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A first assessment of microplastics and other anthropogenic particles in Hudson Bay and the surrounding eastern Canadian Arctic waters of Nunavut

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Abstract

Microplastics are a globally ubiquitous contaminant, invading the most remote regions, including the Arctic. To date, our understanding of the distribution and sources of microplastics in the Arctic is limited but growing. This study aims to advance our understanding of microplastics in the Arctic. Surface water, zooplankton, sediment, and snow samples were collected from Hudson Bay to north Baffin Bay onboard the CCGS *Amundsen* from July to August 2017. Samples were examined for microplastics, which were chemically identified via Raman spectroscopy for surface water and zooplankton and Fourier transform infrared spectroscopy for sediment. We found that 90% of surface water and zooplankton samples, and 85% of sediment samples, contained microplastics or other anthropogenic particles. Mean anthropogenic particle concentrations, which includes microplastics, were 0.22 ± 0.23 (per litre) for surface water, 3.51 ± 4.00 (per gram) for zooplankton, and 1.94 ± 4.12 (per gram) for sediment. These concentrations were not related to the human populations upstream, suggesting that microplastic contamination in the Arctic is from long-range transport. Overall, this study highlights the presence of microplastics across the eastern Canadian Arctic, in multiple media, and offers evidence of long-range transport via ocean and atmospheric currents. Further research is needed to better understand sources, distribution, and effects to Arctic ecosystems.

Key words: microplastic, Arctic, Canada, zooplankton, water, sediment, plastic

Introduction

The Arctic is a region of great natural and cultural value to both Canadians and the world. It is, however, under pronounced stress from human drivers, including climate change (Wassman et al. 2011) and anthropogenic contaminants (Bard 1999; Kallenborn et al. 2018). Historically, many anthropogenic contaminants, including persistent organic pollutants (POPs) have been present at elevated levels in human and wildlife populations in the far north (Rigét et al. 2010; Gibson et al. 2016) and are known to be primarily transported via long-range atmospheric transport, ocean currents, and rivers (Galbán-Malagón et al. 2012; Ma et al. 2018). Pollutants, and specifically POPs, have been detected

throughout Arctic ecosystems (Outridge et al. 2008; Soltwedel et al. 2016; Sun et al. 2016; Jahnke et al. 2018). Examples of POPs in the Arctic include dichlorodiphenyltrichloroethane (DDT), polychlorinated biphenyls (PCBs), and flame retardants such as polybrominated diphenyl ethers (PBDEs) and hexabromocyclododecane (HBCDD) (Braestrup et al. 1974; Zhulidov et al. 2002; Su et al. 2007; de Wit et al. 2010; Wu et al. 2011). These compounds bioaccumulate and biomagnify up the food chain (Ottar 1981; Kelly and Gobas 2001).

Microplastics, small fragments of plastic <5 mm in size, have recently been identified as emerging contaminants in polar regions (Obbard et al. 2014; Lusher et al. 2015; Amélineau et al. 2016; Bergmann et al. 2017b; Kanhai et al. 2018, 2019; Morgana et al. 2018; Peeken et al. 2018; Mu et al. 2019a, 2019b). Their presence in the Arctic has been identified as higher than other locations on Earth (Barrows et al. 2018). Consequently, the Arctic Monitoring and Assessment Programme has added marine plastics and microplastics to their list of chemicals of emerging concern, signifying plastics as a threat to the Arctic. Like POPs, microplastics are persistent, and are transported long distances via ocean and air currents (e.g., Dris et al. 2015; van Sebille et al. 2015), and can accumulate in organisms (e.g., Galloway et al. 2008; Chae and An 2017). It is therefore important to measure the concentrations and distribution of microplastics across the Arctic marine environment to further understand the effects of microplastics as an environmental contaminant.

Microplastics consist of an array of synthetic polymers (Anderson et al. 2016) that come from a diverse range of products, including textiles, personal care products, durable consumer goods, packaging, and components of planes and cars (Andrady and Neal 2009; Thompson et al. 2010). Because of the broad utility of plastics, the demand is ever increasing, and global production was more than 348 million tonnes in 2017 (PlasticsEurope 2018). This increased consumption, coupled with an insufficient materials management system, has led to contamination of the environment with microplastics in a multitude of shapes (e.g., fibres, fragments, films), colours, and polymers. Contamination of freshwater and marine habitats with microplastics is ubiquitous throughout the world, but they are generally found at higher concentrations in more populated areas (e.g., Browne et al. 2011; Ballent et al. 2016; Mani et al. 2015).

Although the Arctic is not densely populated, microplastics have been found in a range of organisms and media, and it is thought that the Arctic is an accumulation area where microplastics are transported to and persist (van Sebille et al. 2012; Cózar et al. 2017; Peeken et al. 2018). Recent studies have shown microplastics are present in Arctic surface water (Lusher et al. 2015; Cózar et al. 2017; Kanhai et al. 2018; Raubenheimer and McIlgorm 2018), fish (Kühn et al. 2018), birds (Weslawski et al. 1994; Mallory 2008; Provencher et al. 2010; Trevail et al. 2015; Amélineau et al. 2016; Avery-Gomm et al. 2018), sharks (Leclerc et al. 2012; Nielsen et al. 2014), the seafloor (Bergmann et al. 2017b), marine vertebrates (Lydersen et al. 1989), ice (Obbard et al. 2014), sub-surface waters (Morgana et al. 2018; Peeken et al. 2018), and benthic organisms (Fang et al. 2018). With climate change, the transportation of microplastics may differ with changes in water circulation and ice cover, which is also seen for POPs (Wöhrnschimmel et al. 2013). For example, it has been demonstrated that microplastics frozen in sea ice are being released back into the water column as the ice melts (Obbard et al. 2014). Further, temperature and pH are changing in the Arctic, and these factors affect the sorption of hydrophobic contaminants to microplastics as well as desorption in the environment to biota (Teuten et al. 2007, 2009; Bakir et al. 2014; IPCC 2014; Goethel et al. 2017).

Despite the increase in research on microplastics in the Arctic over the past few years, we still know relatively little about their origin and pathways by which they enter the Arctic (Obbard 2018). Previous studies have hypothesised that microplastics enter the Arctic region through ocean currents and atmospheric transport and from sources such as local input and sewage (Lusher et al. 2015; Bergmann et al. 2017a, 2019; Kanhai et al. 2018). Hence, it is important to

investigate the role of northern populations in the Arctic as a source of microplastics to local ecosystems. Several studies have shown that bulk atmospheric deposition contains microplastics comprised predominantly of fibres (Dris et al. 2015). Atmospheric transport is therefore a probable contributing transport mechanism for microplastics entering polar regions (Obbard 2018; Bergmann et al. 2019).

