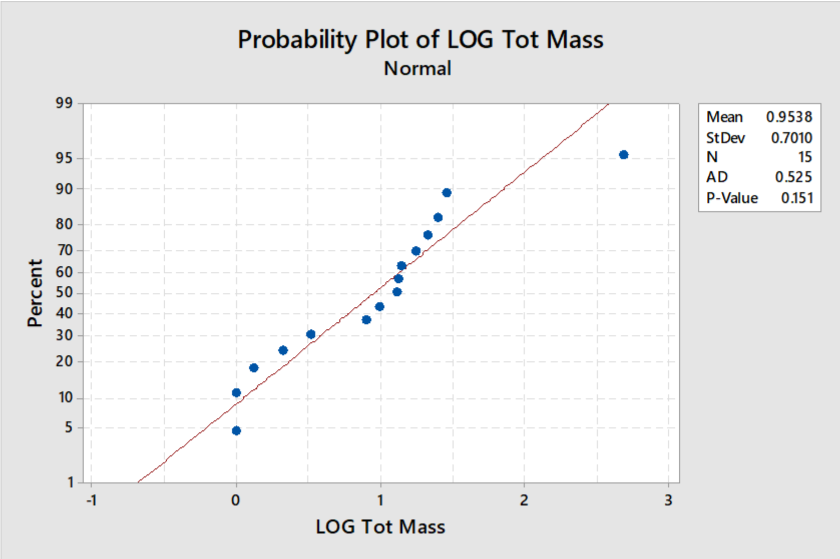
### 8.3.2 Minitab analysis on total mass of debris vs. categorical factors

#### Normality Test of Total Mass

shows no normal distribution, conclusion: ANOVA not possible, try LOG transformed data.

#### Normality Test and Probability Plot of LOG Tot Mass

p=0.151, we conclude the transformed data follow a normal distribution, as the significance level of 0.05 is exceeded -> continue with Variance Test




## Test and CI for Two Variances: LOG Tot Mass; Wood

### Method

| |
|---|
| $\sigma_1$: standard deviation of LOG Tot Mass |
| $\sigma_2$: standard deviation of Wood |
| Ratio: $\sigma_1/\sigma_2$ |
| The Bonett and Levene's methods are valid for any continuous distribution. |

### Descriptive Statistics

| Variable | N | StDev | Variance | 95% CI for σ |
|---|---|---|---|---|
| LOG Tot Mass | 15 | 0.701 | 0.491 | (0.449; 1.258) |
| Wood | 13 | 0.707 | 0.500 | (0.518; 1.138) |

### Ratio of Standard Deviations

| Estimated Ratio | 95% CI for Ratio using Bonett | 95% CI for Ratio using Levene |
|---|---|---|
| 0.991298 | (0.436; 1.734) | (0.422; 2.942) |

### Test

| | |
|---|---|
| Null hypothesis | $H_0$: $\sigma_1 / \sigma_2 = 1$ |
| Alternative hypothesis | $H_1$: $\sigma_1 / \sigma_2 \neq 1$ |
| Significance level | $\alpha = 0.05$ |

| Method | Test Statistic | DF1 | DF2 | P-Value |
|---|---|---|---|---|
| Bonett | * | | | 0.976 |
| Levene | 0.04 | 1 | 26 | 0.837 |

Failed test for two variances, no ANOVA possible, continue with Kruskal-Wallis Test

## Kruskal-Wallis Test: Total Mass versus Wood

### Descriptive Statistics

| Wood | N | Median | Mean Rank | Z-Value |
|---|---|---|---|---|
| 1 | 3 | 8.8180 | 6.3 | -0.34 |
| 2 | 7 | 12.8440 | 7.0 | 0.00 |
| 3 | 3 | 12.1006 | 7.7 | 0.34 |
| Overall | 13 | | 7.0 | |

### Test

| | |
|---|---|
| Null hypothesis | $H_0$: All medians are equal |
| Alternative hypothesis | $H_1$: At least one median is different |

| DF | H-Value | P-Value |
|---|---|---|
| 2 | 0.18 | 0.916 |

*The chi-square approximation may not be accurate when some sample sizes are less than 5.*

**Differences between medians are not statistically significant for Total Mass vs. Wood.**

## Test and CI for Two Variances: LOG Tot Mass; Beach Type

### Method

| |
|---|
| $\sigma_1$: standard deviation of LOG Tot Mass |
| $\sigma_2$: standard deviation of Beach Type |
| Ratio: $\sigma_1/\sigma_2$ |
| The Bonett and Levene's methods are valid for any continuous distribution. |

### Descriptive Statistics

| Variable | N | StDev | Variance | 95% CI for σ |
|---|---|---|---|---|
| LOG Tot Mass | 15 | 0.701 | 0.491 | (0.449; 1.258) |
| Beach Type | 15 | 1.163 | 1.352 | (0.919; 1.693) |

### Ratio of Standard Deviations

| Estimated Ratio | 95% CI for Ratio using Bonett | 95% CI for Ratio using Levene |
|---|---|---|
| 0.602753 | (0.278; 0.974) | (0.231; 0.859) |

