Science of the Total Environment 957 (2024) 177602

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Microplastic accumulation in one-year freshwater ice: A four-year monitoring study reveals winter dynamics of microplastics

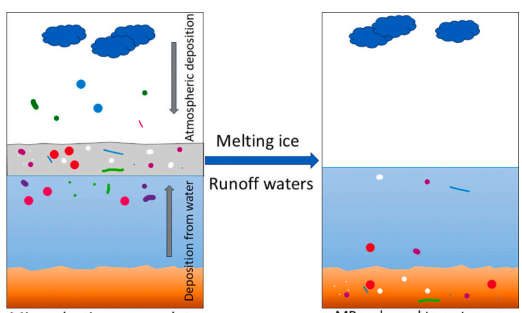
Tuomo Soininen [a,*], Emilia Uurasjärvi [a,b], Jouni Sorvari [d,e], Saija Saarni [c], Arto Koistinen [a]

[a] University of Eastern Finland, Department of Technical Physics, Yliopistonranta 8, 70210 Kuopio, Finland
[b] Finnish Safety and Chemicals Agency, Yliopistonkatu 38, 33100 Tampere, Finland
[c] Department of Geography and Geology, University of Turku, Akatemiankatu 1, 20500 Turku, Finland
[d] Natural Resources Institute Finland, Latokartanonkaari 9, 00790 Helsinki, Finland
[e] Department of Environmental and Biological Sciences, University of Eastern Finland, Finland

HIGHLIGHTS

- Microplastics accumulate to one-year freshwater ice.
- Microplastics accumulate to sediments quickly after spring floods.
- Monitoring of microplastics in sediment and ice provides information on microplastic fluxes at yearly and seasonal levels.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Damià Barceló

Keywords:
Plastic pollution
FTIR-imaging
Sedimentation
Microplastic flux

ABSTRACT

Microplastic research has reached a point where microplastics (MPs) have been found in virtually every environment studied. However, MP studies of freshwater ice are scarce, and the winter dynamics of MPs are less understood. Measuring MPs from one-year freshwater ice samples can aid understanding seasonal MP fluxes in freshwater systems. In this study we explored the same four sites close to urban/suburban areas over four subsequent years. We collected a total of 48 ice samples across all the years and sites with an average sample volume of 2.9 to 5.0 L of liquid water. In addition, we sampled an annually laminated section of bottom sediments representing these four years in seasonal resolution. MP concentrations varied considerably between years and samples, being 1–44 MPs/L in all the ice samples. The MPs found in ice were small with a mean (± average) size of 142 ± 177 μm. In total, 9 different polymer types were identified: the most common types being polypropylene, polyethylene and polyethylene terephthalate. We found that MPs accumulate to one-year freshwater ice, because the MP concentrations found from ice are one to two orders of magnitude higher than concentrations from surfaces waters in the same area. This further confirms that ice acts as a temporal repository for MPs in the aquatic freshwater systems. Our study also indicates that the properties of MPs were relatively similar in all sites around the city. The accumulation of MPs in sediments was highest during the spring flood periods, when MPs

* Corresponding author.
E-mail address: tuomo.soininen@uef.fi (T. Soininen).

https://doi.org/10.1016/j.scitotenv.2024.177602
Received 20 June 2024; Received in revised form 1 November 2024; Accepted 15 November 2024
Available online 25 November 2024

were released from the ice and snow at the catchment area of the sediment samples. We highlight the importance of monitoring to collect representative MP data from various environmental compartments.

1. Introduction

Microplastics (MPs) are defined as 1–5000 μm synthetic polymer particles, insoluble in water at 20 °C (GESAMP, 2016; Hartmann et al., 2019). MPs have been studied extensively during the past few years, and they exist in every environment studied. Yet, freshwater systems, especially freshwater ice, are under reported, even though these systems at boreal and arctic climate zones are covered in ice for several months a year. While winter conditions largely control the transport and availability of both natural materials (Ojala et al., 2013; Saarni et al., 2017) and pollutants into the lake systems (Saarni et al., 2023; Zhao et al., 2014), the conditions between winters greatly vary in boreal regions. While climate change is expected to cause large changes especially in winter conditions (Calvin et al., 2023), it is critical to describe MP dynamics during altering winter conditions at the boreal to arctic regions described by seasonal snow accumulation and ice formation. Data on MP accumulation in lake ice covers and on the origin of this accumulation (i.e., deposition from air or water) is lacking. This knowledge gap in the winter dynamics of microplastics needs assessing to better understand the possible ecological and environmental effects. In this study we give temporal information on the accumulation of plastics into different matrices; thus, providing knowledge on timing and what kind of microplastic fluxes different ecological niches will encounter. For example, a sudden burst of microplastics released from ice at the start of the growing season might have effects on the aquatic biota.

