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High-levels of microplastic pollution in a large, remote, mountain lake

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ABSTRACT

Despite the large and growing literature on microplastics in the ocean, little information exists on microplastics in freshwater systems. This study is the first to evaluate the abundance, distribution, and composition of pelagic microplastic pollution in a large, remote, mountain lake. We quantified pelagic microplastics and shoreline anthropogenic debris in Lake Hovsgol, Mongolia. With an average microplastic density of 20,264 particles km⁻², Lake Hovsgol is more heavily polluted with microplastics than the more developed Lakes Huron and Superior in the Laurentian Great Lakes. Fragments and films were the most abundant microplastic types; no plastic microbeads and few pellets were observed. Household plastics dominated the shoreline debris and were comprised largely of plastic bottles, fishing gear, and bags. Microplastic density decreased with distance from the southwestern shore, the most populated and accessible section of the park, and was distributed by the prevailing winds. These results demonstrate that without proper waste management, low-density populations can heavily pollute freshwater systems with consumer plastics.

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1. Introduction

Global plastic production has increased rapidly since mass production began in the 1950s and currently exceeds 288 million tons per year (PlasticsEurope, 2013). An estimated 10% of this plastic ends up in the ocean (Thompson, 2006). As a result, plastics now contaminate every ocean of the world, including those formerly thought of as pristine (Ainley et al., 1990; Barnes et al., 2009; Provencher et al., 2010). Large plastic debris, known as “macroplastics,” present an aesthetic problem with economic repercussions for tourism (Jang et al., 2014), pose a risk to various marine industries (Sheavly and Register, 2007), threaten marine life through entanglement and ingestion, transport invasive species, and smother the seabed (Gregory, 2009). “Microplastics,” generally defined as plastics less than 5 mm diameter, are formed through the breakdown of macroplastics or sourced from the abrasives used in cosmetics and blasting media and are of increasing environmental concern (Thompson et al., 2004; Fendall and Sewell, 2009; Browne et al., 2010, 2011). Due to the durability of plastic and its persistence in marine environments (Sivan, 2011),

pelagic microplastics have accumulated steadily since first being observed in the 1970s (Carpenter and Smith, 1972), and are now a ubiquitous contaminant of the world’s oceans (Derraik, 2002; Barnes et al., 2009).

The consequences of microplastic pollution for marine fauna are only just emerging (Wright et al., 2013b). Microplastics represent a threat to marine biota because their small size makes them bioavailable to organisms throughout the food web (Betts, 2008; Thompson et al., 2009a; Wright et al., 2013b). Marine invertebrates (Murray and Cowie, 2011; Cole et al., 2013; Goldstein and Goodwin, 2013), fish (Boerger et al., 2010; Davison and Asch, 2011), seabirds (Ryan et al., 2009; Thompson et al., 2009b), and mammals (Eriksson and Burton, 2003; Fossi et al., 2012, 2014) have all been shown to ingest microplastics, often with negative health consequences. Microplastic ingestion can reduce feeding, deplete energy reserves, and decrease ecophysiological function as a result of physical injury, physiological stress, and false satiation (von Moos et al., 2012; Browne et al., 2013; Cole et al., 2013; Rochman et al., 2013; Wright et al., 2013a,b). Furthermore, microplastics are susceptible to contamination by water-borne organic pollutants and to the leaching of potentially toxic plastic additives known as “plasticizers” (Teuten et al., 2007). If consumed, microplastics can thereby introduce toxins into the food

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chain, which can biomagnify to higher trophic levels (Farrell and Nelson, 2013; Setälä et al., 2014).

Despite the large and growing literature describing the abundance, composition, sources, and impacts of microplastics in the ocean (Andrady, 2011; Browne et al., 2011; Cole et al., 2011), little information exists on microplastics in freshwater systems. A handful of recent studies have examined microplastics in lakeshore sediments (Zbyszewski and Corcoran, 2011; Imhof et al., 2013), pelagic microplastics in rivers (Dubai and Liebeck, 2013) and lakes (Faure et al., 2012, 2013; Eriksen et al., 2013a;), and the ingestion of microplastics by freshwater fauna (Faure et al., 2012, 2013; Imhof et al., 2013; Sanchez et al., 2014). These limited studies reveal that microplastics are present in freshwater rivers and lakes, sometimes in densities comparable to the oceans (see Lake Erie, Eriksen et al., 2013a), and are ingested by freshwater fauna (Imhof et al., 2013; Sanchez et al., 2014). Eriksen et al. (2013a) show that plastic microbeads, commonly used in facial cleansers and other consumer products, are a significant microplastic pollutant in the Great Lakes. Like Faure et al. (2012), Eriksen et al. (2013a) link microplastic abundance to urban population density and propose three major pathways to pollution: (1) effluent from wastewater treatment facilities; (2) sewage treatment overflow during high-volume rain events; and (3) runoff from sewage-based fertilizer deposited on agricultural or public lands.

