



Seasonal variation observed in microplastic deposition rates in boreal lake sediments

S. Saarni¹ · T. Soininen² · E. Uurasjärvi² · S. Hartikainen³ · S. Meronen¹ · T. Saarinen¹ · A. Koistinen²

Received: 18 October 2022 / Accepted: 11 February 2023 / Published online: 23 February 2023
© The Author(s) 2023

Abstract

Purpose The sediment trap method allows measurements of vertical microplastic flux rate into sediments and provides comparable information of the spatial microplastic deposition rates. Such data are essential for comparison of the microplastic pollution rates in different sedimentary systems and for future risk assessments.

Materials and methods We monitored microplastic fluxes using sediment traps in a boreal lake seasonally during 1 year. The sites represent different level of exposure to anthropogenic activities, from construction work to the open water site. Microplastic fluxes were compared to sediment characteristics (organic content) and sediment accumulation rates.

Results and discussion The highest annual microplastic deposition rate (2300 items m⁻² year⁻¹) was recorded at snow disposal site, a location where the snow collected from the city streets during winter is transported. The lowest rate was observed at the control site (660 items m⁻² year⁻¹) upstream from the city. Our results reveal the seasonal variation in microplastic deposition rates. In general, the highest microplastic flux rates were measured during growing season, accompanied with higher sedimentation rate. The low microplastic deposition rate during winter is likely explained by ice cover, frozen soil, and snow cover in the catchment. In contrast, microplastic concentration was higher in winter samples due to ceased sediment transport from catchment to lake. The sediment accumulation rate did not predict microplastic accumulation rate.

Conclusion Our data suggest seasonal variation in microplastic deposition rates. The microplastic flux rates compared to their concentrations indicates that sites with high sedimentation rates can lead to underestimation of microplastic deposition and hence hamper recognition of hot spots.

Keywords Microplastic flux · Microplastic concentration · Seasonal changes · Flux rate · Fresh water environment · Sedimentation

1 Introduction

Microplastics (MPs) are acknowledged as emergent pollutants that can potentially cause a serious risk for the environment, ecosystem functioning and human health. MPs are

particles that have been either manufactured to small size (<5 mm) or formed by degradation of plastic litter because of UV radiation and physical abrasion. Although microbeads in cosmetics are recently banned, more than 300 million tons (Mt) of plastic is produced every year (Tiseo et al. 2021). While approximately only 9% of all produced plastic is recycled and 12% incinerated, at least 7000 Mt of plastic is estimated to be accumulated in the environment (Geyer et al. 2017). Plastic litter fragments to micro- and nanoplastics, which become incorporated in the natural cycles and food chains, harming ecosystem functioning. MP pollution is persistent and pervasive, being found worldwide in the deepest marine basins (Van Cauwenberghe et al. 2013; Bergmann et al. 2017), the remote mountain lakes (Free et al. 2014), glaciers (Stefánsson et al. 2021; Zhang et al. 2021a), soils (Yang et al. 2021a), and animals including

Responsible editor: Olivier Evrard

✉ S. Saarni
saija.saarni@utu.fi

¹ Department of Geography and Geology, University of Turku, 21100 Turku, Finland

² SIB Labs, University of Eastern Finland, Yliopistonranta 1 E, 70210 Kuopio, Finland

³ School of Pharmacy, University of Eastern Finland, Yliopistonranta 1 C, 70210 Kuopio, Finland

humans (Amato-Lourenço et al. 2021; Leslie et al. 2022). While the production and processing of plastic materials are continuing, the unintended leaking of plastics to the natural systems is further cumulating. Even if production stopped today, tons of plastic litter are already in the environment, producing increasing amounts of MPs by degrading into smaller fragments.

Recent research suggest severe ecological risks caused by MPs, yet many of the studies testing the risks use microplastic concentrations that are not found in natural environments (Botterell et al. 2019; Koelmans et al. 2020). While the risky concentrations for different species are being investigated, the current concentrations in natural environments are not fully known and are expected to increase with time. However, the rate of change in the MP concentrations in natural environments has been poorly investigated. To be able to predict future risk and estimate when the dangerous levels of MP concentrations are exceeded, the current flux of microplastics to the environment needs to be deciphered related to sediment flux. The MP concentrations in surface sediments are controlled by the vertical flux of microplastics but also the overall sedimentation rates. Hence, it is critical to understand the rate of change in both variables (microplastic accumulation rate and sediment accumulation rate) and their relationships, which are expected to vary greatly depending on location and sedimentary environment.

While a large part of all plastics is suggested to enter the marine realm after being incorporated in the terrestrial ecosystems and transported by the rivers and streams, the freshwater systems could still be at greater risk. The deposition of MPs in the lacustrine sediments are already widely recognized (Li et al. 2020; Yang et al. 2021b). However, lacustrine environments close to human activities can experience huge loads of MPs compared to their surface area and water volume (Saarni et al. 2021). Being sources for drinking water and food, freshwater environments are very critical in terms of water quality from many aspects, such as recreational use, drinking water, food storage, and commercial use. While the proximity for human activities lead to larger input of MPs, and the sedimentation rates tend to be lower in lake basins (Ojala et al. 2012) than in coastal marine systems such as estuaries, bays and river deltas (Schimmelman et al. 2016; European Commission, [open data](#)) also subjected to intensified human influence, the concentrations of MPs in the surface sediments of lake systems can rise faster than those in marine coastal systems.

Sequential sediment trapping with multiple trap approach is a powerful tool to assess temporal changes in sediment fluxes and sediment characteristics as well as local variations within the basin (Chu et al. 2005; Pospelova et al. 2018; Salmela et al. 2022). The sediment trap approach has already been shown to yield detailed information on local vertical MP flux rates (Saarni et al. 2021). MPs are a heterogeneous

group of synthetic polymers, and their characteristics, such as chemical composition, particle size, and shape, vary greatly. The density variation of MPs is wide from below water density (e.g., polyethylene and polypropylene 0.9 g cm^{-3}) up to densities close to minerogenic material (e.g., polytetrafluoroethylene 2.2 g cm^{-3}). Density controls the fate of MPs in water, and their routes into sediment deposits can be very different. Additionally, particle shape can play a critical role in MPs tendency to be transported and/or deposited in the bottom sediments (Khatmullina and Isachenko 2017). Like in the case of any particle in nature, size and density have a large influence on MPs fate with respect to transport and deposition, but also seasonal changes in climatic conditions controls where and when the particle can be deposited or further resuspended. While there is still little understanding of seasonal controls of MP release and deposition, seasonal sediment trap data can shed light on the release-transport-accumulation path of MP particles.

In this study, we used multiple sediment trap approach to investigate Lake Kallavesi surrounding the city of Kuopio (population of approximately 118,000), Finland. The aim was to measure vertical MP fluxes in regard of different municipal activities to evaluate the sources and timing of the transport of MPs from the catchment to the water body. Furthermore, we measured vertical flux of microplastics into the sediments, and local sedimentation rate accompanied with sediment characteristics. Our results contribute to understanding the way in which microplastic particles become accumulated in lake sediments. The data enables prediction of the future MP concentrations in the ecologically active surface sediments and provides an understanding of how sedimentary environment may control the accumulation of various MP materials.