### Test

| | |
|---|---|
| Null hypothesis | $H_0$: $\sigma_1 / \sigma_2 = 1$ |
| Alternative hypothesis | $H_1$: $\sigma_1 / \sigma_2 \neq 1$ |
| Significance level | $\alpha = 0.05$ |

| Method | Test Statistic | DF1 | DF2 | P-Value |
|---|---|---|---|---|
| Bonett | 4.24 | 1 | | 0.040 |
| Levene | 7.00 | 1 | 28 | 0.013 |

Basing conclusions on **Levene Method**, as we have less than 20 samples. The p-values are lower than our significance level (0.05), concluding the standard deviations between beach types are different. Possible to continue with ANOVA:

## One-way ANOVA: LOG Tot Mass versus Beach Type

### Method

| | |
|---|---|
| Null hypothesis | All means are equal |

| | |
|---|---|
| Alternative hypothesis | Not all means are equal |
| Significance level | α = 0.05 |

*Equal variances were assumed for the analysis.*

### Factor Information

| Factor | Levels | Values |
|---|---|---|
| Beach Type | 5 | 1; 2; 3; 4; 5 |

### Analysis of Variance

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Beach Type | 4 | 0.4813 | 0.1203 | 0.19 | 0.939 |
| Error | 10 | 6.3974 | 0.6397 | | |
| Total | 14 | 6.8787 | | | |

### Model Summary

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 0.799836 | 7.00% | 0.00% | * |

### Means

| Beach Type | N | Mean | StDev | 95% CI |
|---|---|---|---|---|
| 1 | 1 | 1.399 | * | (-0.383; 3.181) |
| 2 | 6 | 0.922 | 0.413 | (0.194; 1.649) |
| 3 | 2 | 0.610 | 0.702 | (-0.650; 1.871) |
| 4 | 5 | 1.008 | 1.124 | (0.211; 1.805) |
| 5 | 1 | 1.117 | * | (-0.665; 2.899) |

*Pooled StDev = 0.799836*

## Tukey Pairwise Comparisons

### Grouping Information Using the Tukey Method and 95% Confidence

| Beach Type | N | Mean | Grouping |
|---|---|---|---|
| 1 | 1 | 1.399 | A |
| 5 | 1 | 1.117 | A |
| 4 | 5 | 1.008 | A |
| 2 | 6 | 0.922 | A |
| 3 | 2 | 0.610 | A |

*Means that do not share a letter are significantly different.*

### Tukey Simultaneous Tests for Differences of Means

| Difference of Levels | Difference of Means | SE of Difference | 95% CI | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 2 - 1 | -0.477 | 0.864 | (-3.318; 2.364) | -0.55 | 0.979 |
| 3 - 1 | -0.788 | 0.980 | (-4.009; 2.433) | -0.80 | 0.923 |
| 4 - 1 | -0.391 | 0.876 | (-3.272; 2.490) | -0.45 | 0.991 |
| 5 - 1 | -0.28 | 1.13 | (-4.00; 3.44) | -0.25 | 0.999 |
| 3 - 2 | -0.311 | 0.653 | (-2.459; 1.836) | -0.48 | 0.988 |
| 4 - 2 | 0.086 | 0.484 | (-1.506; 1.679) | 0.18 | 1.000 |

| | | | | | |
|---|---|---|---|---|---|
| 5 - 2 | 0.196 | 0.864 | (-2.645; 3.036) | 0.23 | 0.999 |
| 4 - 3 | 0.398 | 0.669 | (-1.803; 2.598) | 0.59 | 0.973 |
| 5 - 3 | 0.507 | 0.980 | (-2.714; 3.728) | 0.52 | 0.984 |
| 5 - 4 | 0.109 | 0.876 | (-2.772; 2.990) | 0.12 | 1.000 |

*Individual confidence level = 99.18%*

**P-value of 0.939 is greater than significance level (0.05), concluding the beach types do not differ significantly regarding total mass of debris.**

## Test and CI for Two Variances: LOG Tot Mass; Beach Exposure

### Method

| |
|---|
| $\sigma_1$: standard deviation of LOG Tot Mass |
| $\sigma_2$: standard deviation of Beach Exposure |
| Ratio: $\sigma_1/\sigma_2$ |
| The Bonett and Levene's methods are valid for any continuous distribution. |

### Descriptive Statistics

| Variable | N | StDev | Variance | 95% CI for σ |
|---|---|---|---|---|
| LOG Tot Mass | 15 | 0.701 | 0.491 | (0.449; 1.258) |
| Beach Exposure | 15 | 1.335 | 1.781 | (1.015; 2.019) |

### Ratio of Standard Deviations

| Estimated Ratio | 95% CI for Ratio using Bonett | 95% CI for Ratio using Levene |
|---|---|---|
| 0.525246 | (0.242; 0.888) | (0.193; 1.480) |

### Test

| | |
|---|---|
| Null hypothesis | $H_0$: $\sigma_1 / \sigma_2 = 1$ |
| Alternative hypothesis | $H_1$: $\sigma_1 / \sigma_2 \neq 1$ |
| Significance level | $\alpha = 0.05$ |

| Method | Test Statistic | DF1 | DF2 | P-Value |
|---|---|---|---|---|
| Bonett | 5.44 | 1 | | 0.020 |
| Levene | 2.36 | 1 | 28 | 0.136 |

Levene shows higher p-value than significance level, no ANOVA possible.