MP studies of freshwater ice are scarce, as current studies only include Lakes Baikal and Vesijärvi (Karnaukhov et al., 2022; Scopetani et al., 2019). Also, MPs from the ice of rivers Songhua and Majiagou in China have been studied (Chen et al., 2024). More marine ice studies exist, including on Japan (Chubarenko et al., 2022), Gulf of Bothnia (Geilfus et al., 2019), and the Arctic sea (Peeken et al., 2018). To our knowledge, no published multiyear MP studies for marine or freshwater ice exist. Furthermore, this is the first study combining MP ice monitoring data with the winter conditions related to simultaneous MP accumulation in sediments within seasonal resolution. Regardless of the environment, it is known that MP concentrations are several magnitudes higher in ice compared to water. Moreover, MP abundance in snow has been reported to be magnitudes higher compared to ice (Scopetani et al., 2019).

Atmospheric deposition of MPs is an important route of MP accumulation in the environment, as MPs can travel up to tens of kilometers by air (Allen et al., 2019; Goßmann et al., 2023). Thus, we suspect that atmospheric deposition is also a key factor when studying MP concentration in lake ice. Investigating the significance of atmospheric fall out of microplastics is very critical to assess the total microplastic budgets of lake systems, in future. In addition, melting of snow cover influences the MP amounts accumulating in sediment. We conduct this study to further explore whether MPs accumulate to the ice layer of the studied lake and what are the properties of given particles. Moreover, we examine possible patterns and differences between sampling years and sites. On one of the sites, we also explore whether MPs concentrate to sediments after the winter season and compare the MP signatures between these two compartments.

We aim to give further insight on the transport and distribution mechanisms of plastics in the studied lake, by comparing ice and sediment data to previously collected data from the surface waters and fish of the same lake and sampling sites (Uurasjärvi et al., 2020, 2021).

2. Materials and methods

2.1. Area of study

Lake Kallavesi is a northern freshwater lake near Kuopio city (population ca. 120,000). Lake Kallavesi has an area of 48,000 ha and a mean depth of 9.65 m; the deepest point is 75 m (Järvi-Meri Wiki, 2022). This lake is covered in ice for several months annually; 138 days is the mean number of frozen days per winter season in the 21st century. The period this lake is covered in ice yearly has been constantly decreasing. The mean of frozen days in the 19th century was 177; in the 20th century, it was 162.

During 2020–2023, each spring, we collected ice samples from four different sites around Kuopio city (Fig. 1, Table 1). The sites chosen for this study are Harbor, Shallow bay, Snow dump site, and Open lake. Harbor has a runoff stream that discharges close to the sampling location. Shallow bay is a site located near the University and University hospital. Snow dump site sampling location is located next to the city's snow dump, where up to 300,000 cubic meters of snow is dumped each winter season. Open lake site is located further away from densely populated areas, approximately 500 m of the shore.

2.2. Ice sampling

Utilizing a battery-powered chainsaw, a manual ice saw, and battery-powered auger, we extracted the pieces. Using two sets of log grabbers among other steel tools, we lifted the floating pieces of ice from the water. On top of the ice cover, we used the chainsaw to remove the cloudy top layer of ice. This was done to make the samples more comparable to each other. We cut the remaining pieces into three equally sized pieces, which we further sawed down to fit into three different stainless-steel containers (Fig. S1). In 2023, we modified the sampling slightly and fit as much ice as possible into one 20-L steel container on each site (Fig. S2). From these 20-L containers, we conducted subsampling in the laboratory by dividing each sample volume into three roughly equal sized subsamples. We could thus streamline the sampling process and minimize contamination during sampling and sample pretreatment.