2 Materials and methods

2.1 Study site

Lake Kallavesi is a large brown water lake in central Finland surrounding the city of Kuopio. The population of Kuopio city is approximately 118,000. The lake has an area of 478 km^2 , maximum depth of 75 m and mean depth of 9.7 m. It receives waters from Iisalmi and Nilsä water courses from northern and northeastern side and drains towards south. Lake basin is a complex multi basin system with fragmented shorelines, islands and many semi-detached basins separated by glacial deposits, bedrock shear zones, and Precambrian domes. The bedrock consists of Archaean and Proterozoic crystalline rocks, mostly dominated by gneisses (Geological Survey of Finland, [online map](#)). The basin was formed after the Weichselian ice sheet retreat more than 9500 years ago (Saarnisto 2000). The annual mean temperature is $+4.1 \text{ }^\circ\text{C}$,

the mean temperature of the coldest month, January is $-7.8\text{ }^{\circ}\text{C}$, and the warmest month (July) is $+17.7\text{ }^{\circ}\text{C}$ (period of 1991–2020; Finnish Meteorological Institute 2022). The annual precipitation is 644 mm yr^{-1} , nearly half of it precipitates as snow. The lake is covered by ice approximately 6 months from November to April (Finland's Environmental Administration 2022). The catchment of the lake, including upper lakes, is $16,270\text{ km}^2$. The catchment area has industrial and agricultural activities, forestry, and traffic.

Five sediment traps were deployed in Lake Kallavesi (Fig. 1) to measure local MP accumulation rates and observe seasonal variation of MP characteristics and variation in the vertical flux. Two traps were deployed upstream from the city of Kuopio, of which trap 1 serves as a control trap for background contamination to Lake Kallavesi system from the head waters. Trap 2 records bridge construction work that occurred at the Northern branch from 2016 to 2018 (Finnish Transport Infrastructure Agency 2018). Trap 3 is in the central part of the northeast basin of Lake Kallavesi, surrounded by human activities and downstream from the industrial water release. Trap 4 is located at the bay next to the snow disposal site. Trap 5 is located downstream from the city of Kuopio, about 2 km downstream from the wastewater treatment plant discharge pipe. The lake likely receives MPs also from surrounding holiday cabins and permanent residency as well as fishing, transport, and recreational water use. Table 1 shows the detailed location and water depths at each monitoring site.

2.2 Sediment trap monitoring

The sediment trap configuration described in Saarni et al. (2021) was used to monitor vertical flux of sedimentary material in five locations. The trap configuration consisted of the anchor weight (10–15 kg), trap body of stainless steel, and two collector tubes made from polymethyl methacrylate (PMMA) with diameter of 6.6 cm, height 51 cm, and volume of 1.7 L. The 3 L signal buoy of PVC was submerged about 3 m below the surface to avoid attachment to the ice or boat traffic. The trap body was attached to the anchor and signal buoy using sinking 3 mm polyester ropes.

The sediment traps were deployed in spring 2017, and the samples were collected on following autumn and spring 2018 to have samples representing winter season and growing seasons separately (Table 1). Sediment traps were collected and maintained on site from the boat. The sample from each collector tube was poured and rinsed into a 3 L prewashed bucket (white, food-grade polypropylene) using distilled water. The samples from both collector tubes A and B were retrieved in their own buckets, of which the A sample was used for microplastic analyses and B for sediment analyses. After sample collection, the tubes were washed, attached to the trap body, and gently placed back at the same location. All samples were stored under sealed lids at $+5\text{ }^{\circ}\text{C}$ until the treatment.

Fig. 1 Sediment trap locations in Lake Kallavesi shown with relevant catchment and basin characteristics. Trap 1 upstream control, 2 bridge construction, 3 highway, 4 central basin, 5 snow disposal site, 6 downstream city area and wastewater treatment plant

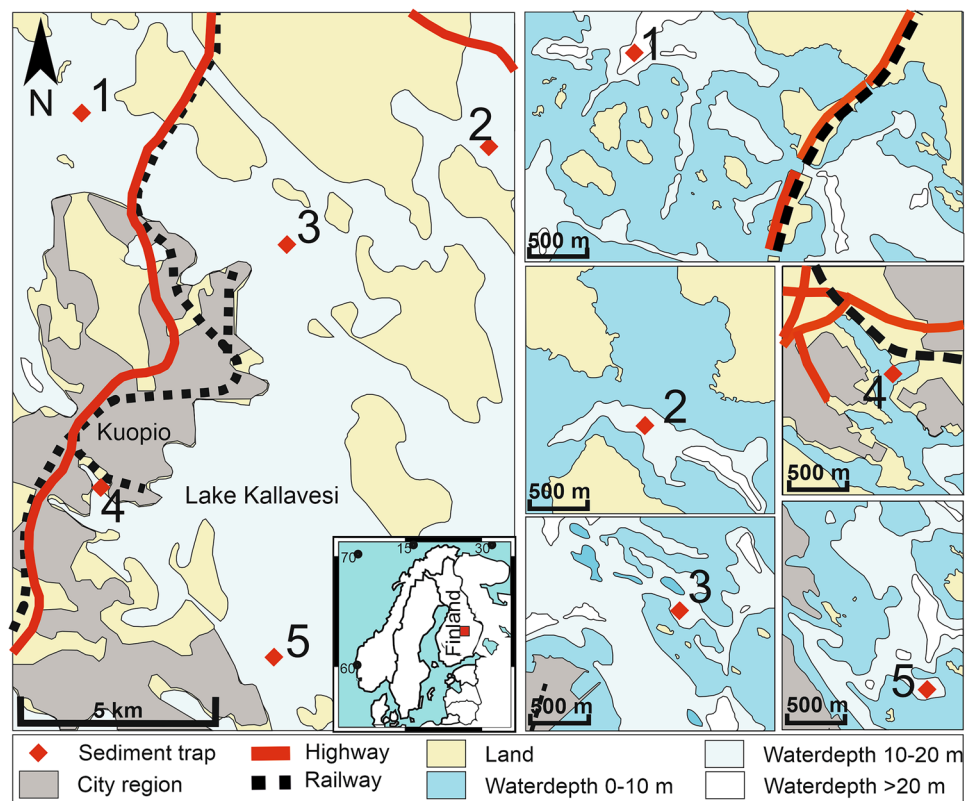


Table 1 Sediment trap locations and depths, deployment date, and collection dates of each sequential sample collection. Sample 1 represents growing season and sample 2 winter season

Trap	N	E	Depth	Deployment date	Sample 1	Sample 2	Description
1	62°57,4'	27°38,6'	30	3.6.17	21.10.17	26.5.18	Up-stream control
2	62°56,9'	27°50,1'	11	3.6.17	21.10.17	26.5.18	Downstream from construction
3	62°55,7'	27°44,4'	15	3.6.17	21.10.17	26.5.18	Open-water central basin
4	62°52,7'	27°39,1'	9	3.6.17	21.10.17	26.5.18	Snow disposal site
5	62°50,4'	27°43,8'	13	3.6.17	21.10.17	26.5.18	Downstream from city area

2.3 Sediment analysis

The excess water was decanted, and the samples were rinsed to large crucibles. The B-samples were dried at 60 °C for 24 h. The sediment weight was measured to calculate total mass and sediment accumulation rate (SAR). Sediment samples were homogenized and powdered using agate mortar, and subsamples were taken to measure the organic matter content (Heiri et al. 2001). About 0.5 g samples were weighed in crucibles and burned at 550 °C for 4 h for measuring loss on ignition (LOI). The samples were cooled in an exicator and the change of sample weight after burning was recorded for calculating the organic content of the sediment samples. The sedimentary material does not include calcium carbonate minerals and hence LOI reflects organic carbon content.