## Kruskal-Wallis Test: Total Mass versus Beach Exposure

### Descriptive Statistics

| Beach Exposure | N | Median | Mean Rank | Z-Value |
|---|---|---|---|---|
| 1 | 8 | 10.4593 | 8.8 | 0.69 |
| 2 | 2 | 0.0000 | 1.5 | -2.21 |
| 3 | 1 | 11.7778 | 8.0 | 0.00 |
| 4 | 4 | 16.4102 | 9.8 | 0.91 |
| Overall | 15 | | 8.0 | |

### Test

| | |
|---|---|
| Null hypothesis | $H_0$: All medians are equal |

| | |
|---|---|
| Alternative hypothesis | $H_1$: At least one median is different |

| Method | DF | H-Value | P-Value |
|---|---|---|---|
| Not adjusted for ties | 3 | 5.06 | 0.167 |
| Adjusted for ties | 3 | 5.07 | 0.167 |

*The chi-square approximation may not be accurate when some sample sizes are less than 5.*

**P-value of 0.167 is higher than significance level, concluding no statistically significant differences between the medians.**

## Test and CI for Two Variances: LOG Tot Mass; Marine Regions

### Method

| |
|---|
| $\sigma_1$: standard deviation of LOG Tot Mass |
| $\sigma_2$: standard deviation of Marine Regions |
| Ratio: $\sigma_1/\sigma_2$ |
| The Bonett and Levene's methods are valid for any continuous distribution. |

### Descriptive Statistics

| Variable | N | StDev | Variance | 95% CI for σ |
|---|---|---|---|---|
| LOG Tot Mass | 15 | 0.701 | 0.491 | (0.449; 1.258) |
| Marine Regions | 15 | 0.724 | 0.524 | (0.511; 1.179) |

### Ratio of Standard Deviations

| Estimated Ratio | 95% CI for Ratio using Bonett | 95% CI for Ratio using Levene |
|---|---|---|
| 0.968507 | (0.444; 1.814) | (0.368; 1.721) |

### Test

| | |
|---|---|
| Null hypothesis | $H_0$: $\sigma_1 / \sigma_2 = 1$ |
| Alternative hypothesis | $H_1$: $\sigma_1 / \sigma_2 \neq 1$ |
| Significance level | $\alpha = 0.05$ |

| Method | Test Statistic | DF1 | DF2 | P-Value |
|---|---|---|---|---|
| Bonett | 0.01 | 1 | | 0.913 |
| Levene | 0.29 | 1 | 28 | 0.595 |

Levene shows higher p-value than significance level, no ANOVA possible.

## Kruskal-Wallis Test: Total Mass versus Marine Regions

### Descriptive Statistics

| Marine Regions | N | Median | Mean Rank | Z-Value |
|---|---|---|---|---|
| 1 | 2 | 17.9102 | 10.5 | 0.85 |
| 2 | 6 | 10.8310 | 7.4 | -0.41 |
| 3 | 7 | 7.0081 | 7.8 | -0.17 |
| Overall | 15 | | 8.0 | |

### Test

| | |
|---|---|
| Null hypothesis | $H_0$: All medians are equal |
| Alternative hypothesis | $H_1$: At least one median is different |

| Method | DF | H-Value | P-Value |
|---|---|---|---|
| Not adjusted for ties | 2 | 0.74 | 0.690 |
| Adjusted for ties | 2 | 0.74 | 0.689 |

*The chi-square approximation may not be accurate when some sample sizes are less than 5.*

**P-value of 0.690 is higher than significance level, concluding no statistically significant differences between the medians.**

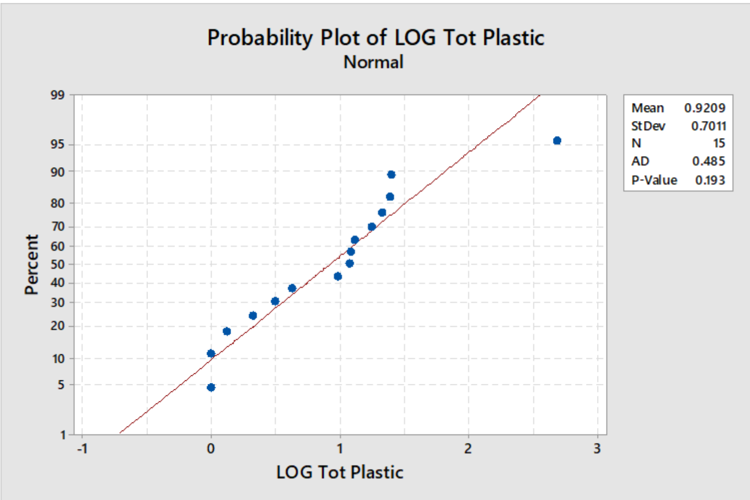
### 8.3.3 Minitab analysis on total plastic mass of debris vs. categorical factors