Here, we contribute to the growing body of research on the presence of microplastics in Arctic ecosystems by studying their abundances and distribution in multiple matrices across the Eastern Canadian Arctic. Currently, the bulk of Arctic research efforts have focused on the Eurasian Arctic, whereas data are still relatively scare concerning the North American Arctic. We collected surface water, sediment, and zooplankton samples from Hudson Bay to north Baffin Bay onboard the Canadian Coast Guard Ship (CCGS) *Amundsen*. We also sampled snow from Alert, Nunavut. From each sample, we quantified and characterized microplastics and other anthropogenic particles (e.g., cotton textiles). Our overarching objectives were to quantify and characterize microplastics in the Canadian Arctic across multiple matrices to better understand contamination and to explore patterns that may relate to their sources.

Materials and methods

Sampling locations

Surface water, sediment, and zooplankton samples were collected from onboard the CCGS *Amundsen* in July and August 2017 from Hudson Bay and the Canadian Arctic Archipelago of Nunavut (**Fig. 1**; **Table 1**). Surface water samples were collected from 22 stations, and zooplankton and sediment samples were collected from 20 stations. Sampling was done opportunistically aboard the vessel at sites where sampling was permitted. At some sites it was only possible to take one type of sample due to scheduling or feasibility. In addition, snow samples were collected from one site near the research station in Alert, Nunavut, in the spring of 2018.

In this study, the ship covered a range of sites across a large geographical area. Ice levels varied throughout sampling, with areas towards the pole tending to be more ice heavy and southern areas less so. The samples taken in Baffin Bay are influenced by Atlantic origin waters and glacier melting (Oksman et al. 2017). In the Hudson Bay, there are several rivers that drain into the area, none of which flow through large populated areas.

Surface water sampling and analysis

At each station a surface water sample was collected with a triple-rinsed metal bucket lowered from the port side of the ship with a metal wire and transferred to a clean 40-L stainless-steel soda keg prior to filtration onboard the vessel. Immediately after collection, samples were filtered onto a 142-mm diameter polycarbonate filter (10-µm pore size, MilliporeSigma, Burlington, Massachusetts, USA). If the samples were turbid and the filter began to clog, <40 L of water was used for the sample. Each filter was transferred to a clean glass petri dish (142-mm diameter), sealed with tape and stored at room temperature until analysis (roughly one year). To avoid contamination of microplastics during sampling, the soda keg and bucket were rinsed with surface water three times before collection. The filter holder was rinsed between each sample with 1 L of reverse osmosis (RO) water that had been filtered through a 10-µm polycarbonate filter. To account for any procedural contamination, three field blanks were randomly sampled at different times during the cruise. Field blanks were sampled identically to field samples by lowering RO water down the side of the boat in the bucket, transferring it to the soda keg, running it through the filter and sealing it in a clean petri dish for future analyses. Samples were shipped to the University of Toronto, Toronto, Ontario, to be analysed.

Table 1. A list of all stations and matrices that were sampled from each site onboard the CCGS *Amundsen* from July to August 2017.

Station	Longitude and latitude	Matrix
732	−77.9924, 55.3856	Z
736	−78.3000, 58.4295	W, Z
720	−78.5593, 60.6981	W, Z
694	−78.7116, 61.4016	W, Z
688	−74.6616, 62.36706	W, Z
684	−71.9168, 61.7891	Z
682	−69.7145, 61.0426	W, Z
676	−69.0575, 60.126	W, Z
670	−67.9375, 58.9893	W, Z
A16	−68.8505, 63.7211	Z
180	−61.3712, 67.4198	W, Z
Diskofan	−59.5033, 67.9675	W, S
8.1	−64.7321, 69.4072	S
BB2	−67.0045, 72.7684	W, Z, S
101	−77.5151, 76.3575	Z, S
115	−71.2246, 76.3372	W, S
111	−74.1359, 78.326	W
TS233	−71.1812, 76.3329	Z, S
Belcher Glacier	−80.7526, 75.7022	S
323	−80.4503, 74.1615	W, S
Pond Inlet	−77.6098, 72.8279	W
301	−83.3193, 74.2776	Z, S
304	−91.5130, 74.2462	Z, S
5.1	−99.0764, 74.4883	S
Resolute Bay	−95.1280, 74.7280	W
QMG-M	−101.7431, 68.3027	W, S
QMG-4	−103.4267, 68.4842	S
QMG-1	−99.8962, 68.4917	Z, S
QMG-2	−100.8004, 68.3062	W
QMG-3	−102.9424, 68.3277	Z
312	−100.7042, 69.1704	W, S
3.7	−96.0440, 2.0960	W, S
3.4	−91.9931, 71.4753	Z, S
3.5	−91.2363, 70.4366	W, S
333	−80.8492, 68.7752	Z. S
1.1	−81.3544, 65.1550	W, S

Note: The locations of each station number can be found in Fig. 1. W, surface water; Z, zooplankton, S, sediment.