2.4 Microplastic analysis

The A-sample was opened and handled only in the clean laboratory under laminar flow hood or vacuum hood to protect samples from contamination. Water from the trap samples was decanted carefully and filtered through 12–15 µm paper filters (Munktell Ahlstrom, general purpose paper, size 90, grade 1003), and the filters were stored on petri dishes. The sediments were rinsed to 50 ml polypropylene (PP) centrifuge tubes using ultrapure water. Excess water was filtered and stored after centrifuging the samples (VWR Mega Star 1.6; 3000 rpm, 10 min, brake rate of 6). Clastic lithic matter was separated from lighter fraction by density separation with heavy liquid (lithium heteropolytungstate, LST fast float, diluted in ultrapure water to density of 2.0 g ml⁻¹) according to Saarni et al. (2021). The density separation was repeated three times. Each time, the supernatant (light fraction result of extraction) was filtered through 12–15 µm paper filters and stored in sealed petri dishes.

Light fraction contained a lot of organic matter, and hence samples on the paper filters were visually inspected using a stereo microscope (Zeiss Stemi 508, 6.3–50× magnification; AxioCam ERc 5 s camera), and microplastic-appearing particles were selected and hand-picked using micro tweezers. Particles were selected, if they had at least one of the

following features: bright “unnatural” color, reflective surface, or rigidity when handling. Lower size limit of the selected particles was around 100 µm. The samples did not contain any particles larger than microplastic scale (5 mm). The selected particles were rinsed with filtered ethanol to a 50-mL centrifuge tube (made from PP). From the tubes, the particle-ethanol suspensions were filtered to 5 µm silver membrane filters (Sterlitech Co).

Fourier-transform infrared (FTIR) spectral maps were measured from the silver membrane filters with Agilent Cary 670/620 imaging FTIR spectrometer equipped with 128×128 focal plane array (FPA) detector. The whole filter area (diameter 12 mm) was measured in reflection mode, using 15×Cassegrain objective, 8 cm⁻¹ spectral resolution, four scans, 3800–800 cm⁻¹ spectral range, and 5.5 µm pixel resolution, similarly as in Uurasjärvi et al. (2020) and Saarni et al. (2021).

Data from FTIR was analyzed with SiMPle software (Pimpke et al. 2020). SiMPle is a freeware tool that automatically counts and identifies MPs by calculating Pearson’s correlation between each sample spectrum and reference spectra of plastics. SiMPle provides particle counts by polymer types, particle sizes, and estimated masses of particles, based on the estimated volume and density of a particle. The reference library consisted of polyethylene (PE), PP, polyamide (PA), polyethylene terephthalate (PET), polystyrene (PS), acrylonitrile butadiene styrene (ABS), polyurethane (PU), polyvinyl chloride (PVC), polymethyl methacrylate (PMMA), polyacrylonitrile (PAN), and natural polymers (cotton, proteins). The correlation thresholds and other parameters for identification of polymers in siMPle were similar as in Uurasjärvi et al. (2020). Particles sized < 100 µm were ignored from the siMPle data, because of size limit due to visual inspection and manual handling.

2.5 Contamination controls and recovery

Three control samples were prepared to evaluate the laboratory contamination. Control sediment samples were prepared and analyzed simultaneously with microplastic samples through all the methodological steps. The control sediment was collected from a lake sediment core from Lake Korttajärvi

at sediment depth of 1.8 m, dated to about 2000 years before present (Tiljander et al. 2003). The microplastic-appearing particles were visually selected, hand-picked, and identified using FTIR. None of the picked particles from control samples were plastic. Consequently, no corrections were required to our data set.

Recovery rate was evaluated using three replicate samples, all of which included 100 pieces of red colored PET particles of size 250–500 μm and 100 pieces of white PE particles of size 200–250 μm (self-made, cryomilled, and sieved). The recovery samples were treated using the previously described heavy liquid separation method. The recovered particles were identified and calculated from the paper filters using binocular microscope. Our method showed 98% recovery for red PET particles and 89% for white PE particles.

2.6 Statistical analyses

The PAST 4.03 software (Hammer et al. 2001) was used to investigate correlations between the microplastic accumulation rate and sedimentary variables such as organic content, and SAR. Shapiro–Wilk test was used to verify the normal distribution of the data ($n=10$) accompanied with Pearson's correlation.

3 Results

3.1 Sedimentary conditions

The total dry weight of sediment trap samples varied between 0.4 g and 3.14 g leading to SAR values between 0.62 and 7.42 $\text{g m}^{-2} \text{day}^{-1}$ (Table 2). The sediment accumulation is very site specific, but accumulation rates during growing season were consistently larger. Sediment organic content varied between 11.8 and 20.8%, being higher in the growing season samples except for site 5. The organic content

Table 2 Total weight of each trap sample, sediment accumulation rate (SAR), and organic matter content (OM %). Sample number refers to seasonal sample number (cf. Table 1)

Trap/sample no	Sample season	Total weight (g)	SAR $\text{g m}^{-2} \text{d}^{-1}$	OM %
1–1	GS 2017	1.98	4.69	20.8%
1–2	W 17–18	n/a	n/a	n/a
2–1	GS 2017	3.14	7.42	11.8%
2–2	W 17–18	n/a	n/a	n/a
3–1	GS 2017	1.78	4.22	17.6%
3–2	W 17–18	0.41	0.62	15.8%
4–1	GS 2017	2.24	5.3	15.2%
4–2	W 17–18	0.58	0.88	14.8%
5–1	GS 2017	1.88	4.44	18.8%
5–2	W 17–18	0.80	1.22	19.7%

data was missing for trap 1 and 2 winter samples, because in both sites, a fish had entered one of the two trap tubes and decayed causing a loss of the entire sample. The other trap tube remained unharmed but was prioritized for microplastic analyses, which was the main objective of the study.

3.2 Microplastic accumulation

The annual accumulation rate of MPs varied between 660 and 2320 $\text{pcs m}^{-2} \text{yr}^{-1}$ (Table 3). The highest annual rate is observed at site 4, while lowest rates at sites 1 and 3. The daily accumulation rate of MPs is up to four times higher during the growing season than during wintertime at all sites excluding site 1 where no microplastic particles were found from growing season sample (Table 4). Most of the particles (75%) were fragments, and the remaining 25% were fibers. The most frequently found polymer types were PP, PE, and PA, respectively (Fig. 2). Larger variety of materials were documented from growing season samples, where PP was clearly dominant material. PE dominated in winter season samples. No statistically significant correlations were found between the sedimentary variables and microplastic accumulation rate, likely because the small sample size available. The blank control samples did not show any contamination, likely due to the careful handling of the samples and due to relatively large lower limit of the analyzed particles (100 μm). Hence, no corrections to the MP results were required. Since the loss of MP particles during the process was less than 10%, we did not use any corrections regarding the possible loss of particles during handling, but only note that the actual number of particles in the sediment samples can have been larger.