The predominance of microbeads and association of microplastic pollution with industrial centers and areas of high population density, though similar to patterns observed in the ocean (Gregory, 1996; Fendall and Sewell, 2009), are not necessarily representative of all freshwater systems, especially those characterized by low population density, a lack of industry and agriculture, and limited wastewater or sewage treatment facilities. In these remote and undeveloped areas, microplastic is more likely to be introduced through the degradation and fragmentation of consumer plastics blown or washed into the water from shore (Coe and Rogers, 1997; Ryan et al., 2009). However, little is known about the microplastic profile of remote freshwater systems (Imhof et al., 2013) and the validity of these basic assumptions is unknown. It is important to understand the characteristics of microplastics in remote lakes and rivers to understand the scope of the problem and, potentially, to direct preventative measures and cleanup activities in these regions.

In this study, we conducted surveys for shoreline macroplastics and pelagic microplastics in Lake Hovsgol, Mongolia to examine the abundance, composition, distribution, and sources of microplastic pollution in a large, remote, mountain lake. Lake Hovsgol was established as a National Park in 1992 and is characterized by a low population density, a lack of industry and agriculture, and no modern wastewater or sewage treatment facilities. Still, it is a growing tourist destination and a small permanent population lives along the lakeshore. Without a formal waste management system, this relatively small community generates a disproportionately large volume of improperly disposed of trash. For these reasons, Lake Hovsgol presents a useful system for studying microplastics in a near-pristine freshwater system.

2. Methods

3.1. Study site

Lake Hovsgol (51°05'50"N, 100°30'E) is located in the mountains of northern Mongolia, at the southern edge of the Siberian taiga forest. It is the 19th largest lake in the world by volume (480 km³), with a maximum depth of 262 m and a surface area of 2760 km² (Herdendorf, 1982; Goulden et al., 2006). For size reference, Lake Hovsgol is similar to Lake Erie in volume (483 km³),

despite being a tenth of its size in area (25,655 km²). It is an ultra-oligotrophic lake characterized by low primary production (2–5 mg C m⁻³ day⁻¹), high oxygen content year-round throughout the water column (8–11.5 mg O₂ l⁻¹), and clear water (with Secchi disk readings commonly up to 20 m) (Kozhova et al., 1994; Urabe et al., 2006). Nearly 100 seasonal streams flow into Lake Hovsgol and a single outlet, the Eg River, drains Lake Hovsgol to the south. It has a long estimated residence time of 300–600 years (Hayami et al., 2006).

The lake was designated as a National Park in 1992 and is characterized by low average population density. The majority of the population lives in Hatgal (pop. 2980) in the south and Hankh (pop. 2460) in the north (NSOM, 2012). Tourist camps line the southwestern shore and herding families live along primitive roads that follow the eastern and western shores (Fig. 1). There are no waste management or water treatment facilities within the park: trash is burned, buried, or dumped by individual households. Although Lake Hovsgol has low endemism compared to Lake Baikal (Kozhova et al., 1994; Karabanov et al., 2004), it is inhabited by a number of endemic invertebrates and fish and threatened water birds (Goulden et al., 2006), all of which could be negatively impacted by plastic pollution.

3.2. Shoreline debris surveys

We surveyed and collected anthropogenic debris at nine sites on the Lake Hovsgol shoreline from July 18 to 26, 2013. Sites were selected in 2009 as part of a long-term fish monitoring study (Ahrenstorff et al., 2012) and though non-random, they provide excellent spatial coverage and access to points and bays on all sides of the lake (Fig. 1, Supp. Fig. 1). At each site, we conducted surveys for derelict fishing gear (Free, unpublished data), and within these longer transects (0.4–8.5 km, 14 surveys total), we conducted one to four randomly placed shorter surveys for all anthropogenic debris (0.1–1.2 km, 18 surveys total). A total of 7.8 km, approximately 2% of the lake shoreline, was censused for visible anthropogenic debris between the water and wrack lines. Because transect widths were variable, we report linear (i.e., km⁻¹) rather than areal (i.e., km⁻²) debris density. We recorded the location of all debris items, weighed them after drying them in sunlight, and categorized them into the following material types: plastic, glass, metal, wood, foam, textiles (fabric or fiber), rubber, fishing debris, and other items (Keller et al., 2010; Viehman et al., 2011). The type of plastic debris (e.g., flour bag, salt bag, candy wrapper, soda bottle, motor oil bottle, etc.) was identified when possible. Individual items found in multiple fragments were identified, counted, and weighed as a single item.