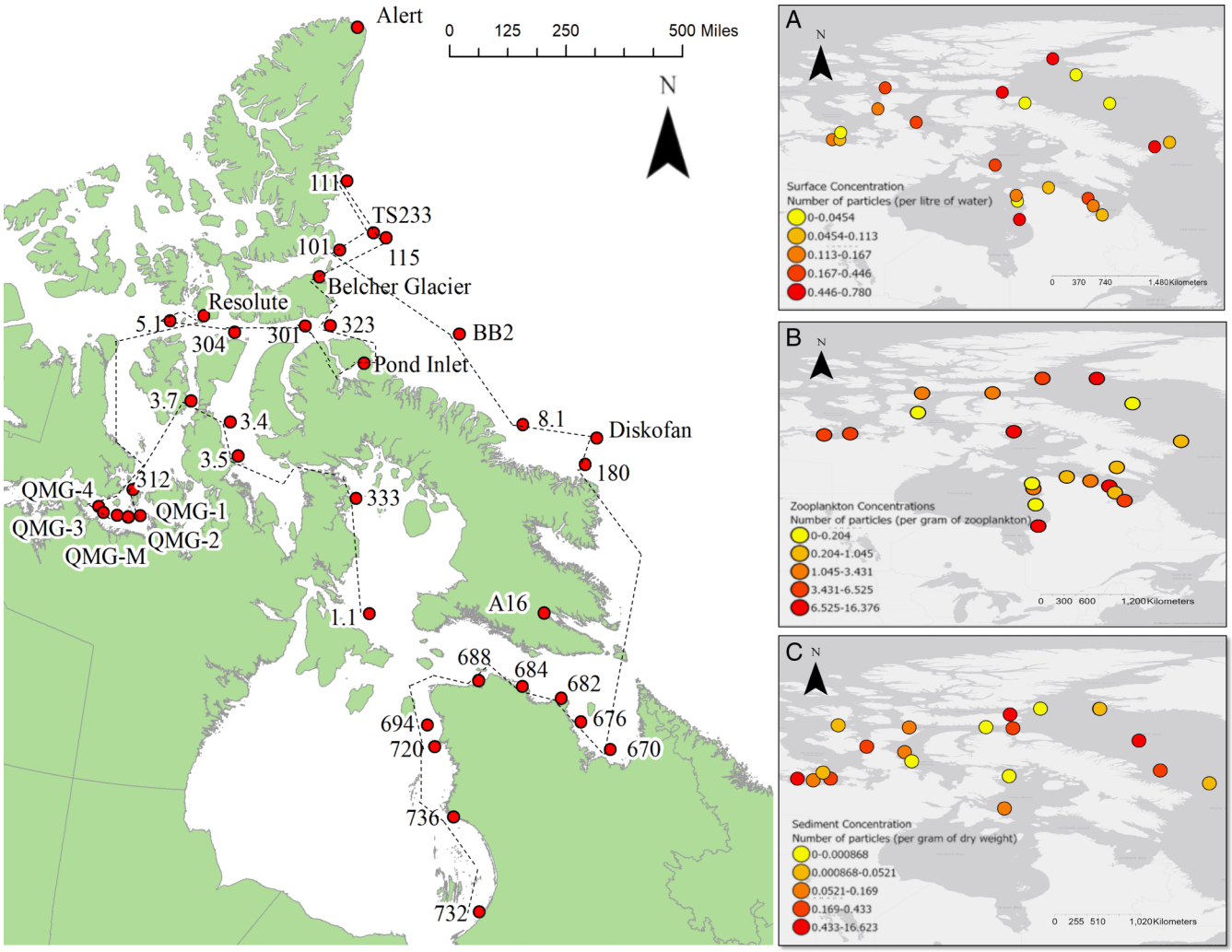

Fig. 1. Map showing the locations of Arctic sampling sites. Samples were collected from on board the CCGS *Amundsen* in July and August 2017, with the exception of snow samples that were collected in the spring of 2018 near the Alert research station. See **Table 1** for information regarding which samples were collected at each station (marked with a red dot). Maps (A)–(C), show the distribution of particles found according to site for (A) surface water , (B) zooplankton, and (C) sediment. Cruise map produced via ArcMap (version 10.6) and maps A-C produced in ArcGIS Pro (version 2.4).

At the University of Toronto, the filters were sonicated for 1 h to remove particles in precleaned jars with RO water. After sonication, the sample was placed in the oven at approximately 50 °C for 24 h to dissolve any salts that may have been present. The sample was refiltered through a 47-mm diameter, 10-µm pore size polycarbonate filter. Anthropogenic particles (down to ~100 µm) were extracted visually under a dissecting microscope. The particles were picked off the filter with tweezers and placed on double-sided tape. Particles were categorized according to shape and colour. They were then photographed and measured using ImageJ (Schneider et al. 2012) software. To determine how successful we were at identifying anthropogenic particles, and to get an idea of the types of materials in our samples, Raman spectroscopy (Xplora Plus; Horiba Scientific with LabSpec 6 software; New Jersey, USA) was conducted on a random number generated selection of 14% of the total particles aiming for 10% of each colour morphology combination (e.g., blue fiber, white fragment) per sample. Following Raman spectroscopy, we used the data from the analysis to normalize the final particle counts per

sample to report an anthropogenic particle count (which includes microplastics) and a microplastic particle count. We include the category "anthropogenic particle" to include dyed cellulosic textiles (e.g., cotton), dyed textiles of unknown material, and other materials such as paint where the Raman signal gave us a dye spectrum only. We also report a microplastic count, which includes particles we can confirm as plastic via Raman spectroscopy.

Zooplankton sampling and analysis

Zooplankton were collected using a Tucker trawl with two individual sampling nets. One of the nets had a mesh size of 750 μm, with openings of 1 m^2. The Tucker is an oblique tow pulled alongside the boat that collects zooplankton as it descends to approximately 10 m above the sea floor. The net was held for 1 min before being brought slowly back to the surface. Zooplankton were picked from the samples with metal forceps and placed into filtered RO water with 10% isopropyl alcohol. The samples consisted of multiple species that varied across samples. Examples of organisms include chaetognaths and krill. To account for any procedural contamination, five field blanks were collected. Field blanks consisted of RO water in clean glass jars that were left open during sampling. Fixed zooplankton samples were stored at room temperature until analysis (roughly one year). Samples were shipped to the University of Toronto to be analysed.

Zooplankton samples were poured from the jars they were stored in through a 500-μm stainless-steel mesh sieve, where they were rinsed using RO water. This was done to remove any noningested microplastics from the sample. Zooplankton were analysed in bulk, and as samples varied greatly in the number (some having <10 and others having >50), and species, their wet weight, in grams, was recorded. Because it was not possible to count zooplankton in samples with more than 50 very small organisms, we do not report this value. Samples were then photographed and transferred to a clean jar that had been tripled rinsed with RO water. They were then covered in a 20% KOH solution in RO water, capped, and held at room temperature for 7–14 d, or until the zooplankton were fully digested. Each sample was then sieved using a 45-μm stainless-steel sieve to remove the KOH solution and retain the microplastics (Lusher et al. 2017). Anthropogenic particles (down to ~100 μm) were extracted visually under a dissecting microscope. The particles were picked off the filter with tweezers and placed on double-sided tape. Particles were categorized according to shape and colour. They were then photographed and measured using ImageJ (Schneider et al. 2012) software. Using the same method as the surface water samples, we analysed 13% of the particles, based on our subsampling strategy described above. Following Raman spectroscopy, we used the data from the analysis to normalize the final particle counts for each sample to report an anthropogenic particle count (which includes microplastics) and a microplastic particle count.

Sediment sampling and analysis

Twenty sediment samples were collected using a box corer. A clean metal trowel was used to scrape the top 5 cm (measured with a ruler) of the sediment. Surface sediment was placed in glass jars and capped with aluminium foil under Teflon-lined lids. A field blank consisted of RO water in a clean glass jar that was left open during collection of one sediment sample. The sediment samples were processed in a sample separation facility at the University of Western Ontario.

Each sample was wet sieved using a 20-μm stainless-steel sieve to remove the size fractions finer than medium silt. This step was required to avoid flocculation of very fine particles during drying. Samples were emptied onto aluminum pie trays, covered with aluminum foil, and dried at 70 °C in a drying oven. Each sample was weighed and then emptied into a glass beaker containing 250 mL of sodium polytungstate (SPT) solution with a specific gravity of 1.5 g/cm^3. The samples were magnetically stirred for 5 min and were then transferred to glass separatory funnels. Additional SPT solution was

used to rinse the glass beaker to ensure a quantitative transfer. Once the sediment settled completely, the nonbuoyant material could pass through the stopcock into a 750-mL glass beaker. The buoyant material was then drained into a separate 750-mL glass beaker containing a glass conical funnel lined with filter paper. The separatory funnel was rinsed with SPT and drained onto the filter paper. Using RO water in a squirt bottle, the material on the filter paper was transferred onto a 53-µm, 7.5-cm diameter polycarbonate–polyester sieve. The material was rinsed, transferred using the squirt bottle from the sieve to a glass petri dish, covered with aluminum foil, and redried at 70 °C. One sample (A19) was composed entirely of shells and was processed simply by pouring the material into an aluminum pie plate, rinsing the jar with RO water, pouring the water into the same pie plate, and allowing the water to evaporate in the oven. The sample was then weighed and placed into a petri dish for microscopic examination.