#### Normality Test of Total Plastic

no normal distribution, try with LOG transformation

#### Normality Test and Probability Plot of LOG Tot Plastic

normal distribution confirmed




#### Test and CI for Two Variances: LOG Tot Plastic; Wood

#### Method

| |
|---|
| $\sigma_1$: standard deviation of LOG Tot Plastic |
| $\sigma_2$: standard deviation of Wood |
| Ratio: $\sigma_1/\sigma_2$ |
| The Bonett and Levene's methods are valid for any continuous distribution. |

#### Descriptive Statistics

| Variable | N | StDev | Variance | 95% CI for σ |
|---|---|---|---|---|
| LOG Tot Plastic | 15 | 0.701 | 0.492 | (0.443; 1.276) |
| Wood | 13 | 0.707 | 0.500 | (0.518; 1.138) |

#### Ratio of Standard Deviations

| Estimated Ratio | 95% CI for Ratio using Bonett | 95% CI for Ratio using Levene |
|---|---|---|
| 0.991529 | (0.424; 1.740) | (0.453; 2.985) |

#### Test

| | |
|---|---|
| Null hypothesis | $H_0: \sigma_1 / \sigma_2 = 1$ |
| Alternative hypothesis | $H_1: \sigma_1 / \sigma_2 \neq 1$ |
| Significance level | $\alpha = 0.05$ |

| Method | Test Statistic | DF1 | DF2 | P-Value |
|---|---|---|---|---|
| Bonett | * | | | 0.977 |
| Levene | 0.07 | 1 | 26 | 0.789 |

Levene shows higher p-value than significance level, no ANOVA possible, continue with Kruskal-Wallis Test:

## Kruskal-Wallis Test: Total Plastic versus Wood

### Descriptive Statistics

| Wood | N | Median | Mean Rank | Z-Value |
|---|---|---|---|---|
| 1 | 3 | 8.4972 | 6.3 | -0.34 |
| 2 | 7 | 11.8628 | 7.0 | 0.00 |
| 3 | 3 | 11.0000 | 7.7 | 0.34 |
| Overall | 13 | | 7.0 | |

### Test

| | |
|---|---|
| Null hypothesis | $H_0$: All medians are equal |
| Alternative hypothesis | $H_1$: At least one median is different |

| DF | H-Value | P-Value |
|---|---|---|
| 2 | 0.18 | 0.916 |

*The chi-square approximation may not be accurate when some sample sizes are less than 5.*

**P-value of 0.916 is higher than significance level, concluding no statistically significant differences between medians.**

## Test and CI for Two Variances: LOG Tot Plastic; Beach Type

### Method

| |
|---|
| $\sigma_1$: standard deviation of LOG Tot Plastic |
| $\sigma_2$: standard deviation of Beach Type |
| Ratio: $\sigma_1/\sigma_2$ |
| The Bonett and Levene's methods are valid for any continuous distribution. |

### Descriptive Statistics

| Variable | N | StDev | Variance | 95% CI for σ |
|---|---|---|---|---|
| LOG Tot Plastic | 15 | 0.701 | 0.492 | (0.443; 1.276) |
| Beach Type | 15 | 1.163 | 1.352 | (0.919; 1.693) |

### Ratio of Standard Deviations

| Estimated Ratio | 95% CI for Ratio using Bonett | 95% CI for Ratio using Levene |
|---|---|---|
| 0.602894 | (0.270; 0.978) | (0.247; 0.867) |

### Test

| | |
|---|---|
| Null hypothesis | $H_0: \sigma_1 / \sigma_2 = 1$ |

| | |
|---|---|
| Alternative hypothesis | $H_1$: $\sigma_1$ / $\sigma_2$ ≠ 1 |
| Significance level | α = 0.05 |

| Method | Test Statistic | DF1 | DF2 | P-Value |
|---|---|---|---|---|
| Bonett | 4.18 | 1 | | 0.041 |
| Levene | 6.85 | 1 | 28 | 0.014 |

ANOVA possible, as p-value of 0.014 is lower than significance level.

## One-way ANOVA: LOG Tot Plastic versus Beach Type

### Method

| | |
|---|---|
| Null hypothesis | All means are equal |
| Alternative hypothesis | Not all means are equal |
| Significance level | α = 0.05 |

*Equal variances were assumed for the analysis.*

### Factor Information

| Factor | Levels | Values |
|---|---|---|
| Beach Type | 5 | 1; 2; 3; 4; 5 |

### Analysis of Variance

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Beach Type | 4 | 0.4584 | 0.1146 | 0.18 | 0.944 |
| Error | 10 | 6.4235 | 0.6423 | | |
| Total | 14 | 6.8819 | | | |

### Model Summary

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 0.801467 | 6.66% | 0.00% | * |

### Means

| Beach Type | N | Mean | StDev | 95% CI |
|---|---|---|---|---|
| 1 | 1 | 1.393 | * | (-0.393; 3.179) |
| 2 | 6 | 0.910 | 0.413 | (0.181; 1.639) |
| 3 | 2 | 0.597 | 0.682 | (-0.666; 1.860) |
| 4 | 5 | 0.939 | 1.130 | (0.140; 1.737) |
| 5 | 1 | 1.072 | * | (-0.713; 2.858) |