3.3. Pelagic microplastic surveys

We sampled pelagic microplastics along 9 transects while in transit between our long-term monitoring sites (Fig. 1, Supp. Fig. 1). Sea state on the Beaufort wind force scale remained 0 for all but the southwestern transect (Beaufort 2). Transects ranged from 0.3 to 6.0 km offshore. Transects were not equidistant, ranging from 3.1 to 4.1 km in length, but were all 60 min long with a target tow speed of 3.5 knots. Samples were collected using a manta trawl with a rectangular opening 16 cm high × 61 cm wide and a 3 m long 333 μm mesh net with a 30 × 10 cm² collecting bag. The net was towed along the surface on the starboard side of the vessel using a metal pole to position the towline outside of the bow wake. The area sampled was calculated by multiplying the length of sea surface trawled, determined from the onboard GPS, by the width of the trawl, allowing particle abundance per square kilometer to be calculated. A flowmeter was not used because currents in the lake are negligible and start and stop

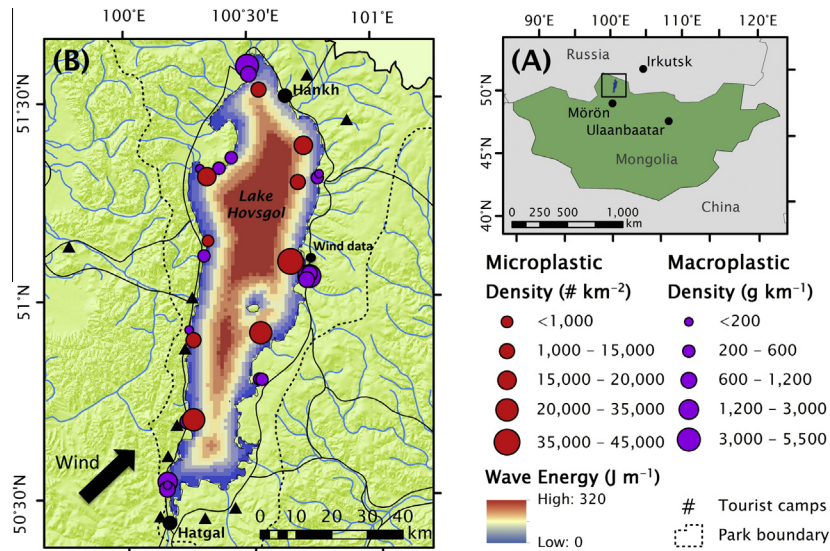


Fig. 1. Density of pelagic microplastics and shoreline macroplastics relative to wave energy and pollution sources. (A) Location of Lake Hovsgol in northern Mongolia. (B) Density of macroplastic debris in the shoreline surveys (purple, g km⁻¹) and microplastic debris in the pelagic surveys (red, particles km⁻²); symbols graduated by density. Wave energy was modeled using shoreline shape, fetch, bathymetry, and wind direction and speed. Direction of the prevailing winds and location of the wind weather station are shown. Potential sources for pollution include towns (black circles), tourist camps (black triangles), roads (solid black lines), and rivers (solid blue lines). Dashed line indicates the park boundary. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

coordinates were sufficient to determine flow. All samples were preserved with 70% ethanol for potential future identification of plankton.

Preserved samples were processed using a modified NOAA protocol (Baker et al., 2011) as detailed below. Samples were rinsed through a set of Tyler sieves sorting the material into 3 size classes: 0.355–0.999 mm, 1.00–4.749 mm, and >4.75 mm. A variety of size classes have been used in the literature (Hidalgo-Ruz et al., 2012), but these size classes are comparable to those used by Eriksen et al., 2013a,b and other studies (e.g., Moore et al., 2001, 2002). For each size classification, labile organic matter was digested using 30% hydrogen peroxide in the presence of an iron (II) catalyst. Plastic debris is resistant to this wet peroxide oxidation (WPO) processing. The WPO mixture is subjected to salt water density separation ($d = 1.62 \text{ g mL}^{-1}$) to isolate the plastic debris through flotation. Using a light microscope, plastic particles within each size classification were counted and categorized as fragment, foam, line/fiber, pellet, or film (Table 1).