The material in each petri dish was examined using a dissecting microscope to separate microplastics from any remaining sediment and organic material. The particles that were visually identified as microplastics were categorized according to their colour, morphology (fibre, film, fragment), and size. Each particle was removed from the petri dish using tweezers and placed in a glass vial labelled according to sample number. A total of 29 (13%) particles identified as potential microplastics were randomly selected and analyzed using micro-Fourier Transform Infrared Spectroscopy (micro-FTIR) at Surface Science Western, University of Western Ontario, London, Ontario. Following FTIR spectroscopy, we used the data from the analysis to normalize the final particle counts for each sample to report an anthropogenic particle count (which includes microplastics) and a microplastic particle count. Because sediment samples were analysed at the University of Western Ontario and surface water and zooplankton were analysed at the University of Toronto, chemical identification methods differed due to access to different equipment.

Snow sampling and analysis

Seven snow samples (~450 mL melted volume) were collected from Alert, Nunavut, near the Dr. Neil Trivett Global Atmosphere Watch Observatory. Untouched snow, upwind from the station and sampler, was collected to limit procedural contamination. Two field blanks were also sampled to account for procedural contamination during sampling. Snow was collected into a clean glass (rinsed 3× with RO water) jar using a clean stainless-steel spoon. The field blank was collected by leaving a clean jar open during sampling. Samples were shipped to the University of Toronto for analysis.

All melted snow samples were processed in a clean cabinet to prevent contamination from dust. The volume of each sample of melted snow was measured using a clean graduated cylinder and then filtered onto a 47-mm, 20-µm polycarbonate filter (Merck Millipore Ltd.). After filtration, the filter was transferred into a clean petri dish. Anthropogenic particles (down to ~100 µm) were extracted visually under a dissecting microscope. Using the same method as both surface water and zooplankton samples, particles were photographed and measured using ImageJ software. All particles underwent Raman spectroscopy (Xplora Plus; Horiba Scientific) with LabSpec 6 software (Schneider et al. 2012). We did not subsample due to the small number of particles in total.

Quality assurance and quality control

Throughout the study, consistent efforts were made to minimize sample contamination. Bright orange flotation suits were worn while collecting samples on board the CCGS *Amundsen*, and cotton laboratory coats were worn in both laboratories. In Rochman's laboratory (Univeristy of Toronto), all materials used were made of stainless steel or glass and were rinsed a minimum of three times with RO water prior to use. When collecting all samples, clothing type and colour were noted. In the laboratory, samples were filtered under a clean cabinet to prevent contamination. Prior to using the

microscopes, the area was wiped down to reduce contamination. For surface water samples, three field blanks were collected on the CCGS *Amundsen*. Lastly, one laboratory blank for surface water, and two for zooplankton, were included during laboratory extraction and processing. All blanks were extracted by following the sample protocol as outlined above, using RO water instead of real samples. These samples were then analysed under a dissecting microscope and particles were picked and transferred to double sided tape. Particles found in blanks from the field and the laboratory were subtracted from samples according to morphology and colour. This was done by averaging the field blanks and then the laboratory blanks separately for each matrix type and then adding them together to remove this total value from each sample within that matrix (e.g., 10 blue fibres were removed from each surface water sample). See **Table S1** for data related to blank subtraction in each sample and sample type.

In Corcoran's laboratory (University of Western Ontario), all materials were made of stainless steel, aluminium, or glass, except for the small polycarbonate–polyester sieve used to transfer material from the filter paper to the glass petri dish. The dissecting microscope had a metal enclosure along the sides and top of it, protecting the petri dish from airborne particles. Corcoran's laboratory has two portable air filtration systems with HEPA filters, one for the processing laboratory and one in the microscope lab. The filter papers were composed of white translucent cellulose and a minor amount of clear resin. Squirt bottles were made of clear polyethylene. Cellulose fibres derived from the paper were easily identified when found in the samples and were not included in the counts. No clear fragments that might represent resin were identified in any of the samples. The samples were covered with aluminium foil while stored in aluminium pie plates, beakers, and separatory funnels. When wet sieving, cross contamination between samples was avoided as the sieve was cleaned in an ultrasonic bath filled with RO water for 1 h between sieving each sample. The sediment sample was then immediately poured into the sieve then placed under RO running water and gently stirred with the flat part of a metal tablespoon until the clay and fine silt fraction had seeped through the sieve. The amount of time that each sample was exposed to the air (during wet sieving and transfer from one vessel to another) is estimated to be no longer than 30 min. The average time required for visual analysis was ~1 h. Two laboratory blanks were sampled; one from the processing laboratory for a period of 30 min, and one from the microscope laboratory for a period of 1 h. The laboratory blanks were sampled using a petri dish containing a small mixture of pre-examined sedimentary material. The blanks were examined under a dissecting microscope and any particles resembling microplastics were counted. The number of plastic particles in the field blank and the laboratory blanks were subtracted from the samples according to morphology and colour. **Table S2** contains initial totals, types, and colours of microplastic particles as well as final totals following blank subtraction and normalizing to FTIR results.

Statistical analyses

Statistical analyses were completed in Excel 2016 (version 16.13.1) and R Studio (version 1.0.143). We used simple linear regression to measure the relationship between the concentration of microplastics sampled from each station and the population size nearby and upstream of the station location. Population data came from the most recent or available census data (Statistics Canada. 2020a, 2020b). If the sample site was within 100 km of a community and the water current flowed towards the sample site, then the population from that community was used and included (Canadian Coast Guard, 2019). If a site was not within 100 km of a community or was upstream of a current, then a value of 0 was used; 100 km was selected as it was deemed local enough to influence plastic quantities, whereas anything beyond this could be seen as a long-distance source and therefore not local.

To assess the relationship between microparticles among media, a nonmetric multidimensional scaling (nMDS) plot was created. We used nMDS to examine patterns of assemblage structure of microplastics (i.e., by particle morphology—fibre, fragment, film, and foam) among matrices. For nMDS

plots, we made two-dimensional ordinations using Euclidean distances. We used the function "metaMDS" in the vegan community ecology package (Oksanen et al. 2009) in R.