4 Discussion

4.1 Depositional environment

Fastest sediment accumulation rate occurs during growing season at all sites. The total accumulation rate during growing season is up to sixfold compared to winter season. This

Table 3 The annual sediment accumulation rate (SAR) and microplastic flux at the studied sites

Site	annual SAR $\text{g m}^{-2} \text{a}^{-1}$	Annual MP flux $\text{pcs m}^{-2} \text{a}^{-1}$
1	n/a	663
2	n/a	1325
3	742	663
4	954	2318
5	905	1656

Table 4 Number of MPs in sample (no of pcs), MP concentration (Items g^{-1}) in sediment dry weight, calculated daily MP flux, particle shape as percent of fragments, mean particle size and percentage of the MP fraction with density less than $1 g cm^{-3}$ are shown

Sample	Season	No of pcs	Items g^{-1}	MP flux $pcs m^{-2} d^{-1}$	Particle shape fragment %	Particle size mean	Light fraction %
1–1	GS 2017	None	0	n/a	n/a	n/a	n/a
1–2	W 17–18	2	n/a	3.1	100	348	100
2–1	GS 2017	3	1.0	7.1	100	156	66.7
2–2	W 17–18	1	n/a	1.5	0	849	0
3–1	GS 2017	1	0.6	2.4	100	179	0
3–2	W 17–18	1	2.4	1.5	100	89	100
4–1	GS 2017	4	1.8	9.5	75	282	100
4–2	W 17–18	3	5.2	4.6	100	302	100
5–1	GS 2017	3	1.6	7.1	33.3	439	100
5–2	W 17–18	2	2.5	3.1	50	606	0

is most likely explained by the open water conditions, frost free catchment, resuspension of littoral sediments due to wave activity, and enhanced biogenic production (Ojala et al. 2013; Saarni et al. 2015; Johansson et al. 2019; Salmela et al. 2022). During winter season, Lake Kallavesi is covered by ice, which lasted for 130 days on winter 2017–2018. It is shown that during winter, the sediment accumulation underneath the ice cover is negligible (Ojala et al. 2013; Saarni et al. 2015; Johansson et al. 2019). Spring flood caused by snow melt, however, is a significant incident at boreal spring, increasing catchment erosion, sediment transport, and accumulation. The peak transport by the floods occurs

while the ice is not completely melted (Johansson et al. 2019), and this event is incorporated into winter season samples. While spring flood mostly explains the sediment accumulation observed in our winter samples, typical in boreal lakes (Ojala et al. 2013; Zolitschka et al. 2015; Johansson et al. 2019), the short-lived event is not able to increase the sedimentation rate over the growing season sedimentation rate. The daily sediment trap measurements of previous study in Lake Kallavesi shows that the material transport by snow-melt induced spring flood is very punctuated, lasting for several days, not weeks (Johansson et al. 2019).

The largest sedimentation rate is measured during growing season from site 2. The minerogenic content of the growing season sample at this site was exceptionally high. The high SAR and large quantity of minerogenic matter is likely related to construction work taking place at the bridge less than 2.5 km upstream from the trap site. The bridge construction work started in 2016 and was active until November 2018, and the majority of dredging was carried out on autumn 2017 and May 2018 (Finnish transport Infrastructure Agency 2018). These activities likely released clastic material and increased erosion as well as resuspension of earlier sediment deposits leading to peak in SAR in trap site 2. Increased sedimentation rates over natural background conditions due to construction work at the catchment are already previously documented from Lake Kallavesi (Johansson et al. 2019). The lowest SAR was documented at the open water site 3, located furthest on the coastlines, and terrigenous sediment sources.

The variability of organic content is remarkable among the sites and the seasons. In general, lower OM content is observed during winter season, which directly reflects the cyclic availability and production of biogenic material (Ojala et al. 2013; Zolitschka et al. 2015). In general, higher OM contents are measured from the sites further from coasts (site 1, 3, and 5), which suggest that at these sites, autochthonous organic production is of higher importance than at coastal sites. In addition, these locations are deepest sites.

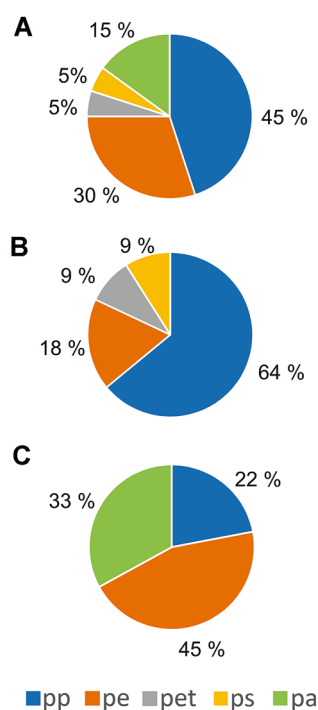


Fig. 2 Polymer types in all samples (A), growing season (B), and winter season (C) samples

Maximum OM of 20 % was collected at the 30 m depth (site 1), while the lowest OM content of 15 % was documented from shallowest site at 9 m water depth (site 4) if the site 2 impacted by the construction work is excluded. The relatively small difference between winter season and growing season is likely due to accumulation of the fine amorphous organic matter at the calm waters underneath the ice and transport of organic remnants during spring flood (Ojala et al. 2013; Saarni et al. 2015).

4.2 Occurrence of microplastics in sediment samples

The majority of particles found from sediment trap samples are fragments (75%), the rest being fibers. The dominance of fragments over fibers is previously reported in deeper lake bed sediments (Hengstmann et al. 2021; Cera et al. 2022); however, many studies report dominance of fibers (Li et al. 2020; Lenaker et al. 2021; Yang et al. 2021b). The lower portion of fragments (36%) reported from surface water samples from Lake Kallavesi (Uurasjärvi et al. 2020) may suggest that fragments are more likely deposited than fibers. Overall, our number of data and the low number of MPs observed in the samples do not allow an extensive analysis and interpretation of the data; however, it allows discussion of the following interesting points.

Despite the small number of particles detected, the most common material types identified (PP, PE; Fig. 2) reflect globally most produced and used plastic types (Geyer et al. 2017). PP and PE are among the most frequently found synthetic polymers in previously published results from lake sediments (Hengstmann et al. 2021; Lenaker et al. 2021; Saarni et al. 2021). This is in accordance with surface water samples from the same lake (Uurasjärvi et al. 2020) with the two most abundant polymer types of PP and PE. In total, wider range of polymer types is observed in growing season samples than in winter season samples; however, this cannot be considered significant, because of low total amount of particles and large variation between the sites. The most diverse polymer range was observed at site 2 downstream from the bridge construction work that likely denotes to intensive digging, dredging, and material use during the construction work. The proportion of lighter materials (density less than that of water, e.g., PE, PP) are more common in growing season samples. This could be related to biofouling, which is reported to be a significant factor to cause light materials to sink through the water column (Kowalski et al. 2016; Semcesen and Wells 2021; Zhang et al. 2021a, b).