3.4. Wind and wave exposure

We used the NOAA Wave Exposure Model (WEMo v4.0; Malhotra and Fonseca, 2007) to compare differences in wave exposure among sites to determine whether debris accumulation is a

function of wind and wave exposure. The model derives wave energy from shoreline shape, fetch, bathymetry, and wind speeds and hindcasts wave energy and height for the top 5% of wind events during the specified period. We digitized the lake shoreline at 1:2500 using the best available Bing, ESRI, and Landsat imagery. We generated a bathymetry surface by interpolating 50 m depth contours mapped by a 1982 Russian expedition to the lake (Bogoyavlensky, 1989) using the ArcGIS 10.1 Topo to Raster tool (ESRI, 2013) constrained within the digitized shoreline (Supp. Fig. 1). We compared the mean and maximum depth of the interpolated bathymetry surface with the depth statistics reported by Bogoyavlensky (1989) as a form of pattern matching validation. Wind speed and direction were recorded at 20 min intervals in 2009 using a HOBO U30-NRC Weather Station in the Dalbay River Valley (51°01'26"N, 100°45'46"E, 70 km from the furthest sampling site, Fig. 1). The WEMo model was parameterized using data from June 3 to November 5 when the lake is unfrozen (Hatgal Meteorological station, unpublished data) and wind can drive debris distribution. Because storms and rainwater can increase pelagic microplastic density (Moore et al., 2002; Lattin et al., 2004) and remove shoreline macroplastics (Garrity and Levings, 1993), we examined rainfall data from the Hatgal Meteorological station to ensure that total rainfall during the sampling month (July 2013) was within a standard deviation of the historical monthly average.

3.5. Data analysis

We used multiple linear regression to evaluate the contribution of several measures of wave exposure and proximity to development to microplastic and macroplastic density. The full model for pelagic transect microplastic density (count km⁻²) included the following terms: average wave energy (J m⁻¹), average distance from the closest town center (km), average distance from Hatgal center (km), average distance from the shore (km), average latitude, and average longitude. The full models for shoreline transect macroplastic density (both g km⁻¹ and count km⁻¹) included the same terms with the addition of average aspect and the omission of average distance from the shore. No interaction terms were included. Backward selection with a p -value <0.10 to stay in the

Table 1
Definitions and potential sources of microplastic types.

Microplastic type	Definition	Potential sources
Fragment	Hard, jagged plastic particle	Bottles; hard, sturdy plastics
Line/fiber	Thin or fibrous, straight plastic	Fishing line/nets; clothing or textiles
Pellet	Hard, rounded plastic particle	Virgin resin pellets; facial cleansers
Film	Thin plane of flimsy plastic	Plastics bags, wrappers, or sheeting
Foam	Lightweight, sponge-like plastic	Foam floats, Styrofoam, cushioning

model was used to refine the full model. Average distances, aspects, and coordinates were calculated in ArcGIS 10.1 (ESRI, 2013). All statistical analyses were performed using the *lm* function in R version 3.0.2 (R Development Core Team, 2013).

4. Results

4.1. Wind and wave exposure

The interpolated bathymetry surface resulted in average (125 m) and maximum (282 m) depths consistent with those reported by the original, but unavailable, bathymetry data (138 m, 262 m, respectively; Bogoyavlensky 1989; Supp. Fig. 1). During the ice-free period, winds were predominantly from the southwest. These southwesterly winds were most frequently 0–2 m s⁻¹ (mean: 1.7 m s⁻¹) but reached a maximum of 9.7 m s⁻¹ and were calm 5.3% of the time (Supp. Fig. 2). WEMo model outputs hindcast average wave energies along pelagic microplastic transects ranging from 148 to 305 J m⁻¹ and wave energies along shoreline debris transects ranging from 0 to 72 J m⁻¹ (Fig. 1). In July 2013, the month of sampling, it rained 62.7 mm, which is nearly identical to the historical monthly average of 63 mm.

4.2. Shoreline debris surveys

A total of 409 debris items (10.3 kg) were collected during the shoreline surveys. Macroplastic debris, which included all items from the ‘plastic’, ‘fishing’, and ‘foam’ debris categories, were the most abundant shoreline debris items, accounting for 77% of the total items and 60% of the total weight (Fig. 2). By weight, shoreline macroplastics were dominated by plastic bottles (37%), fishing gear (25%), plastic bags (16%), and plastic fragments (18%) (Table 2). Plastic debris was found along every survey transect, but the density of debris varied considerably among transects (37–5324 g km⁻¹). Linear models with backwards model selection indicate that none of the explanatory variables were significant predictors of shoreline macroplastic density (g km⁻¹ or count km⁻¹).