2.3. Sediment sampling

An HTH-type gravity corer (core tube diameter 5.2 cm) was used to collect a sediment sample with an intact water sediment interface at the deepest part of 10 m of the Maljalahti basin (Harbor). The PVC core tube with diameter of 3.8 cm was used to collect a sediment core from inside the HTH-core tube to allow core splitting and investigation of detailed sediment structure. The PVC core tube was cut in two halves using a circular saw. The annually laminated structures of the sediments (varves) were photographed (Fig. 2) and thickness of each individual lamina was measured from the photograph using Image J image analysis software. The measurements were repeated three times, and the calculated mean thickness of each lamina is used to report seasonal linear sedimentation rate (LSR). The minerogenic layer represents spring and is formed rapidly due to erosion at the catchment caused by spring floods as a result of melting of snow (Ojala et al., 2013; Johansson et al., 2019; Fig. 2). The accumulation of biogenic matter occurs during the growing season resulting in a black lamina (Fig. 2). A marker horizon, the 2 cm thick clayey layer, caused by the dredging at the harbor area during winter 2019, was used to verify the sediment chronology in addition to varve counting.

The subsampling in seasonal resolution was carried out using scalpel along the boundaries between seasonal laminations. Spring flood layers were separated from growing season layers and collected in the pre-washed and muffled crucibles instantly covered by foil. The seasonal samples were freeze dried and weighed.

2.4. Pre-treatment

The ice samples were left to thaw in a 50 °C oven for 24 h, after which they were filtrated on stainless-steel filters (mesh size 20 μm). The sample volumes were measured from the filtrated volumes of water, and these volumes were used when calculating the results. After filtration the filters were treated with 50 mL of H_2O_2 (>30 % v/v) for 24 h to break down possible organic matter in the samples. In addition, density separation was used to separate inorganic matter from the 2020–2022 samples. The density separation was done with sodium polytungstate solution (density 1.8 g cm^{-3}) in separation funnels lasting 24 h. After these treatments the samples were filtered on silver membrane filters (Sterlitech Silver Membrane, mesh size 5.0 μm). Density separation was not used for the 2023 samples as it was deemed unnecessary.

The freeze-dried sediment samples were pretreated following the heavy liquid protocol described by Saarni et al. (2021) to separate MPs from sediment matrix. In short, three repeated treatments including heavy liquid (density 2.0 g cm^{-3}), centrifugation (3000 rpm for 12 min) and filtering (aluminum filters with 20 μm mesh size) were performed. Thereafter, the samples were treated with the enzymatic treatment described by Löder et al. (2017) and with fenton reaction as described by Dimante-Deimantovica et al. (2022). Methodological blank samples were treated parallel to the sediment samples through every step. The treated samples were stored in pre-filtered 70 % ETAX solution for transport.

After all the pre-treatment steps the sediment samples still contained a lot of chitin and black, most likely carbon, particles. Filtration trough stainless-steel filter (pore size 50 μm) was deemed necessary to get presentable samples. After this filtration the final filtration on silver membrane filters was performed.

2.5. Contamination precautions and quality control

In the laboratory, only stainless-steel or glassware was used. Every instrument and filter, except the silver filters, were rinsed twice with ultrapure water before use. All the treatment steps were done in a fume hood when possible. In 2023 with the larger 20-L containers the sub-samples had to be poured to large beakers outside the fume hood. Before sampling all the sample containers were washed with soap and tap water and rinsed carefully with tap water. No chain oil was ever used in the chainsaw, nor was it ever used in any other application.

Blank samples were prepared in the lab similarly to ice samples. Three 3-L containers were first thoroughly washed with tap water and soap and rinsed with ultrapure water. 100 mL of ultrapure water was then used as the blank sample and treated the same way as the 2020–2022 samples. From three blank samples we detected in total of 6 PP, 3 PE, and 2 PMMA particles. From which the limit of detection (LoD) was calculated as:

$$LoD = Mean + SD*3 = 3.7 + 2.4*3 = 10.9$$

Three recovery samples were prepared using polystyrene beads

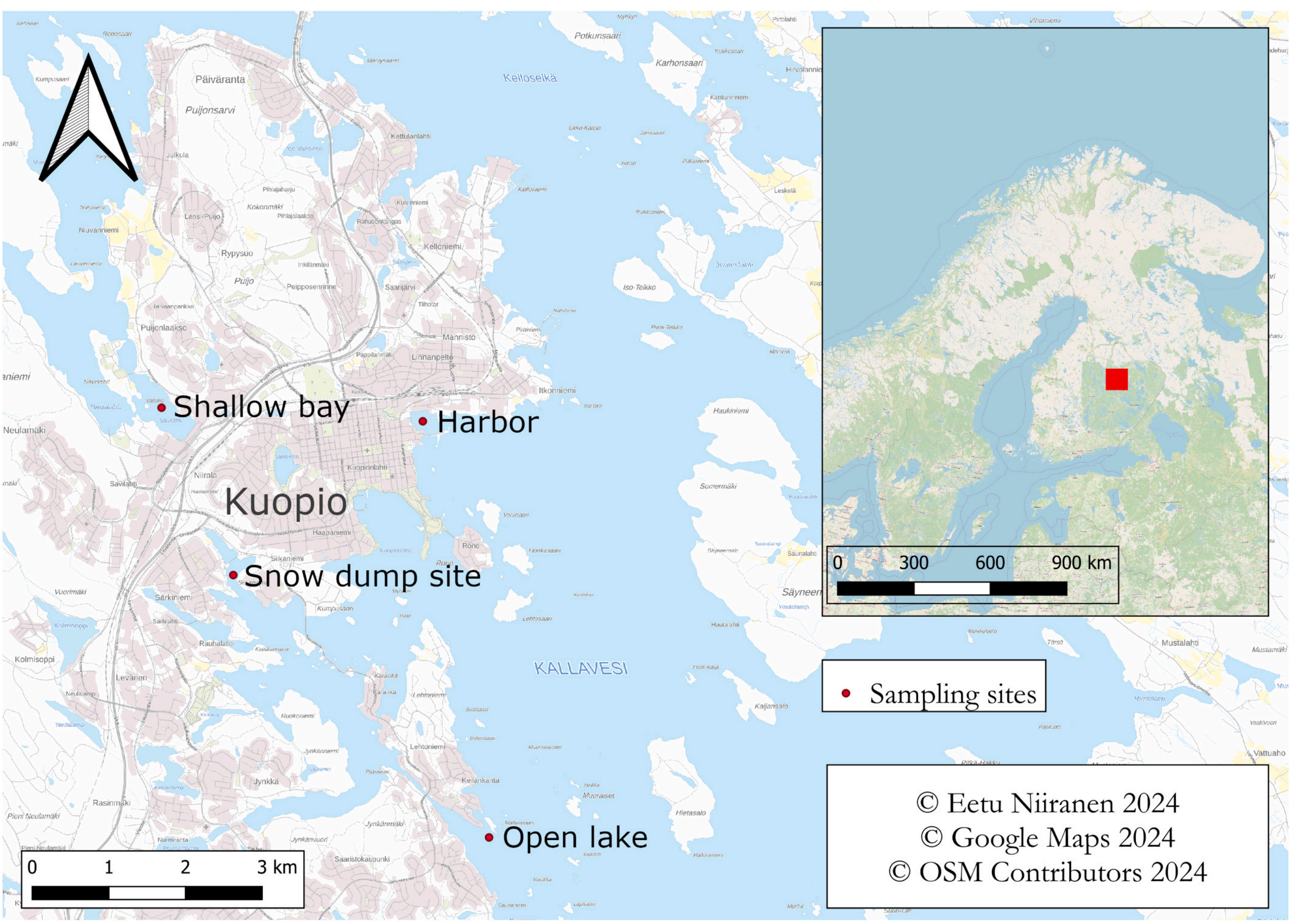


Fig. 1. Locations of all four sampling sites around Kuopio city.

(NIST Traceable Size Standards, 100 μm) by counting 40 to 55 beads to a petri dish. The beads were in 20 pcs/mL solution, hence approximately 2 mL of solution was pipetted per sample. After counting, the beads were filtrated on 20 μm mesh size stainless-steel filters and treated the same way as ice samples (H_2O_2 and density separation steps). The mean recovery rate was 23.6 ± 1.3 %. The reasons why the recovery rate was so low are lacking. Nevertheless, these samples represent only one size, shape, and polymer type of a particle and cannot be extrapolated to real MP particles found in the environment.

The sediment samples were subjected to contamination caused by PVC core tube, and hence all PVC particles were removed from the sediment data. However, this does not compromise our data set, because limited number of PVC materials in general are found and described from sediment records.

2.6. FTIR and data analysis

Fourier-transform infrared (FTIR) spectral maps were measured with an Agilent Cary 670/620 imaging FTIR spectrometer equipped with 128 × 128 focal plane array (FPA) detector. The whole filter area of 12 mm in radius was measured in reflection mode using 15× cassegrain objective, 8 cm^{-1} spectral resolution, 4 scans, 3800–800 cm^{-1} spectral range, and 5.5 μm pixel resolution. For analyzing spectra data siMPle software (Primpke et al., 2020) was used. The reference spectra used was compiled of siMPle provided and in-house spectra (Uurasjärvi et al., 2021). Reference spectra included the following plastic polymers: acrylonitrile butadiene styrene (ABS), polyamide (PA), polyacrylonitrile (PAN), polyethylene (PE), polymethyl methacrylate (PMMA), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), polyvinyl chloride (PVC) and polyurethane (PU). In addition to plastic polymers, also organic polymers such as proteins and wool were included in the reference material. In total 43 different spectra were used, from which 30 were from synthetic polymers and 13 from natural polymers. Different threshold values were assigned for the classification of different polymer types in siMPle similarly to Soininen et al. (2024). For most polymers, a threshold of 0.6 was used, were as for PS it was 0.55 and for PE 0.7.