Results

Surface water samples

Following blank subtraction, microplastics and other anthropogenic particles were found in 19 of 21 (90%) samples. After normalization following Raman spectroscopy, the anthropogenic particle concentration in the samples ranged from 0 to 0.61 particles per litre (Fig. 2A). All particles were categorized as either fibres or fragments. Fibres were more abundant in samples, comprising 98% of all particles found in surface water (Fig. 2A) where the remaining 2% were fragments. The predominant colour of particles was blue, making up 72% of the particles found. Roughly 50% of particles were <1 mm in size (Fig. S1). Overall, 86% of the particles analysed with Raman were anthropogenic. Anthropogenic particles are defined here as having been created or processed by humans, including dyed cellulosic fibres. Of these, 29% were definitively plastic—which included polyester and polypropylene (PP). The mean number of microplastics per sample was thus 0.07 ± 0.08 (per litre). Because of band overlay from the dyes used in textiles or due to fluorescence, anthropogenic fibres of an unknown base were the most dominant category found (Fig. 4). This is a common issue for coloured microfibres (Lenz et al. 2015). Nonanthropogenic, natural fibres comprised ~14% of particles

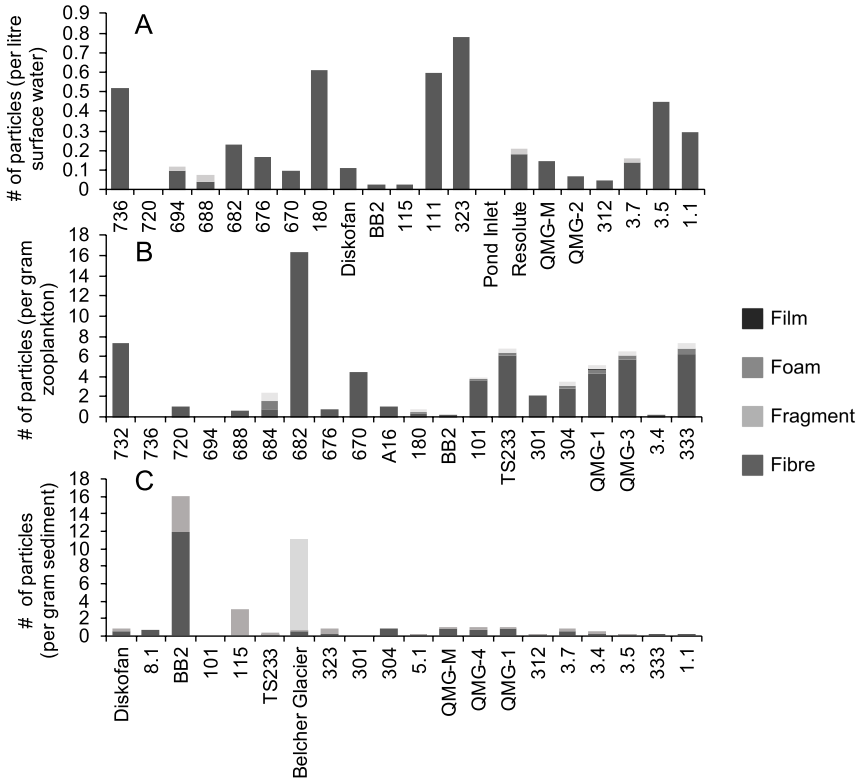

Fig. 2. Stacked bar plots showing the amount and shape of anthropogenic particles in (A) surface water (particles per litre), (B) zooplankton (particles per gram), and (C) sediment (particles per gram). The stations (along the *x*-axis) follow the order in which the samples were collected from onboard the CCGS *Amundsen*. Data used here are after blank subtraction and normalization following Fourier transform infrared spectroscopy or Raman spectroscopy.

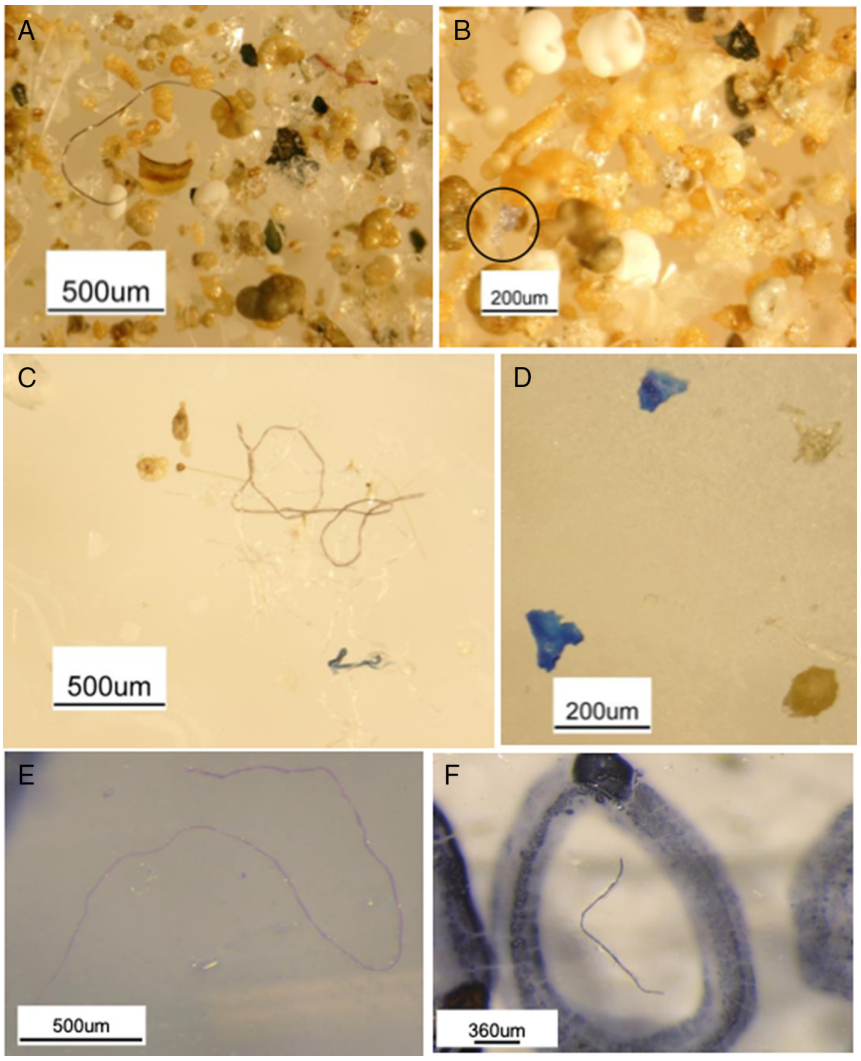

Fig. 3. Images of microplastic particles found in Eastern Canadian Arctic. (A) Black and red fibres in sediment from station Diskofan, (B) pale blue fragment (circled) in sediment from station Diskofan, (C) grey and blue fibres in sediment from station 8.1, (D) blue films in sediment from station Belcher Glacier, (E) purple fibre in surface water from station Diskofan, and (F) blue fibre in zooplankton from station 101.

analysed. The densities of microplastics found in surface water samples were not consistently buoyant and ranged from lower density plastics such as polyurethane to higher density plastics such as polyvinyl chloride. Across all samples, we found that there was not a significant relationship between population density and the quantity of anthropogenic particles found in surface water ($p = 0.694$) (Fig. 5).