4.3. Pelagic microplastic surveys

Microplastics were observed in all nine pelagic survey transects (Fig. 3). Microplastic density averaged 20,264 particles km⁻² and ranged from 997 to 44,435 particles km⁻². Fragments, films, and lines/fibers were the most abundant microplastic types (Table 3); fragments and lines/fibers were found in all 9 samples and films were found in 8 samples. 4 foams were found in 1 sample, 2 pellets were found in 2 samples, and no microbeads were present (Supp. Table 1). A linear model with backwards selection indicates that

Table 2

The abundance, weight (g), and percent by weight of plastic debris types observed in the shoreline anthropogenic debris surveys.

Plastic debris type	Count	Weight (g)	Percent by weight (%)
Plastic bottles	52	2317.5	36.6
Plastic bottles	39	1912.4	30.2
Plastic oil bottles	3	381.2	6.0
Plastic bottle caps	9	22.8	0.4
Plastic bottle label	1	1.1	0.0
Plastic fishing gear	62	1593.5	25.2
Pillnet fragments	7	1232.4	19.5
Gillnet bottle floats	6	283.5	4.5
Gillnet lead lines	11	37.7	0.6
Gillnet float lines	3	19.5	0.3
Gillnet foam floats	31	16.8	0.3
Plastic bags	51	1008.5	15.9
Plastic flour bags	10	564.4	8.9
Plastic bags	33	426.1	6.7
Plastic salt bags	8	18.0	0.3
Plastic clothing	3	93.1	1.5
Plastic flip flop	1	74.7	1.2
Plastic head band	1	18.1	0.3
Plastic ribbon	1	0.3	0.0
Plastic wrappers	33	43.7	0.7
Plastic wrappers	17	26.3	0.4
Plastic candy wrappers	14	11.0	0.2
Plastic bubble wrap	1	5.9	0.1
Cellophane wrapper	1	0.5	0.0
Miscellaneous	10	157.3	2.5
Plastic bucket	2	89.9	1.4
Mylar balloon	1	27.2	0.4
Plastic flooring	1	24.6	0.4
Plastic aerosol cap	1	8.4	0.1
Plastic rope	1	3.8	0.1
Plastic cup	1	2.1	0.0
Plastic label	1	1.0	0.0
Plastic string	1	0.3	0.0
Plastic mesh	1	0.0	0.0
Plastic unknown	118	1118.1	17.7
Total	325	6328.1	

wave energy, distance from land, latitude, and longitude are significant predictors of pelagic microplastic density ($r^2 = 0.81$, $df = 4$, $F = 9.26$, $p = 0.027$). Microplastic density increases with wave energy ($p = 0.025$) and longitude ($p = 0.054$) and decreases with latitude ($p = 0.005$) and distance from shore ($p = 0.036$). In general, microplastic density was higher along the eastern shore than the western shore and decreased along a south-to-north gradient (Fig. 1).

5. Discussion

We present the first study to evaluate pelagic microplastic pollution in a large, remote, mountain lake. Despite its remoteness,

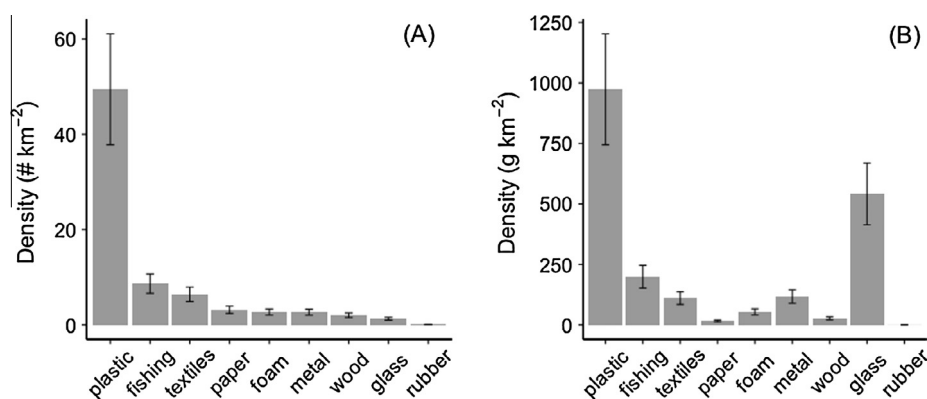


Fig. 2. Average density in terms of (A) abundance (items km⁻¹) and (B) weight (g km⁻¹) of shoreline anthropogenic debris types across surveys transects (18 transects, 7.8 km total; 409 items, 10.3 kg total). Error bars indicate ±1 standard error from the mean.