Microplastic abundance in sediments is previously related to population density as well as proximity of the urban and agricultural land use, industry, road runoff, and wastewater treatment plants as well as paints and coatings from marine traffic (Horton et al. 2017; Xiong et al. 2018; Bergmann et al. 2019; Campanale et al. 2020; Grbić et al. 2020; Li et al.

2020; Lenaker et al. 2021; Kallenbach et al. 2022). Indeed, we record the highest microplastic concentrations at sites closer to human activities. The annual concentrations from Lake Kallavesi trap samples vary from 4000 to 20,000 items kg^{-1} , which is broadly in accordance to previously reported concentrations from lake basin sediments (Ballent et al. 2016; Turner et al. 2019; Jian et al. 2020; Zobkov et al. 2020; Lenaker et al. 2021) although the comparison of microplastic concentrations is always hampered by the different sampling and analyze methods in addition to microplastic particle size range investigated in each study. Furthermore, the lower detection limit of 100 μm in our study likely underestimates the microplastic concentrations and fluxes. The microplastic concentrations and accumulation rates show large variability within the Lake Kallavesi basin, which is in agreement with previous studies reporting multiple sediment samples within a single lake basin (Ballent et al. 2016; Baldwin et al. 2020; Jian et al. 2020; Zobkov et al. 2020; Hengstmann et al. 2021).

Higher microplastic concentrations in sediment beds are generally documented closer to coastal areas compared to open water sites (Baldwin et al. 2020; Hengstmann et al. 2021; Lenaker et al. 2021). This is explained by population, urban, and agricultural land use and transport processes. Our data show that not only concentrations, but also the microplastic accumulation rate is generally higher at sites near coasts. The highest accumulation rates are observed at site 4, close to the snow disposal site and city activities. The snow disposal site receives all the snow collected from the streets of the city during wintertime. The snow is transported and accumulated to the coast of the Siikalahti Bay (site 4) and is left to melt during the growing season. During winter season 2017/2018, in total of 288,000 m^3 of snow was disposed. All the contaminants from the snow pile are released by melting of snow during the growing season, and they become transported to the lake basin. In addition, because the site is located near the coastline, it likely receives MPs also from the recreational use of the bay (beach and small boat harbor) as well as storm waters. However, the result highlights the need of reconsideration of location of snow disposal sites at the vicinity of natural water bodies. The vertical flux rates of microplastics are equally high at sites 2 and 5, both influenced by human activities. The site 2 receives microplastics likely from the redeposition of dredged sediments and construction activities up stream, while site 5 indicates downstream influence from the waste water treatment plant and the urban region, in general. The lowest accumulation rates observed at the open water site 3, in the central part of the Northern Basin, could be explained by the distance from the shoreline and source areas. Equally low accumulation rates were observed at the control site upstream from the Kuopio city area and its activities. This is in line with the conclusions of several studies suggesting the importance of nearby microplastic sources for hot spot areas in Finnish coastal areas (Talvitie

et al. 2015; Martyanov et al. 2021; Sainio et al. 2021) and globally (Ballent et al. 2016; Zobkov et al. 2020; Grbić et al. 2020; Hengstmann et al. 2021; Yang et al. 2021b; Cera et al. 2022).

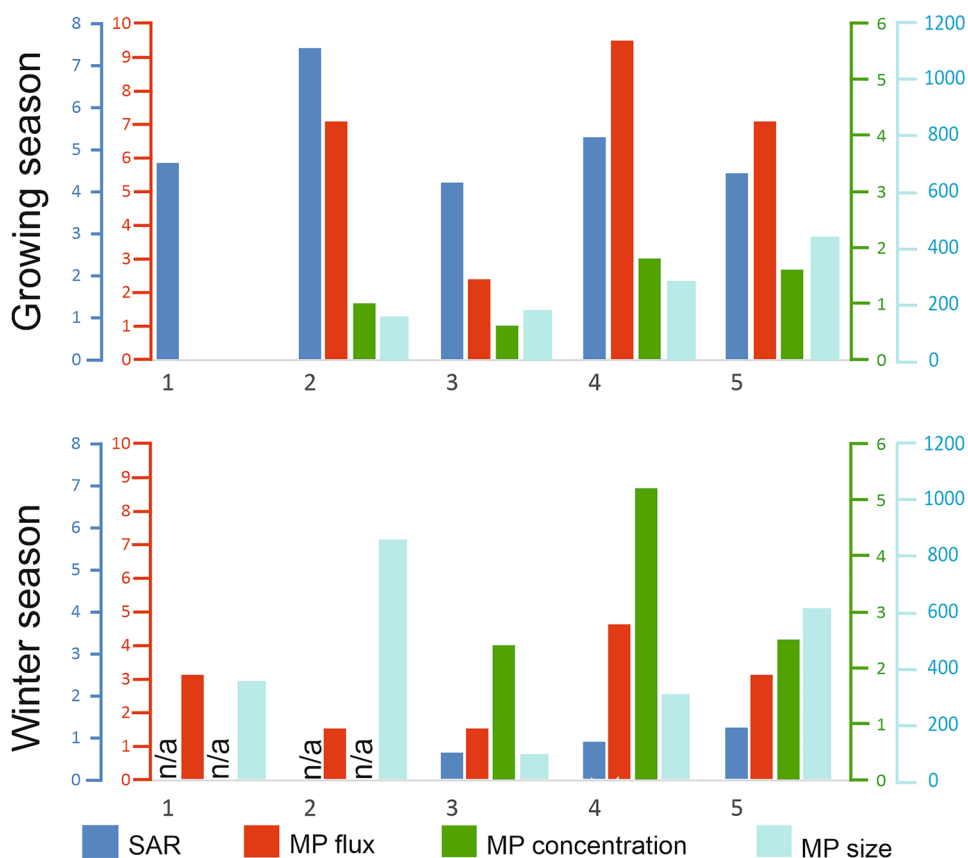
4.3 Seasonal variation of vertical microplastic flux

Previously, microplastic concentrations are observed to change over time; the microplastic abundance in sedimentary profiles are closely linked to global plastic production rate (Brandon et al. 2019; Turner et al. 2019). Moreover, increasing vertical microplastic flux rates are observed in varved sediment sequence from Santa Barbara Basin (Brandon et al. 2019). However, the large research gap lies in seasonal variation of microplastic deposition rates, and there is an urgent need for high-resolution microplastic-accumulation data in order to discuss the controlling factors on microplastic accumulation, in depth. The studies have already shown the seasonal variation of microplastics in beach sediments, where higher occurrence of microplastics is related to water level changes, run off events, wave activity, and winds (Corcoran et al. 2020; Iannilli et al. 2020; Hengstmann et al. 2021). In addition to spatial variation, our data suggest seasonal variation in vertical microplastic flux rate and concentrations in the sediments. Larger vertical microplastic fluxes occur during growing season period compared to winter season. In

contradiction, the microplastic concentration in sediments is higher during wintertime (Fig. 3).