*Pooled StDev = 0.801467*

## Tukey Pairwise Comparisons

### Grouping Information Using the Tukey Method and 95% Confidence

| Beach Type | N | Mean | Grouping |
|---|---|---|---|
| 1 | 1 | 1.393 | A |
| 5 | 1 | 1.072 | A |
| 4 | 5 | 0.939 | A |
| 2 | 6 | 0.910 | A |
| 3 | 2 | 0.597 | A |

*Means that do not share a letter are significantly different.*

### Tukey Simultaneous Tests for Differences of Means

| Difference of Levels | Difference of Means | SE of Difference | 95% CI | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 2 - 1 | -0.483 | 0.866 | (-3.329; 2.363) | -0.56 | 0.978 |
| 3 - 1 | -0.796 | 0.982 | (-4.024; 2.431) | -0.81 | 0.921 |
| 4 - 1 | -0.454 | 0.878 | (-3.341; 2.432) | -0.52 | 0.984 |
| 5 - 1 | -0.32 | 1.13 | (-4.05; 3.41) | -0.28 | 0.998 |
| 3 - 2 | -0.313 | 0.654 | (-2.465; 1.838) | -0.48 | 0.988 |
| 4 - 2 | 0.029 | 0.485 | (-1.567; 1.624) | 0.06 | 1.000 |
| 5 - 2 | 0.162 | 0.866 | (-2.684; 3.009) | 0.19 | 1.000 |
| 4 - 3 | 0.342 | 0.671 | (-1.863; 2.547) | 0.51 | 0.984 |
| 5 - 3 | 0.476 | 0.982 | (-2.752; 3.703) | 0.48 | 0.987 |
| 5 - 4 | 0.134 | 0.878 | (-2.753; 3.020) | 0.15 | 1.000 |

*Individual confidence level = 99.18%*

**P-value of 0.944 is greater than significance level, concluding the beach types do not differ significantly regarding total plastic mass of debris.**

### Test and CI for Two Variances: LOG Tot Plastic; Beach Exposure

### Method

| |
|---|
| $\sigma_1$: standard deviation of LOG Tot Plastic |
| $\sigma_2$: standard deviation of Beach Exposure |
| Ratio: $\sigma_1/\sigma_2$ |
| The Bonett and Levene's methods are valid for any continuous distribution. |

### Descriptive Statistics

| Variable | N | StDev | Variance | 95% CI for σ |
|---|---|---|---|---|
| LOG Tot Plastic | 15 | 0.701 | 0.492 | (0.443; 1.276) |
| Beach Exposure | 15 | 1.335 | 1.781 | (1.015; 2.019) |

### Ratio of Standard Deviations

| Estimated Ratio | 95% CI for Ratio using Bonett | 95% CI for Ratio using Levene |
|---|---|---|
| 0.525369 | (0.235; 0.891) | (0.205; 1.505) |

### Test

| | |
|---|---|
| Null hypothesis | $H_0$: $\sigma_1 / \sigma_2 = 1$ |
| Alternative hypothesis | $H_1$: $\sigma_1 / \sigma_2 \neq 1$ |
| Significance level | $\alpha = 0.05$ |

| Method | Test Statistic | DF1 | DF2 | P-Value |
|---|---|---|---|---|
| Bonett | 5.40 | 1 | | 0.020 |
| Levene | 2.28 | 1 | 28 | 0.142 |

p-value higher than significance level, no ANOVA possible, as standard deviation between beach exposures is not different. Continue with Kruskal-Wallis Test:

## Kruskal-Wallis Test: Total Plastic versus Beach Exposure

### Descriptive Statistics

| Beach Exposure | N | Median | Mean Rank | Z-Value |
|---|---|---|---|---|
| 1 | 8 | 9.6564 | 8.8 | 0.69 |
| 2 | 2 | 0.0000 | 1.5 | -2.21 |
| 3 | 1 | 11.0000 | 9.0 | 0.23 |
| 4 | 4 | 15.9196 | 9.5 | 0.78 |
| Overall | 15 | | 8.0 | |

### Test

| | |
|---|---|
| Null hypothesis | $H_0$: All medians are equal |
| Alternative hypothesis | $H_1$: At least one median is different |

| Method | DF | H-Value | P-Value |
|---|---|---|---|
| Not adjusted for ties | 3 | 4.95 | 0.175 |
| Adjusted for ties | 3 | 4.96 | 0.175 |

*The chi-square approximation may not be accurate when some sample sizes are less than 5.*

**P-value (0.175) is higher than significance level, concluding no statistically significant differences between the medians.**

## Test and CI for Two Variances: LOG Tot Plastic; Marine Regions

### Method

| |
|---|
| $\sigma_1$: standard deviation of LOG Tot Plastic |
| $\sigma_2$: standard deviation of Marine Regions |
| Ratio: $\sigma_1/\sigma_2$ |
| The Bonett and Levene's methods are valid for any continuous distribution. |