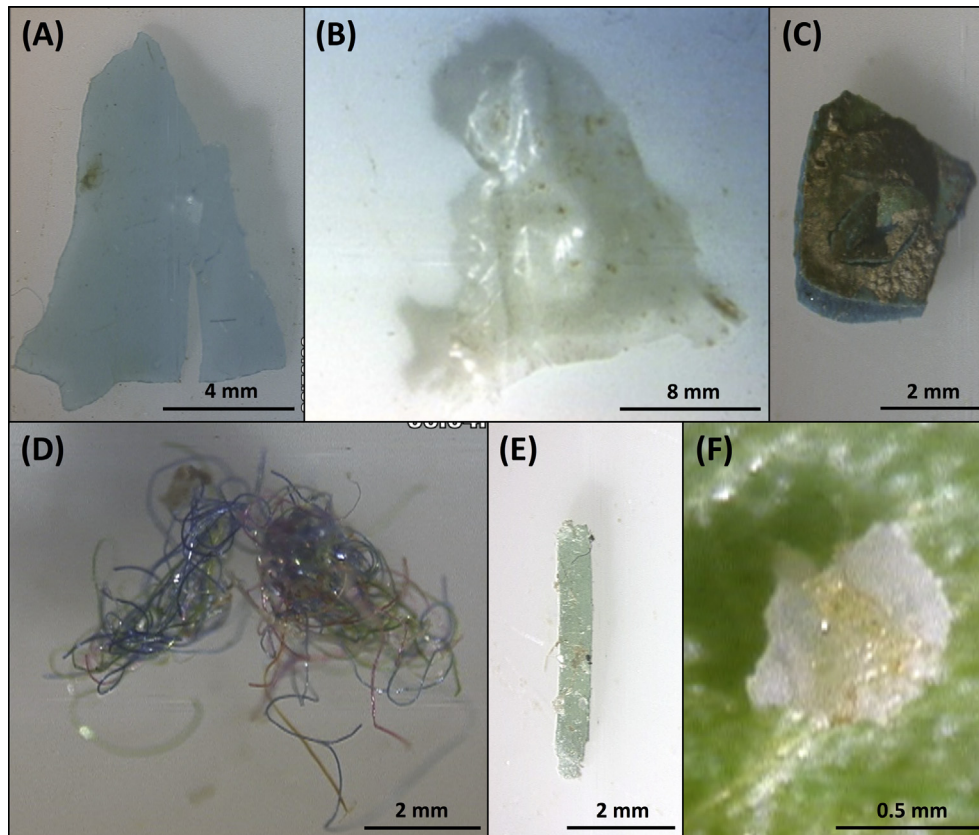


Fig. 3. Photographs of (A) fragment, (B) film, (C) foam, (D) fiber, (E) line, and (F) pellet microplastics observed in the manta trawl samples.

Table 3
Average density (particles km⁻²) and proportion of microplastics by type and size.

Plastic type	Average microplastic density (particles km ⁻²)			Total	Percent (%)
	0.333–0.999 mm	1.000–4.749 mm	>4.75 mm		
Fragment	5950	1876	335	8160	40
Film	881	4164	2740	7786	38
Line/fiber	1237	2044	702	3984	20
Foam	219	0	0	219	1
Pellet	0	58	57	115	1
Total	8287	8142	3834	20,264	
Percent (%)	41	40	19		

protected status, and low population density, Lake Hovsgol is more polluted with microplastics than the more developed and densely populated Lakes Huron and Superior (Eriksen et al., 2013a). Although less polluted with microplastics than the more developed and industrialized Lakes Erie and Geneva (Faure et al., 2012; Eriksen et al., 2013a; Table 4) and many of the world's oceans (e.g., Yamashita and Tanimura 2007; Collignon et al., 2012; Faure et al., 2012; Carson et al., 2013; Eriksen et al., 2013b), Lake Hovsgol's high-level of contamination is likely to increase as new and existing macroplastics degrade and enter the lake (Thompson et al., 2004).