The seasonal variation has strong influence on boreal lake systems (Ojala et al. 2013; Johansson et al. 2019), which could control the vertical flux of microplastics as well. Like sediment flux rate, also microplastic accumulation rate is higher during open water season at all locations, except for site 1. The low accumulation rates during winter season could be explained by decreased erosion and transport from snow covered and frozen catchment (Ojala et al. 2013; Johansson et al. 2019). However, trapping of microplastics in the ice during winter time (Geilfus et al. 2019; Scopetani et al. 2019; Kim et al. 2021) can reduce their accumulation from the water column to bottom sediments, despite the favorable calm conditions under ice cover promoting accumulation of other fine grained detritus (Ojala et al. 2013; Saarni et al. 2015; Johansson et al. 2019). In addition, frozen soil and snow cover reduce catchment erosion and transport of terrigenous material to the aquatic systems during winter. It is shown that mostly organic highly degraded material is deposited into sediments underneath the ice (Ojala et al. 2013). Recent modeling study from Baltic Sea (Martyanov et al. 2021) suggests that microplastics do not accumulate during winter, when surface water temperature is less than 4 °C. This was explained by the absence of biological

Fig. 3 The variation in sediment accumulation rate ($\text{g m}^{-2} \text{day}^{-1}$), microplastic flux rate ($\text{pcs m}^{-2} \text{day}^{-1}$), microplastic concentration in sediment (pcs g^{-1} in sediment dry weight), and mean particle size (μm) of collected microplastic particles between sampling sites 1–5 and seasons



processes related to phytoplankton and zooplankton functioning. While our data show this is not entirely true in lake environment, our results strongly support Martyanov et al. (2021) modeling outcome, showing larger microplastic accumulation rates during warm season.

The ceased sedimentation rate during winter season, however, leads to larger microplastic concentration in winter samples. It is possible that some of the microplastics are truly deposited during ice conditions. However, spring floods, caused by melting of snow, are major erosive events on boreal catchments, and hence it is likely, that majority of the microplastics observed in the winter samples are derived from catchment by the spring floods or accumulated after ice break out. The higher vertical microplastic fluxes during growing season may also suggest that large part of microplastic particles are accumulated relatively fast. Assuming zero transport of microplastic to the lake during the time when catchment and lake are frozen, the plastics enter the lake during spring floods and summer and become deposited within the same season. Relatively fast deposition is supported by the previous studies about sinking velocities of microplastic particles (Kowalski et al. 2016; Semcesen and Wells 2021; Zhang et al. 2021a).

The sites with higher microplastic accumulation rates show generally high sediment accumulation rates. Because many anthropogenic activities lead in enhanced catchment erosion, at the coastal sites close to urban land use, it is likely that the higher microplastic accumulation rates are accompanied with high SARs. The variation in sedimentation rate is a significant component affecting microplastic concentration in natural sediments. High sediment loads dilute the number of microplastic particles in total sample. While SAR can vary seasonally and with longer time periods or occasional events such as extreme floods, construction activities, or mass movements, sedimentation rate alone cannot predict or explain microplastic accumulation rate, especially at sites close to coast lines and/or human activities. Hence, microplastic concentration in bulk sediment sample cannot always recognize the hot spots of microplastics. This is suggested also by our observations. The site 2 under construction work shows high microplastic accumulation rate, but due to enhanced sediment accumulation rate at the site, the concentration of microplastics in the sediment sample remain low. On the other hand, the winter samples showing very low microplastic deposition result in very high microplastic concentrations due to the low sedimentation rate.

We argue that the investigations of actual microplastic deposition rates are crucial to detect the hot spot areas of microplastic accumulation and to understand where microplastics are deposited. Understanding the local sedimentation rates and vertical microplastic fluxes, it is possible to evaluate the future changes in microplastic concentrations of

ecologically active surface sediments. We expect that sediment accumulation rates and microplastic accumulation rates vary independently and not always to same direction. Human activities are expected to increase, while climate change can cause significant changes in sedimentation patterns. Hence, understanding both components affecting concentration will be crucial in understanding future microplastic concentration changes and ecological risks.

5 Conclusions

The freshwater bodies are increasingly exposed to microplastics and the large research gap lies in the rate of accumulation of microplastics to aquatic environments. Temporally resolved samples are required to quantify the microplastic fluxes to natural water bodies. Sediment trap monitoring provides high resolution time series of vertical microplastic fluxes and can provide valuable information of the sources, fate, and behavior in lake systems. The highest microplastic deposition rates occur in the vicinity of terrigenous sediment sources; however, no direct correlation between sediment mass and microplastic accumulation rate were observed. The large seasonal variability in boreal lake systems strongly controls microplastic deposition rates. The vertical flux of microplastic decreased significantly during winter. This is likely due to frozen and snow-covered soils at catchment preventing transport of the released microplastics. In addition, ice cover can trap microplastics from the surface waters and protect littoral sediments from wave induced resuspension further decreasing microplastic deposition. In contrast, microplastic concentration is higher during winter due to ceased sediment accumulation. The temporal and spatial variation in sedimentation rates can lead to under or over estimations of the environmental status of the site due to enrichment or dilution of microplastics. In sites of high sedimentation rates, the use of only microplastic concentration can lead to failure in identifying a hot spot site. We encourage an increase in the research of microplastic flux rates to better compare the microplastic pollution rates and to understand the controlling factors behind the depositional processes of microplastics.

Funding Open Access funding provided by University of Turku (UTU) including Turku University Central Hospital. This work was supported by the Academy of Finland (Grant no. 321869), Finnish Cultural Foundation, Turku University Foundation, and the Finnish Foundation for Nature Conservation.