Zooplankton samples

Following blank subtraction, microplastics and other anthropogenic particles were found in 18 of 20 (90%) samples. The anthropogenic particle concentrations in the samples ranged from 0 to 16 particles per gram of zooplankton (wet weight; Fig. 2B). All particles were categorized as either fibres, fragments, film, or foam. Fibres were the most abundant, consisting of 92% of particles, followed by fragments (6%), films (1%), and foam (one particle was found in all samples). Similar to surface water,

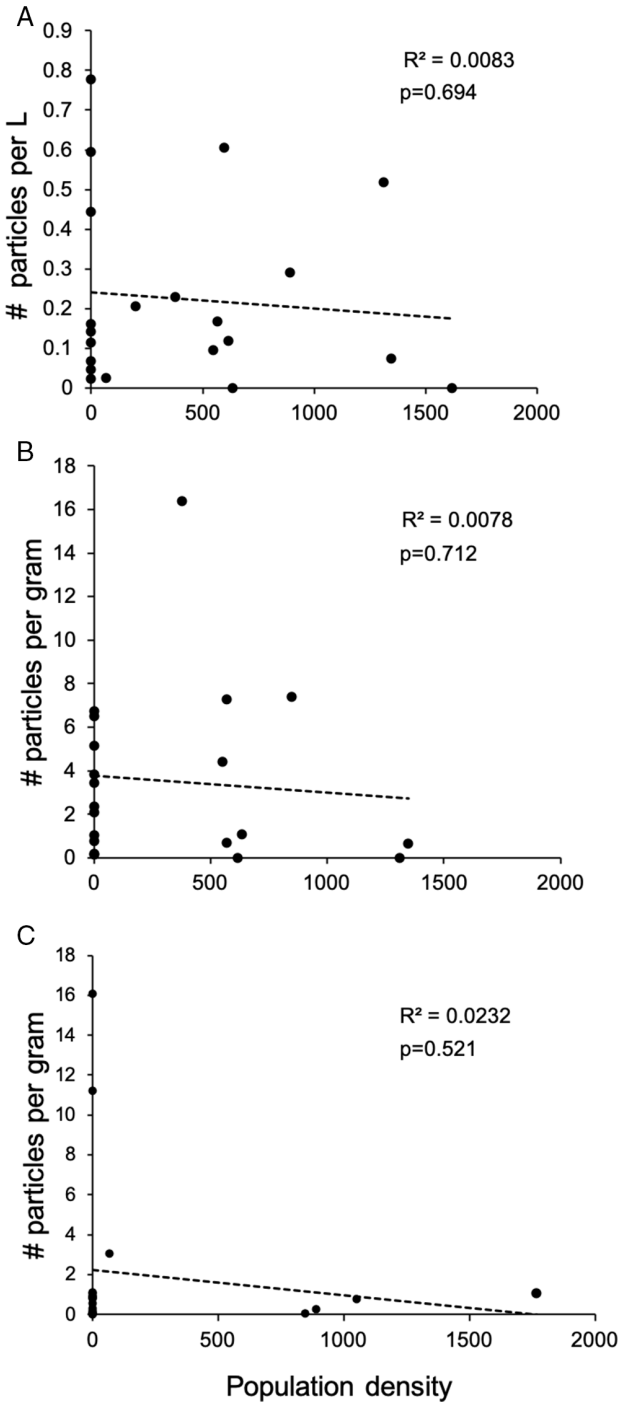

Fig. 4. Chemical composition of particles subsampled for Raman spectroscopy in surface water (top) and zooplankton (middle) and Fourier transform infrared spectroscopy in sediment (bottom).

the most predominant colour of particle found in zooplankton samples was blue, making up 68% of particles found. Additionally, ~42% of particles were <1 mm in size (Fig. S1). Overall, 96% of the particles subsampled for Raman were anthropogenic. Again, anthropogenic fibres with unknown base

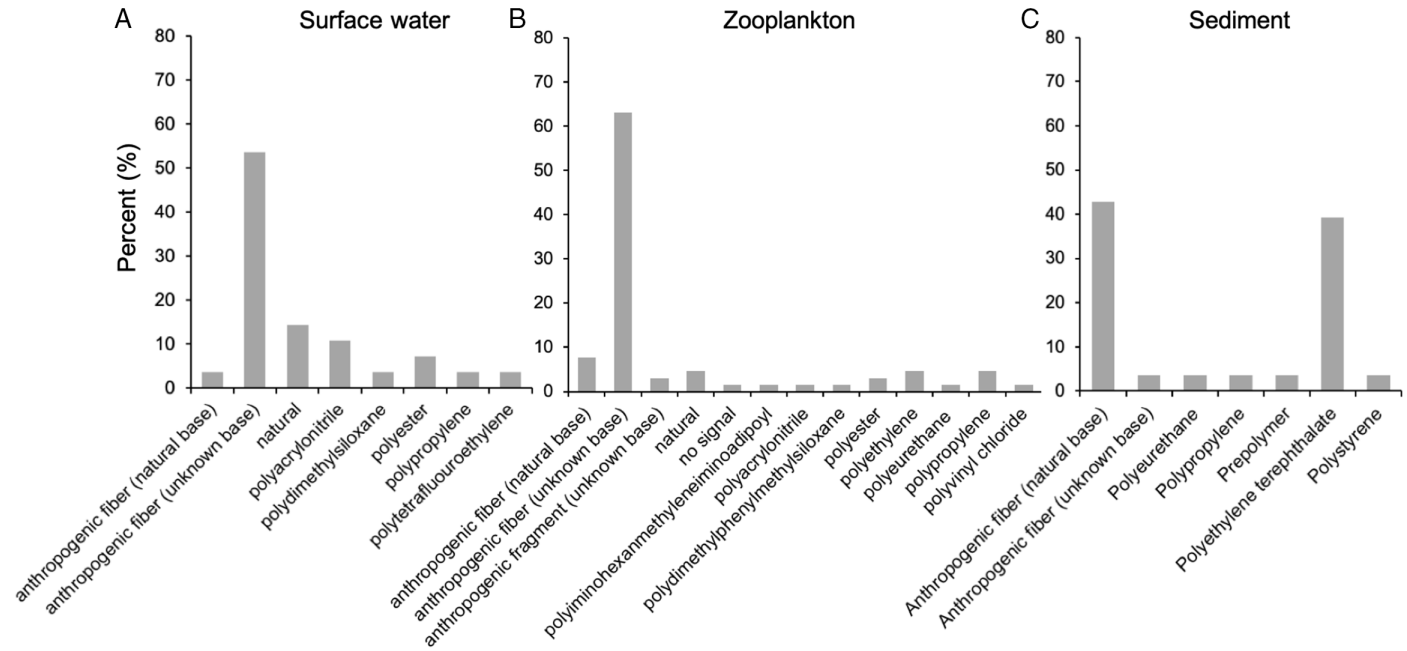

Fig. 5. Scatter plots with linear regression showing the relationship between the number of particles found in (A) surface water samples, (B) zooplankton, and (C) sediment, versus population size.

were the most dominant category (Fig. 4). The remainder of the particles were composed of natural material (4%). Plastic particles consisted of 20% of all analysed particles. Following Raman spectroscopy, data were normalized similarly to surface water (Fig. 2). The mean number of microplastics per sample was 0.7 ± 0.9 (per gram). The densities of microplastics found in zooplankton samples were also not consistent, but they tended towards higher density plastics such as polytetrafluoroethylene. Across all samples, we found no significant relationship between population density and the quantity of anthropogenic particles found in zooplankton ($p = 0.712$). (Fig. 5).