### Descriptive Statistics

| Variable | N | StDev | Variance | 95% CI for σ |
|---|---|---|---|---|
| LOG Tot Plastic | 15 | 0.701 | 0.492 | (0.443; 1.276) |
| Marine Regions | 15 | 0.724 | 0.524 | (0.511; 1.179) |

### Ratio of Standard Deviations

| Estimated Ratio | 95% CI for Ratio using Bonett | 95% CI for Ratio using Levene |
|---|---|---|
| 0.968733 | (0.432; 1.818) | (0.393; 1.743) |

### Test

| | |
|---|---|
| Null hypothesis | $H_0$: $\sigma_1 / \sigma_2 = 1$ |
| Alternative hypothesis | $H_1$: $\sigma_1 / \sigma_2 \neq 1$ |
| Significance level | $\alpha = 0.05$ |

| Method | Test Statistic | DF1 | DF2 | P-Value |
|---|---|---|---|---|
| Bonett | 0.01 | 1 | | 0.915 |
| Levene | 0.23 | 1 | 28 | 0.633 |

No ANOVA possible, as p-value is higher than significance level. Continue with Kruskal-Wallis Test:

### Kruskal-Wallis Test: Total Plastic versus Marine Regions

#### Descriptive Statistics

| Marine Regions | N | Median | Mean Rank | Z-Value |
|---|---|---|---|---|
| 1 | 2 | 17.3640 | 11.5 | 1.19 |
| 2 | 6 | 10.1800 | 7.4 | -0.41 |
| 3 | 7 | 3.2141 | 7.5 | -0.41 |
| Overall | 15 | | 8.0 | |

#### Test

| | |
|---|---|
| Null hypothesis | $H_0$: All medians are equal |
| Alternative hypothesis | $H_1$: At least one median is different |

| Method | DF | H-Value | P-Value |
|---|---|---|---|
| Not adjusted for ties | 2 | 1.41 | 0.493 |
| Adjusted for ties | 2 | 1.42 | 0.492 |

*The chi-square approximation may not be accurate when some sample sizes are less than 5.*

**P-value of 0.493 is higher than significance level, concluding no statistically significant differences between the medians.**

### 8.3.4 Multivariate Analysis (PRIMER) – ANOSIM

This statistical analysis was performed on aggregated fishery data (plastics & metal).

*Factor Values*
Factor: Beach Type
4: Sand, Pebble
2: Pebble
3: Rock
1: Sand
5: Sand, Rock

*Factor Groups*

| Sample | Beach Type |
|---|---|
| Brucebukta | 4 |
| Reindiersodden | 4 |
| Crozierpynten/Sorgfjord 1 | 4 |
| Gåshamna | 4 |
| Boltodden | 4 |
| Sørvika 1 | 2 |
| Lomfjord 1 | 2 |
| Sørvika 2 | 2 |
| Lomfjord 2 | 2 |
| Sorgfjord 2 | 2 |
| Krossfjord | 2 |
| Isflakbukta | 3 |
| Wijkanderøyane | 3 |
| Alpinioya | 1 |
| Wigdehlpynten | 5 |

*Global Test*
**Sample statistic (Global R): 0.034**
**Significance level of sample statistic: 41.9%**
Number of permutations: 999 (Random sample from 3783780)
Number of permuted statistics greater than or equal to Global R: 418

*Pairwise Tests*

| Groups | R Statistic | Significance Level % | Possible Permutations | Actual Permutations | Number >= Observed |
|---|---|---|---|---|---|
| 4, 2 | 0.189 | 8.7 | 462 | 462 | 40 |
| 4, 3 | -0.309 | 100 | 21 | 21 | 21 |
| 4, 1 | -0.36 | 83.3 | 6 | 6 | 5 |
| 4, 5 | -0.28 | 83.3 | 6 | 6 | 5 |
| 2, 3 | 0.313 | 14.3 | 28 | 28 | 4 |
| 2, 1 | -0.244 | 85.7 | 7 | 7 | 6 |
| 2, 5 | 0.2 | 42.9 | 7 | 7 | 3 |
| 3, 1 | -1 | 100 | 3 | 3 | 3 |
| 3, 5 | 0 | 66.7 | 3 | 3 | 2 |

*Failed Pairwise Tests*

| Groups | Error |
|---|---|
| 1, 5 | At least one level must be larger than 1 in size |

**R-value of 0.034 suggests an even distribution of high and low ranks within and between groups, though p-value of 0.419 indicates no statistical significance to results.**

*Factor Values*
Factor: Beach Exposure
4: Strait
1: Fjord
3: Bay
2: Ocean

*Factor Groups*

| Sample | Beach Exposure |
|---|---|
| Brucebukta | 4 |
| Sørvika 1 | 4 |
| Sørvika 2 | 4 |
| Wijkanderøyane | 4 |
| Reindiersodden | 1 |
| Crozierpynten/Sorgfjord 1 | 1 |
| Alpinioya | 1 |
| Lomfjord 1 | 1 |
| Wigdehlpynten | 1 |
| Lomfjord 2 | 1 |
| Sorgfjord 2 | 1 |
| Krossfjord | 1 |
| Isflakbukta | 3 |
| Gåshamna | 2 |
| Boltodden | 2 |