Declarations

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Amato-Lourenço LF, Carvalho-Oliveira R, Júnior GR, dos Santos Galvão L, Ando RA, Mauad T (2021) Presence of airborne microplastics in human lung tissue. *J Hazard Mater* 416:126124. <https://doi.org/10.1016/j.jhazmat.2021.126124>
- Baldwin AK, Spanjer AR, Rosen MR, Thom T (2020) Microplastics in Lake Mead National Recreation Area, USA: Occurrence and biological uptake. *PLOS ONE* 15:e0228896. <https://doi.org/10.1371/journal.pone.0228896>
- Ballent A, Corcoran PL, Madden O, Helm PA, Longstaffe FJ (2016) Sources and sinks of microplastics in Canadian Lake Ontario nearshore, tributary and beach sediments. *Mar Pollut Bull* 110:383–395. <https://doi.org/10.1016/j.marpolbul.2016.06.037>
- Bergmann M, Mützel S, Primpke S, Tekman MB, Trachsel J, Gerdt G (2019) White and wonderful? Microplastics prevail in snow from the Alps to the Arctic. *Sci Adv* 5:eaax1157. <https://doi.org/10.1126/sciadv.aax1157>
- Bergmann M, Wirzberger V, Krumpfen T, Lorenz C, Primpke S, Tekman MB, Gerdt G (2017) High quantities of microplastic in Arctic deep-sea sediments from the HAUSGARTEN Observatory. *Environ Sci Technol* 51:11000–11010. <https://doi.org/10.1021/acs.est.7b03331>
- Botterell ZLR, Beaumont N, Dorrington T, Steinke M, Thompson RC, Lindeque PK (2019) Bioavailability and effects of microplastics on marine zooplankton: A review. *Environ Pollut* 245:98–110. <https://doi.org/10.1016/j.envpol.2018.10.065>
- Brandon JA, Jones W, Ohman MD (2019) Multidecadal increase in plastic particles in coastal ocean sediments. *Sci Adv*. <https://doi.org/10.1126/sciadv.aax0587>
- Campanale C, Stock F, Massarelli C, Kochleus C, Bagnuolo G, Reifferscheid G, Uricchio VF (2020) Microplastics and their possible sources: the example of Ofanto river in southeast Italy. *Environ Pollut* 258:113284. <https://doi.org/10.1016/j.envpol.2019.113284>
- Cera A, Pierdomenico M, Sodo A, Scalici M (2022) Spatial distribution of microplastics in volcanic lake water and sediments: relationships with depth and sediment grain size. *Sci Total Environ* 829:154659. <https://doi.org/10.1016/j.scitotenv.2022.154659>
- Chu G, Liu J, Schettler G, Li J, Sun Q, Gu Z, Lu H, Liu Q, Liu T (2005) Sediment fluxes and varve formation in Sihailongwan, a maar lake from Northeastern China. *J Paleolimnol* 34:311–324. <https://doi.org/10.1007/s10933-005-4694-0>
- Corcoran PL, Belontz SL, Ryan K, Walzak MJ (2020) Factors controlling the distribution of microplastic particles in benthic sediment of the Thames River, Canada. *Environ Sci Technol* 54:818–825. <https://doi.org/10.1021/acs.est.9b04896>
- European Commission, open data. European Marine Observation and Data Network (EMODnet) Geology: seabed substrates and sedimentation rates. <https://emodnet.ec.europa.eu/geoviewer/>. Accessed 3 Feb 2023
- Finland's Environmental Administration (2022) Open data. Internet source: <https://www.syke.fi/avoindata>. Accessed 14 Oct 2022
- Finnish Meteorological Institute (2022) open data. Internet source: <https://www.ilmatieteenlaitos.fi/havaintojen-lataus>. Accessed 14 Oct 2022
- Finnish Transport Infrastructure Agency (2018) Valtatie 9 Jännevirran silta (In Finnish) Internet source: <https://vayla.fi/vt9jannevirta>. Accessed 3 Oct 2022
- Free CM, Jensen OP, Mason SA, Eriksen M, Williamson NJ, Boldgiv B (2014) High-levels of microplastic pollution in a large, remote, mountain lake. *Mar Pollut Bull* 85:156–163. <https://doi.org/10.1016/j.marpolbul.2014.06.001>
- Geilfus N-X, Munson KM, Sousa J, Germanov Y, Bhugaloo S, Babb D, Wang F (2019) Distribution and impacts of microplastic incorporation within sea ice. *Mar Pollut Bull* 145:463–473. <https://doi.org/10.1016/j.marpolbul.2019.06.029>
- Geological Survey of Finland (online map). Bedrock of Finland, version 2.3. 1:200 000. <http://hakku.gtk.fi>. Accessed 2 Feb 2023
- Geyer R, Jambeck JR, Law KL (2017) Production, use, and fate of all plastics ever made. *Sci Adv* 3:e1700782. <https://doi.org/10.1126/sciadv.1700782>
- Gričić J, Helm P, Athey S, Rochman CM (2020) Microplastics entering northwestern Lake Ontario are diverse and linked to urban sources. *Water Res* 174:115623. <https://doi.org/10.1016/j.watres.2020.115623>
- Hammer Ø, Harper DAT, Paul DR (2001) Past: Paleontological Statistics Software Package for Education and Data Analysis. *Paleontologia Electronica* 4:1:4
- Heiri O, Lotter AF, Lemcke G (2001) Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *J Paleolimnol* 25:101–110. <https://doi.org/10.1023/A:1008119611481>
- Hengstmann E, Weil E, Wallbott PC, Tammimga M, Fischer EK (2021) Microplastics in lakeshore and lakebed sediments – external influences and temporal and spatial variabilities of concentrations. *Environ Res* 197:111141. <https://doi.org/10.1016/j.envres.2021.111141>
- Horton AA, Svendsen C, Williams RJ, Spurgeon DJ, Lahive E (2017) Large microplastic particles in sediments of tributaries of the River Thames, UK – abundance, sources and methods for effective quantification. *Mar Pollut Bull* 114:218–226. <https://doi.org/10.1016/j.marpolbul.2016.09.004>
- Iannilli V, Corami F, Grasso P, Lecce F, Buttinelli M, Setini A (2020) Plastic abundance and seasonal variation on the shorelines of three volcanic lakes in Central Italy: can amphipods help detect contamination? *Environ Sci Pollut Res* 27:14711–14722. <https://doi.org/10.1007/s11356-020-07954-7>
- Jian M, Zhang Y, Yang W, Zhou L, Liu S, Xu EG (2020) Occurrence and distribution of microplastics in China's largest freshwater lake system. *Chemosphere* 261:128186. <https://doi.org/10.1016/j.chemosphere.2020.128186>
- Johansson M, Saarni S, Sorvari J (2019) Ultra-high-resolution monitoring of the catchment response to changing weather conditions using online sediment trapping. *Quaternary* 2:18. <https://doi.org/10.3390/quat2020018>
- Kallenbach EMF, Friberg N, Lusher A, Jacobsen D, Hurley RR (2022) Anthropogenically impacted lake catchments in Denmark reveal low microplastic pollution. *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-022-19001-8>
- Khatmullina L, Isachenko I (2017) Settling velocity of microplastic particles of regular shapes. *Mar Pollut Bull* 114:871–880. <https://doi.org/10.1016/j.marpolbul.2016.11.024>
- Kim S-K, Lee H-J, Kim J-S, Kang S-H, Yang E-J, Cho K-H, Tian Z, Andrady A (2021) Importance of seasonal sea ice in the western Arctic ocean to the Arctic and global microplastic budgets.