Sediment samples

Following blank subtraction, microplastics and other anthropogenic particles were found in 18 of the 20 sites (90%). After blank subtraction, we found at total of 106 fibres, 38 fragments, and 42 films. The mean number of particles per gram of dry weight sediment (g^{-1} dw) was 2 g^{-1} dw (Table S2). All particles were characterized as fibres, fragments, or film (Fig. 2C). Fibres were more abundant in samples, comprising 57% of all particles found in sediment, with fragments comprising 20% and film the remaining 23%. The fragments ranged in size from 0.28 to 300 µm, and a variety of colours were identified. From most to least abundant, fragment colours were blue, grey, red, orange, purple, clear, black, green, and white. Fibre lengths ranged from 205 to 380 µm, and from most to least abundant the colours identified included blue, black, grey, purple, pink, white, yellow, and green. The 42 films were identified only in the sample from station Belcher Glacier and they were all the same colour (cobalt blue) with sizes ranging from 0.25 to 125 µm (Fig. 3D). The films were very soft and easily broken into smaller size particles.

The results of FTIR analysis showed that of the 23 fibres analysed, 11 were composed of polyethylene terephthalate (PET) and the remaining 12 of cellulose (all dyed either blue, black, purple, or green) (Fig. 4C). Three of the five fragments analysed are synthetic polymers (PP, polyurethane,

polystyrene-PS). The composition of the remaining two fragments is unknown, but both are dyed blue. The cobalt blue film analysed from sample 101 is a prepolymer, and as it appears to be the same colour and texture as the remaining 41 blue films in the same sample, we infer these all to be prepolymers. These results indicate that 48% and 66% of the fibres and fragments, respectively, are composed of plastic. The mean number of microplastics per sample was 1.66 ± 3.67 (per gram) and of the total particles, 52% were plastic. The densities of microplastics found in sediment samples were not consistent, and predominantly had lower density plastics, including polystyrene and polyurethane. Across all samples, we found no significant relationship between population density and the quantity of anthropogenic particles found in sediment ($p = 0.521$).

Snow samples

After blank subtraction, microplastics and other anthropogenic particles were found in one out of seven (14%) sampling sites. In total, there were four particles that were picked because they appeared anthropogenic, three of which were determined to be natural. The remaining particle was polyethylene. All particles were categorized as fibres. Owing to the small sample volumes, and thus low plastic counts above the noise, it is not practical to discuss patterns of size.

Patterns among sampling sites and media

To look at patterns across sites, we made heat maps showing the anthropogenic particles at each station for each media (**Fig. 1**). **Figure 1** allows for a comparison of concentrations of anthropogenic particles across media. It is worth noting that samples were not taken for all matrices at all sites. For example, there were no sediment samples taken in Hudson Bay, one of the most populated areas in the study area. For the data we have, generally there is not a consistent pattern across all media. For example, at site 736 we see relatively high concentrations in surface water and relatively low concentrations in zooplankton. Still, we observe higher quantities of anthropogenic particles near Belcher Glacier across all media and Ungava Bay (sites 684, 682, 676, 670) for surface water and zooplankton.

For a closer look at patterns among locations and across media we constructed an nMDS plot (**Fig. 6**). The plot considers both the number of anthropogenic particles as well as the morphologies of particles within each sample. It groups together samples with similar "microparticle communities" based on both amount and morphology. Here, we see a pattern suggesting that zooplankton samples are different than sediment and surface water. Sediment and surface water do not separate from each other in space on the plot. Zooplankton had the most diverse morphologies of any sample type, having a mixture of fibres, fragments, foam, and film. This may be the reason for the pattern that we observe.

Discussion

This is the first study to provide insight into the abundance and distribution of microplastics in the Eastern Canadian Arctic across four sample matrices. Previous research across multiple sample media and methods have demonstrated the widespread presence of microplastics in the Arctic. Similar to other studies, we add further confirmation of the ubiquitous presence of microplastics in the Arctic and the predominance of anthropogenic fibres regardless of the medium (Lusher et al. 2015; Morgana et al. 2018). In this study, surface water samples had an average anthropogenic particle abundance of 0.3 fibres and 0.03 fragments per litre of water. For plastic particles, the average abundance was 0.07 fibres and 0.002 fragments, and most particles found were <1 mm in size. This pattern, showing more smaller size plastic (<5 mm) debris is common amongst other studies (Ivar et al. 2013; Lusher et al. 2014). In addition, studies in the Arctic tend to show similar concentrations of microplastics in sub-surface water, ranging from 0.002 to 0.2 particles per litre (Obbard et al. 2014; Kanhai et al. 2018; Morgana et al. 2018). However, Barrows et al. (2018) found much higher concentrations in Arctic surface waters, with an average of 31.3 ± 6.5 per litre and high densities of

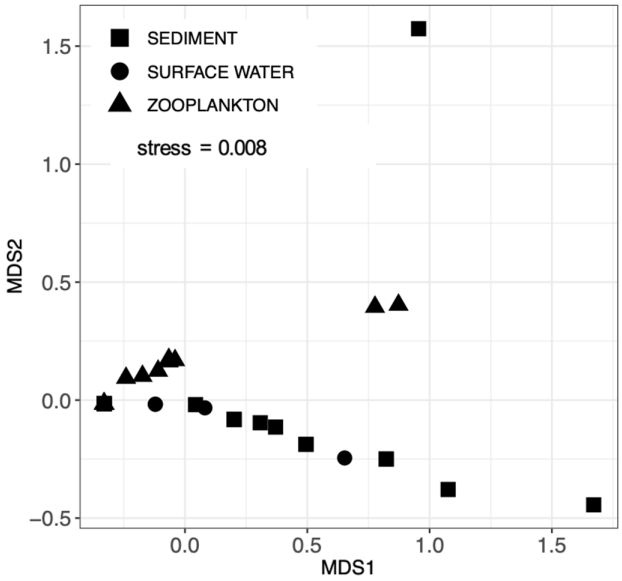

Fig. 6. A nonmetric multidimensional scaling plot created using the proportion of microplastic morphologies within each matrix (sediment, squares; surface water, circles; zooplankton, triangles) using the Bray–Curtis dissimilarity metric and plotted in two dimensions. Data were not transformed. Each point on the figure represents a sample taken at a sampling location, and the different shapes represent each of the matrices. When samples are closer together in space on the plot, this suggests they have a more similar "community" of anthropogenic particle morphologies.

microplastics have been theoretically predicted in other studies (Eriksen et al. 2014; Wilcox et al. 2015). We found an average of three anthropogenic particles per gram of zooplankton, with an average of 0.7 confirmed plastic particles per gram of zooplankton, demonstrating that zooplankton do consume anthropogenic debris, which has been shown to have consequences for their health and the animals that prey on them (Cole et al. 2013; Amélineau et al. 2016). Our sediment samples were found to have much lower concentrations of microplastics compared with the study of sediment samples from the Fram Strait (Bergmann et al. 2017b). The mean abundance of microplastics in the latter study was 4.36 g^{-1} dw compared with our mean abundance of 1.95 g^{-1} dw. These results, however, cannot be directly compared because 80% of the microplastic particles in Bergmann et al. (2017b) were <25 μm in size, whereas we examined sediment of grain sizes between 53 μm and 0.25 mm.