*Global Test*
**Sample statistic (Global R): 0.3**
**Significance level of sample statistic: 6.5%**
Number of permutations: 999 (Random sample from 675675)

Number of permuted statistics greater than or equal to Global R: 64

*Pairwise Tests*

| Groups | R Statistic | Significance Level % | Possible Permutations | Actual Permutations | Number >= Observed |
|---|---|---|---|---|---|
| 4, 1 | -0.079 | 63.6 | 495 | 495 | 315 |
| 4, 3 | -0.167 | 60 | 5 | 5 | 3 |
| 4, 2 | 0.786 | 6.7 | 15 | 15 | 1 |
| 1, 3 | -0.152 | 66.7 | 9 | 9 | 6 |
| 1, 2 | 0.974 | 2.2 | 45 | 45 | 1 |
| 3, 2 | 1 | 33.3 | 3 | 3 | 1 |

**R-value of 0.3 suggests even distribution of high and low ranks within and between groups, though p-value of 0.065 indicates no statistical significance to results.**

*Factor Values*

Factor: **Marine Regions**

3: Greenland Sea

2: Barents Sea

1: Arctic Sea

*Factor Groups*

| Sample | Marine Regions |
|---|---|
| Brucebukta | 3 |
| Reindiersodden | 3 |
| Crozierpynten/Sorgfjord 1 | 3 |
| Wigdehlpynten | 3 |
| Gåshamna | 3 |
| Sorgfjord 2 | 3 |
| Krossfjord | 3 |
| Sørvika 1 | 2 |
| Lomfjord 1 | 2 |
| Sørvika 2 | 2 |
| Lomfjord 2 | 2 |
| Wijkanderøyane | 2 |
| Boltodden | 2 |
| Isflakbukta | 1 |
| Alpinioya | 1 |

*Global Test*

**Sample statistic (Global R): -0.138**

**Significance level of sample statistic: 89%**

Number of permutations: 999 (Random sample from 180180)

Number of permuted statistics greater than or equal to Global R: 889

*Pairwise Tests*

| Groups | R Statistic | Significance Level % | Possible Permutations | Actual Permutations | Number >= Observed |
|---|---|---|---|---|---|
| 3, 2 | -0.113 | 91 | 1716 | 999 | 909 |
| 3, 1 | -0.299 | 88.9 | 36 | 36 | 32 |
| 2, 1 | -0.052 | 53.6 | 28 | 28 | 15 |

**R-value of -0.138 suggests dissimilarities could be greater within groups than between, though the p-value of 0.89 indicates no statistically significant result.**

The ANOSIM was also performed on subset groups, where only the factors values with five or more replicates were present. We found no significant results in this data either.

## 8.4 Provenience data for three big packs

### 8.4.1 Data used for Fig. 11

*Supplementary Table 1. Quantity of provenience data used for Fig. 11*

| Provenience | Kiepertøya 1 | Tommelen | Kiepertøya 2 | Total |
|---|---|---|---|---|
| **Norway** | 10 | 19 | 14 | 43 |
| **Russia** | 22 | 39 | 23 | 84 |
| **Sweden** | 3 | 1 | 3 | 7 |
| **Denmark** | 10 | 11 | 11 | 32 |
| **Finland** | 0 | 1 | 0 | 1 |
| **Iceland** | 0 | 1 | 3 | 4 |
| **Faroes** | 0 | 1 | 0 | 1 |
| **English language** | 6 | 16 | 9 | 31 |
| **UK** | 4 | 6 | 3 | 13 |
| **Germany** | 4 | 6 | 11 | 21 |
| **Lithuania** | 0 | 0 | 1 | 1 |
| **Poland** | 0 | 1 | 0 | 1 |
| **Netherlands** | 2 | 5 | 0 | 7 |
| **Belgium** | 0 | 2 | 0 | 2 |
| **France** | 1 | 7 | 0 | 8 |
| **Spain** | 2 | 1 | 3 | 6 |
| **Italy** | 1 | 1 | 1 | 3 |
| **Greece** | 0 | 0 | 1 | 1 |
| **Bulgaria** | 2 | 9 | 3 | 14 |
| **Turkey** | 0 | 0 | 1 | 1 |
| **Canada** | 1 | 0 | 0 | 1 |
| **USA** | 2 | 2 | 0 | 4 |
| **Brazil** | 1 | 0 | 0 | 1 |
| **Argentina** | 1 | 0 | 0 | 1 |
| **Japan** | 0 | 1 | 0 | 1 |
| **Korea** | 0 | 0 | 1 | 1 |
| **China** | 2 | 2 | 0 | 4 |
| **Philippines** | 0 | 1 | 0 | 1 |
| **Global** | 5 | 20 | 39 | 64 |
| **Total** | **79** | **153** | **127** | **359** |