The surprisingly high microplastic density of Lake Hovsgol relative to the other 4 lakes surveyed to date may be partially explained by its long residence time and small surface area (Table 4). Rigorous measurements of residence time are still lacking, but most authors estimate times in the order of 300–600 years (Hayami et al., 2006; but see 2000 year estimate by Prokopenko et al., 2007), much longer than those of the other 4 lakes. Lake Huron, with a residence time of 22 years (Quinn, 1992), displaces

microplastic pollutants 13–27 times faster than Lake Hovsgol, which may help explain its lower microplastic density. On the other hand, the short residence time of Lake Erie (2.6 years; Quinn, 1992) does not appear to offset the sheer magnitude of urban and industrial microplastic pollution entering its waters (Eriksen et al., 2013a).

Furthermore, the small surface area of Lake Hovsgol relative to the Great Lakes may concentrate its microplastic density. Because low-density consumer plastics (e.g., polyethylene and polystyrene) are buoyant and contained to the surface (Cole et al., 2011), they may be concentrated by Lake Hovsgol's small surface area rather than be diluted by its large volume. This dilution/concentration effect may also help explain the comparatively low densities of microplastics in the areally large Lakes Huron and Superior (Eriksen et al., 2013a) versus the high density of microplastics in the considerably smaller Lake Geneva (Faure et al., 2012; Table 4). However, not all microplastics are positively buoyant (Kukulka et al., 2012), which suggests that differences in the sources and composition of microplastic pollution or in the intensity of

Table 4
Lake characteristics and microplastic densities for all lakes with peer-reviewed surveys of pelagic microplastics.

Lake, Country ^a	Lake area (km ²)	Watershed population	Residence time (yr)	# Tows	Plastic density (particles km ⁻²)		
					Average	Maximum	Dominant type
Lake Geneva, Switzerland ^b	584	950,000	11.8	3	51,556	82,713	Fragments/films
Lake Superior, USA ^c	82,097	673,000	173.0	5	5391	12,645	Pellets/fragments
Lake Huron, USA ^c	59,565	3,000,000	21.0	8	2779	6541	Pellets/fragments
Lake Erie, USA ^c	25,655	12,400,000	2.7	8	105,503	466,305	Pellets/fragments
Lake Hovsgol, Mongolia	2760	6000	300–600	9	20,264	44,435	Fragments/films

^a Lake characteristics for the US Great Lakes are from the NOAA Great Lakes Environmental Research Laboratory (<http://www.glerl.noaa.gov/pr/ourlakes/lakes.html>) and lake characteristics of Lakes Geneva and Hovsgol are from the ILEC World Lakes Database (<http://wldb.ilec.or.jp/>).

^b Faure et al. (2012, 2013).

^c Eriksen et al. (2013a).

biofouling organisms may also be important drivers of microplastic density on the lake surface.

Lake Hovsgol's high-level of microplastic pollution is most likely a result of the lack of a modern waste management system as evidenced by the predominance of household plastics in both the microplastic and macroplastic debris. Whereas plastic pellets, namely virgin resin pellets and microbeads, constituted nearly half of the microplastics in the Great Lakes (48%; Eriksen et al., 2013a), they were essentially absent from the Lake Hovsgol samples (0.006%, 4 pellets). The lack of industrial activity within the Lake Hovsgol watershed explains the near absence of resin pellets, the raw material used to make larger plastic products, which often enter the water in runoff from processing facilities (Gregory, 1996). The lack of microbeads, common in consumer products like facial cleansers, may be due to a lack of use or access to such products and/or the lack of wastewater treatment facilities to flush microbeads into the lake (Fendall and Sewell, 2009; Eriksen et al., 2013a). Instead, plastic fragments, films, and lines/fibers dominated the Lake Hovsgol pelagic microplastic composition. Due to the lack of industry, agriculture, wastewater, and sewage, these microplastics are likely the result of the fragmentation and degradation of plastic household debris, such as the bags, bottles, wrappers, and fishing gear that dominated the Lake Hovsgol shoreline.

Currently, little is known about the rate and mechanisms of plastic degradation and fragmentation in the freshwater environment. On one hand, plastics may easily fragment in Lake Hovsgol and other ultra-oligotrophic lakes due to increased UV penetration and reduced biofouling, which can shield plastics from UV radiation (Andrady et al., 2011; Gregory and Andrady, 2003). On the other hand, plastics may maintain their integrity in Lake Hovsgol and other cold, high-latitude lakes due to reduced thermal degradation and reduced UV exposure resulting from ice cover (Gregory and Andrady, 2003). Ultimately, plastics degrade more quickly when dry and exposed on land than when in the water (Andrady et al., 1993), and the pace of plastic degradation may be driven more by terrestrial processes, which may not vary between freshwater and marine shores. More research is necessary to understand the rate and mechanisms of plastic degradation in freshwater and the role of these processes in determining microplastic density.