- J Hazard Mater 418:125971. <https://doi.org/10.1016/j.jhazmat.2021.125971>
- Koelmans AA, Redondo-Hasselerharm PE, Mohamed Nor NH, Kooi M (2020) Solving the nonalignment of methods and approaches used in microplastic research to consistently characterize risk. *Environ Sci Technol* 54:12307–12315. <https://doi.org/10.1021/acs.est.0c02982>
- Kowalski N, Reichardt AM, Waniek JJ (2016) Sinking rates of microplastics and potential implications of their alteration by physical, biological, and chemical factors. *Mar Pollut Bull* 109:310–319. <https://doi.org/10.1016/j.marpolbul.2016.05.064>
- Lenaker PL, Corsi SR, Mason SA (2021) Spatial distribution of microplastics in surficial benthic sediment of Lake Michigan and Lake Erie. *Environ Sci Technol* 55:373–384. <https://doi.org/10.1021/acs.est.0c06087>
- Leslie HA, van Velzen MJM, Brandsma SH, Vethaak AD, Garcia-Vallejo JJ, Lamoree MH (2022) Discovery and quantification of plastic particle pollution in human blood. *Environ Int* 163:107199. <https://doi.org/10.1016/j.envint.2022.107199>
- Li C, Busquets R, Campos LC (2020) Assessment of microplastics in freshwater systems: a review. *Sci Total Environ* 707:135578. <https://doi.org/10.1016/j.scitotenv.2019.135578>
- Martyanov SD, Isaev AV, Ryabchenko VA (2021) Model estimates of microplastic potential contamination pattern of the eastern Gulf of Finland in 2018. *Oceanologia*. <https://doi.org/10.1016/j.oceano.2021.11.006>
- Ojala AEK, Francus P, Zolitschka B, Besonen M, Lamoureux SF (2012) Characteristics of sedimentary varve chronologies – a review. *Quat Sci Rev* 43:45–60. <https://doi.org/10.1016/j.quascirev.2012.04.006>
- Ojala AEK, Kosonen E, Weckström J, Korkonen S, Korhola A (2013) Seasonal formation of clastic-biogenic varves: the potential for palaeoenvironmental interpretations. *GFF* 135:237–247. <https://doi.org/10.1080/11035897.2013.801925>
- Pospelova V, Zonneveld KAF, Heikkilä M, Bringué M, Price AM, Esenkulova S, Matsuoka K (2018) Seasonal, annual, and inter-annual Spiniferites cyst production: a review of sediment trap studies. *Palynology* 42:162–181. <https://doi.org/10.1080/01916122.2018.1465738>
- Primpke S, Cross RK, Mintenig SM, Simon M, Vianello A, Gerdtz 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* 74:1127–1138. <https://doi.org/10.1177/0003702820917760>
- Saarnisto M (2000) Shoreline displacement and emergence of lake basins. *Geological Survey of Finland Spec Pap* 29:25–34
- Saarni S, Hartikainen S, Meronen S, Uurasjärvi E, Kalliokoski M, Koistinen A (2021) Sediment trapping – an attempt to monitor temporal variation of microplastic flux rates in aquatic systems. *Environ Pollut* 274:116568. <https://doi.org/10.1016/j.envpol.2021.116568>
- Saarni S, Saarinen T, Lensu A (2015) Organic lacustrine sediment varves as indicators of past precipitation changes: a 3,000-year climate record from Central Finland. *J Paleolimnol* 53:401–413. <https://doi.org/10.1007/s10933-015-9832-8>
- Sainio E, Lehtiniemi M, Setälä O (2021) Microplastic ingestion by small coastal fish in the northern Baltic Sea, Finland. *Mar Pollut Bull*. <https://doi.org/10.1016/j.marpolbul.2021.112814>
- Salmela J, Saarni S, Bläfield L, Katainen M, Kasvi E, Alho P (2022) Comparison of cold season sedimentation dynamics in the non-tidal estuary of the Northern Baltic Sea. *Mar Geol* 443:106701. <https://doi.org/10.1016/j.margeo.2021.106701>
- Schimmelmann A, Lange CB, Schieber J, Francus P, Ojala AEK, Zolitschka B (2016) Varves in marine sediments: a review. *Earth-Sci Rev* 159:215–246. <https://doi.org/10.1016/j.earscirev.2016.04.009>
- Scopetani C, Chelazzi D, Cincinelli A, Esterhuizen-Londt M (2019) Assessment of microplastic pollution: occurrence and characterisation in Vesijärvi lake and Pikku Vesijärvi pond. *Finland Environ Monit Assess* 191:652. <https://doi.org/10.1007/s10661-019-7843-z>
- Semcesen PO, Wells MG (2021) Biofilm growth on buoyant microplastics leads to changes in settling rates: implications for microplastic retention in the Great Lakes. *Mar Pollut Bull* 170:112573. <https://doi.org/10.1016/j.marpolbul.2021.112573>
- Stefánsson H, Peternell M, Konrad-Scholke M, Hannesdóttir H, Ásbjörnsson EJ, Sturkell E (2021) Microplastics in glaciers: first results from the Vatnajökull Ice Cap. *Sustainability* 13:4183. <https://doi.org/10.3390/su13084183>
- Talvitie J, Heinonen M, Pääkkönen J-P, Vahtera E, Mikola A, Setälä O, Vahala R (2015) Do wastewater treatment plants act as a potential point source of microplastics? Preliminary study in the coastal Gulf of Finland, Baltic Sea. *Water Sci Technol* 72:1495–1504. <https://doi.org/10.2166/wst.2015.360>
- Tiljander M, Saarnisto M, Ojala AEK, Saarinen T (2003) A 3000-year palaeoenvironmental record from annually laminated sediment of Lake Korttajärvi, central Finland. *Boreas* 32: 566–577. <https://doi.org/10.1111/j.1502-3885.2003.tb01236.x>
- Tiseo I (2021) Plastic production forecast worldwide 2025–2050. *Statista*
- Turner S, Horton AA, Rose NL, Hall C (2019) A temporal sediment record of microplastics in an urban lake, London, UK. *J Paleolimnol* 61:449–462. <https://doi.org/10.1007/s10933-019-00071-7>
- Uurasjärvi E, Hartikainen S, Setälä O, Lehtiniemi M, Koistinen A (2020) Microplastic concentrations, size distribution, and polymer types in the surface waters of a northern European lake. *Water Environ Res* 92:149–156. <https://doi.org/10.1002/wer.1229>
- Van Cauwenbergh L, Vanreusel A, Mees J, Janssen CR (2013) Microplastic pollution in deep-sea sediments. *Environ Pollut* 182:495–499. <https://doi.org/10.1016/j.envpol.2013.08.013>
- Xiong X, Zhang K, Chen X, Shi H, Luo Z, Wu C (2018) Sources and distribution of microplastics in China's largest inland lake – Qinghai Lake. *Environ Pollut* 235:899–906. <https://doi.org/10.1016/j.envpol.2017.12.081>
- Yang L, Zhang Y, Kang S, Wang Z, Wu C (2021a) Microplastics in soil: a review on methods, occurrence, sources, and potential risk. *Sci Total Environ* 780:146546. <https://doi.org/10.1016/j.scitotenv.2021.146546>
- Yang L, Zhang Y, Kang S, Wang Z, Wu C (2021b) Microplastics in freshwater sediment: a review on methods, occurrence, and sources. *Sci Total Environ* 754:141948. <https://doi.org/10.1016/j.scitotenv.2020.141948>
- Zhang B, Yang X, Liu L, Chen L, Teng J, Zhu X, Zhao J, Wang Q (2021a) Spatial and seasonal variations in biofilm formation on microplastics in coastal waters. *Sci Total Environ* 770:145303. <https://doi.org/10.1016/j.scitotenv.2021.145303>
- Zhang Y, Gao T, Kang S, Allen S, Luo X, Allen D (2021b) Microplastics in glaciers of the Tibetan Plateau: evidence for the long-range transport of microplastics. *Sci Total Environ* 758:143634. <https://doi.org/10.1016/j.scitotenv.2020.143634>
- Zobkov M, Belkina N, Kovalevski V, Zobkova M, Efreмова T, Galakhina N (2020) Microplastic abundance and accumulation behavior in Lake Onego sediments: a journey from the river mouth to pelagic waters of the large boreal lake. *J Environ Chem Eng* 8:104367. <https://doi.org/10.1016/j.jece.2020.104367>
- Zolitschka B, Francus P, Ojala AEK, Schimmelmann A (2015) Varves in lake sediments – a review. *Quat Sci Rev* 117:1–41. <https://doi.org/10.1016/j.quascirev.2015.03.019>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.