*Supplementary Table 2. Proportions [%] of provenience data used for Fig. 11*

| Provenience | Kiepertøya 1 | Tommelen | Kiepertøya 2 | Proportion [%] |
|---|---|---|---|---|
| **Norway** | 13 | 12 | 11 | 12 |
| **Russia** | 28 | 25 | 18 | 23 |
| **Sweden** | 4 | 1 | 2 | 2 |
| **Denmark** | 13 | 7 | 9 | 9 |
| **Finland** | | 1 | | 0.3 |
| **Iceland** | | 1 | 2 | 1 |
| **Faroes** | | 1 | | 0.3 |
| **English language** | 8 | 10 | 7 | 9 |
| **UK** | 5 | 4 | 2 | 4 |
| **Germany** | 5 | 4 | 9 | 6 |
| **Lithuania** | | | 1 | 0.3 |
| **Poland** | | 1 | | 0.3 |
| **Netherlands** | 3 | 3 | | 2 |
| **Belgium** | | 1 | | 1 |
| **France** | 1 | 5 | | 2 |
| **Spain** | 3 | 1 | 2 | 2 |
| **Italy** | 1 | 1 | 1 | 1 |
| **Greece** | | | 1 | 0.3 |
| **Bulgaria** | 3 | 6 | 2 | 4 |
| **Turkey** | | | 1 | 0.3 |
| **Canada** | 1 | | | 0.3 |
| **USA** | 3 | 1 | | 1 |
| **Brazil** | 1 | | | 0.3 |
| **Argentina** | 1 | | | 0.3 |
| **Japan** | | 1 | | 0.3 |
| **Korea** | | | 1 | 0.3 |
| **China** | 3 | 1 | | 1 |
| **Philippines** | | 1 | | 0.3 |
| **Global** | 6 | 13 | 31 | 18 |
| **Total** | **100** | **100** | **100** | **100** |

## 8.4.2 Photograph of Arctic debris items of different proveniences.


*Supplementary Figure 7. Items of determined provenience from 2017. © M. Bergmann (AWI).*


*Supplementary Figure 6. Items of determined proveniences for 2019. © J. Hagemann (AWI).*


*Supplementary Figure 8. Items of determined proveniences for 2021. © J. Hagemann (AWI)*

### 8.4.3 Date prints

*Supplementary Table 3. Date prints of provenience debris, showing timeframe, production/expiry year, quantities, and proportions [%].*

| Timeframe | Marked Year | Total | Proportion [%] |
|---|---|---|---|
| **2000 - 2013<br>53%** | 2012-2013 | 1 | 5 |
| | 2008 | 1 | 5 |
| | 2007 | 1 | 5 |
| | 2006 | 3 | 16 |
| | 2003 | 3 | 16 |
| | 2000 | 1 | 5 |
| **1990 - 2000<br>16%** | 1996 | 2 | 11 |
| | 1992 | 1 | 5 |
| **1970 - 1979<br>26%** | 1979 | 2 | 11 |
| | 1971 | 2 | 11 |
| | 1970 | 1 | 5 |
| **1960<br>5%** | 1960 | 1 | 5 |
| **Total sum** | | **19** | **100** |

### 8.4.4 Provenience data used for Fig. 13

*Supplementary Table 4. Pooled quantity and proportions of provenience data, used for Fig. 13*

| Provenience | Quantity | Proportion [%] |
|---|---|---|
| **Norway** | 43 | 16.3 |
| **Russia** | 84 | 31.8 |
| **Sweden** | 7 | 2.7 |
| **Denmark** | 32 | 12.1 |
| **Finland** | 1 | 0.4 |
| **Iceland** | 4 | 1.5 |
| **Germany** | 21 | 8.0 |
| **UK** | 13 | 4.9 |
| **Faroes** | 1 | 0.4 |
| **Lithuania** | 1 | 0.4 |
| **Poland** | 1 | 0.4 |
| **Netherlands** | 7 | 2.7 |
| **Belgium** | 2 | 0.8 |
| **France** | 8 | 3.0 |
| **Spain** | 6 | 2.3 |
| **Italy** | 3 | 1.1 |
| **Greece** | 1 | 0.4 |
| **Bulgaria** | 14 | 5.3 |
| **Turkey** | 1 | 0.4 |
| **Canada** | 1 | 0.4 |
| **USA** | 4 | 1.5 |
| **Brazil** | 1 | 0.4 |
| **Argentina** | 1 | 0.4 |
| **Japan** | 1 | 0.4 |
| **Korea** | 1 | 0.4 |
| **China** | 4 | 1.5 |
| **Philippines** | 1 | 0.4 |
| **Total** | **264** | **100** |

# 9 Affidavit

I hereby declare that I have prepared the present work independently and without outside help and that I have not used any sources or aids other than those specified.
The written version of the thesis submitted corresponds to that of the electronic storage medium.

Furthermore, I assure you that this thesis has not yet been submitted as a thesis elsewhere.

Date, Signature

6. Juni 2022, Anna N. Meze

## Eidesstaatliche Erklärung

Hiermit erkläre ich, dass ich die vorliegende Arbeit selbstständig und ohne fremde Hilfe angefertigt und keine anderen als die angegebenen Quellen und Hilfsmittel verwendet habe.
Die eingereichte schriftliche Fassung der Arbeit entspricht der auf dem elektronischen Speichermedium.

Weiterhin versichere ich, dass diese Arbeit noch nicht als Abschlussarbeit an anderer Stelle vorgelegen hat.

Datum, Unterschrift

6. Juni 2022, Anna N. Meze