The south-to-north decrease in microplastic density and concentration of microplastics along the eastern shore suggests that microplastics are sourced from the more developed southwestern shore and distributed by the prevailing southwesterly winds. Although the residential populations of Hatgal (pop. 2980) and Hankh (pop. 2460) are approximately equal (NSOM, 2012), Hatgal is the larger source of pollution because the vast majority of Lake Hovsgol's 20,000 annual visitors enter and remain in the southern section of the park (MEC, 2014). Furthermore, the lake drains south via the Eg River, and although the residence time is long (Hayami

et al., 2006), this outflow could assist in the southerly concentration of microplastics. These patterns are consistent with studies of microplastics in nearshore marine environments, which indicate that microplastic density is governed by prevailing surface circulation, wind, and proximity to urban centers (e.g., Browne et al., 2010, 2011; Doyle et al., 2011; Desforages et al., 2014; Leite et al., 2014).

Plastic pollution may threaten the aquatic fauna of Lake Hovsgol. Negative health consequences of microplastic ingestion have recently been documented in marine invertebrates (van Moos et al., 2012; Browne et al., 2013; Cole et al., 2013; Wright et al., 2013a,b) and fish (Rochman et al., 2013) and can be expected in Lake Hovsgol's freshwater analogs. Lake Hovsgol's waterbirds may also suffer mortality or a range of sub-lethal effects from macroplastic ingestion and entanglement (Azzarello and Van-Vleet, 1987; Laist, 1987, 1997; Sievert and Sileo, 1993; Gregory, 2009; Lavers et al., 2014). Although freshwater invertebrates (Imhof et al., 2013) and fish (Sanchez et al., 2014) have also been shown to ingest microplastics, more research is necessary to understand the differences in the vulnerability of freshwater and marine taxa to plastic ingestion and entanglement.

Fishing gear and other macroplastic debris can also facilitate the transport of invasive species (Barnes 2002; Gregory 2009). A likely candidate for plastic-assisted introduction to Lake Hovsgol is *Eloidea canadensis* Michx, a highly invasive aquatic plant (Mjelde et al., 2012) that was introduced to nearby Lake Baikal, Russia in the 1970s, and now occurs throughout the lake (Kozhova and Izhboldina, 1992; Kozhova and Silow, 1998). Russian tourists are known to fish in the lake (Free, unpublished data) and could transport *E. canadensis* on contaminated fishing gear (Johnstone et al., 1985; Relini et al., 2000). Aquatic macrophytes are rare in Lake Hovsgol (Hayford and Ferrington, 2006) and the introduction of *E. canadensis* could have cascading impacts on the lake's aquatic biota.

Although there are laws and plans in place to regulate waste management and reduce waste production in Mongolia, the infrastructure to execute and enforce these measures is almost nonexistent. Regulations such as "the law on limited use and importing of some plastic bags", adopted by Parliament in 2009 and initiated in 2010, outlaw the import and use of plastic bags thinner than 0.025 mm, but there is no evidence that these laws are actually enforced. The Ministry of Nature and Green Development (formerly the Ministry of Nature, Environment, and Tourism), the governing body responsible for the development and implementation of all Mongolian environmental policies, operates on an annual budget of only US\$205 million, and admits that "there is a lack of national coordination on waste management policies [and] technical and human resources for solid waste management in the country are inconsistent" (MNET Report, 2010, pg. 3).

It is challenging for developing countries like Mongolia to develop waste management infrastructure, but these projects are

critically important, not only for human and ecosystem health, but also for the tourism economy. Tourism is a major component of the Mongolian economy (5.2% of GDP in 2013; [WTTC Report, 2013](#)) and Lake Hovsgol is one of its most popular attractions with over 20,000 visitors per year ([Yu and Goulden, 2006](#); [MEC, 2014](#)). However, a survey of tourist satisfaction reveals that although tourists highly regarded Mongolia's landscapes and wildlife, especially those within Lake Hovsgol National Park, they were less satisfied with levels of sanitation ([Yu and Goulden, 2006](#)). Thus, with government objectives to increase tourism revenue ([WTTC Report, 2013](#)), proper waste management represents an important ecological and economic issue.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.marpolbul.2014.06.001>.

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