Currently, there is only one study investigating the presence of microplastics in snow in the Arctic, highlighting the need for further research into this area (Bergmann et al. 2019). Unfortunately, we cannot compare our results to those of Bergmann et al. (2019) as we cannot quantitatively analyse our data due to the small sample volume. Based on our results, where concentrations in our samples were similar to the field blanks, we recommend taking a greater sample volume and analysing smaller sized particles. Additionally, samples analysed in this study sorted particles visually and manually subsampled particles for Raman and FTIR, which allows for human error. Other studies use automated spectroscopy to quantify and characterize all particles in a sample (Bergmann et al. 2017b). Finally, Bergmann et al. (2019) found most of their particles in a size range lower than detectable in our study.

We observed no general consistencies between the quantity of particles found across media (**Fig. 1**), although assessing this pattern is limited as not every medium was sampled at each site. There were only a few locations where relative concentrations across media were similarly high (Belcher Glacier

and Ungava Bay). In addition, the quantity of microplastic and anthropogenic particles found at a given site does not appear to be influenced by nearby human populations (Fig. 5). In terms of particle density, we expected to see particles with a lighter density in the surface water and particles with a higher density at the bottom. This trend was not observed, and instead it was rather inconsistent with mixtures of particle densities across all media. We did see a pattern where zooplankton samples differed from surface water and sediments, and we think this was driven by zooplankton having a greater diversity of particle morphologies than other sample matrices (Fig. 6). These inconsistent patterns make it difficult to inform sources of microplastics to this region.

Previous research suggests long-range transport via ocean or air currents is likely the mechanism behind microplastics and anthropogenic debris entering the Arctic region (Lusher et al. 2014; Trevail et al. 2015; Cózar et al. 2017; Bergmann et al. 2019). Others suggest that microplastics in the Arctic may result from the breakdown of larger sized items from local waste and via sewage and wastewater (Lusher et al. 2015). The Nordic Council of Ministers (2016) estimated that approximately 6 million microparticles (≥100 μm) are released per hour into the sea from the Klettagarðar wastewater treatment plant receiving waste water from the city of Reykjavik, Iceland (Nordic Council of Ministers 2016). Areas of the Arctic are reported as having ineffective waste management solutions, which in combination with waste disposed or lost at sea, is creating visible debris on Arctic beaches (Bergmann et al. 2017a). In our study, we tried to investigate this question in two different ways: we measured correlations between microplastic concentrations and population centres, and we collected snow samples from a remote region. When we investigated whether there was a correlation between the amount of microplastics in samples and the population density upstream, we found microplastics at the majority of stations, and across all media, but saw no trend with population densities (Fig. 5), suggesting that microplastics in our samples cannot be attributed to local sources. This reinforces the role of long-range transport as a source of microplastics to polar regions, although we could not probe this hypothesis any further because of the low volume of our own snow samples. Notwithstanding, our findings suggest the transport of microplastics to the Arctic is unique, as research has generally shown that population directly influences the amount of microplastics found in a given area (Browne et al. 2011; Ballent et al. 2013; Yonkos et al. 2014; Dean et al. 2018; Kataoka et al. 2019).

As previously mentioned, we collected snow samples to see if we could detect evidence of long-range atmospheric transport. Unfortunately, we learned that we did not sample enough volume to get a count of microplastics sufficiently above the concentration in our blanks (i.e., 3× the concentration). Thus, we encourage the use of higher volume samples when collecting snow. Snow is a useful matrix to probe the question of long-range atmospheric transport to the Arctic, which has been demonstrated in other areas of the world (Free et al. 2014; Dris et al. 2015; Bergmann et al. 2019). Bergmann et al. (2019) found high quantities of microplastic in snow, and it showed that the majority of microplastic debris are below 20 μm in size.

Overall, our study demonstrates the presence of microplastics in the Eastern Canadian Arctic, which may pose a threat to the organisms inhabiting ecosystems in the region. This study, combined with previous investigations, indicates that organisms are exposed to microplastics, including those from the base of the food web. Because polar regions are ecologically sensitive, it is important to better understand microplastic exposure and effects in this region. In this study, the greatest proportion of anthropogenic particles found were often of an unknown base. This was because of band overlay with a dye signal. Thus, more research is needed to improve methods that help determine the types of materials in complex samples and to understand the mixture of microplastics and other anthropogenic mircoparticles (e.g., cotton from textiles) in the Canadian Arctic. In the North American Arctic, there are few studies concerning microplastic debris, emphasizing the importance of research

in this area. This study, in combination with previous Arctic research demonstrating contamination, shows the need for future studies that help us better understand sources, fate, and effects of microplastics—and whether there is any exacerbation in relation to climate change—in these fragile ecosystems. Such work will allow us to improve management strategies to support the long-term health of the Arctic.

Conclusion

This study demonstrates the prevalence of microplastics across benthic sediment, zooplankton, and surface waters of the Eastern Canadian Arctic. Additional investigation is necessary to determine the presence of microplastics in snow, and the transport mechanisms responsible for microplastic entry into the Arctic. We observed no correlation between population and the quantity of microplastics found in our study, suggesting that sources of microplastics to the Arctic are distal, and not from the immediate vicinity of the region itself. Our findings reiterate that microplastics are ubiquitous throughout the world, even in areas that have low population numbers, emphasizing the importance of viewing microplastics management as a global issue. Further work should focus on the environmentally relevant quantities (i.e., amount and type) of microplastics and their impact on terrestrial and marine biota of the Arctic.

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Author contributions

PLC, LJ, and CMR conceived and designed the study. AH, PLC, CT, SB, and CMR performed the experiments/collected the data. AH, PLC, and CMR analyzed and interpreted the data. PLC, LJ, GAS, and CMR contributed resources. AH, PLC, LJ, CT, SB, GAS, and CMR drafted or revised the manuscript.

Competing interests

The authors have declared that no competing interests exist.

Data availability statement

All relevant data are within the the paper and in the Supplementary Material.

Supplementary materials

The following Supplementary Material is available with the article through the journal website at doi:10.1139/facets-2019-0042.

Supplementary Material 1

Supplementary Material 2

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