3. Results

3.1. Ice sample results

Mean MP concentrations were 3–25 MPs/L of water (Fig. 3). Mean concentration across all 48 samples was 14 ± 8 MPs/L. Highest annual mean concentrations were observed in 2020 (21 MPs/L) and lowest in 2021 (9 MPs/L) (Fig. 4). Mean concentration on each site across all years was 11–15 MPs/L (Fig. 4). On Open lake site the mean concentration across all years was the lowest (11 MPs/L). On the other three sites, the mean annual concentrations were similar.

The size of the particles did not differ from year to year (Fig. 5), with the median size for each year being around 100 μm. Main polymer types were also the same for each year, with PP, PE and PET being the most common types (Fig. 6). There were also small portions of other polymer types in each sample set. In this study we did not categorize the particles into different colors or morphological groups, as the analysis method used is not suitable for detecting fibers reliably (Uurasjärvi et al., 2021).

Correlation coefficients were calculated for 8 different variables (Fig. 7). These correlations were calculated between all 48 samples. Most notable correlations detected were strong positive correlation between sample thickness and temperature (0.81). Moreover, moderate negative correlation between ice thickness and MP concentration (−0.47) and Snow depth and MP concentration (−0.4) were detected. Also, moderate positive correlation was found between sample thickness and MP concentration (0.49) and between mean temperature and MP concentration (0.56). Correlation coefficient of 0.97 between ice thickness and snow depth is caused by snow melting on top of ice and forming new cloudy ice.

3.2. Sediment results

Sediment samples showed clear difference between winter and summer layers, with generally considerably larger MP concentrations occurring in winter laminae (Table 2). However, the overall lowest MP concentration was detected in winter 2020 lamina. The MP concentrations were more consistent within summer season samples.

Linear sedimentation rate (LSR) i.e. the thickness of accumulated seasonal laminae, varies from 2.4 to 8.1 mm per season, showing systematically higher sediment influx related to spring floods (Table 2). The minerogenic laminae (Fig. 2) is formed rapidly following the spring floods caused by snow melt, while biogenic laminae represent the accumulation during the summer.

4. Discussion

This study shows that MPs accumulate into the ice layer of a freshwater lake, but the sites around a densely populated area do not differ significantly from each other. Having data from four consecutive years, we see many of the variables averaging out. Most notably, mean particle sizes between years and sites are alike. Furthermore, the mean particle concentrations on the sampling sites started to average out with more

Table 1
Sampling information and conditions with official snow depth and ice thickness values from closest measuring points on the time of sampling.

Year	Snow depth (cm)	Ice thickness (cm)	Sampling site	Coordinates ETRS-TM35FIN N	E	Sample thickness (cm)	Sample volume (L)
2020	4	33	Harbor	6,973,019	534,759	32	5.0 ± 0.4
			Shallow bay	6,974,225	532,093	40	3.6 ± 0.3
			Snow dump site	6,972,023	533,010	40	4.3 ± 0.1
			Open lake	6,968,464	536,414	30	4.4 ± 0.1
2021	32	51	Harbor	6,973,019	534,759	17	4.6 ± 0.4
			Shallow bay	6,974,225	532,093	16	4.2 ± 0.4
			Snow dump site	6,972,023	533,010	11	4.3 ± 2.7
			Open lake	6,968,464	536,414	17	4.1 ± 0.3
2022	53	60	Harbor	6,973,019	534,759	20	4.0 ± 0.3
			Shallow bay	6,974,225	532,093	15	4.5 ± 0.5
			Snow dump site	6,972,023	533,010	14	3.4 ± 0.3
			Open lake	6,968,464	536,414	32	3.4 ± 0.6
2023	46	52	Harbor	6,973,019	534,759	31	3.2 ± 0.4
			Shallow bay	6,974,225	532,093	24	3.0 ± 0.6
			Snow dump site	6,972,023	533,010	23	2.9 ± 0.7
			Open lake	6,968,464	536,414	32	2.9 ± 0.4

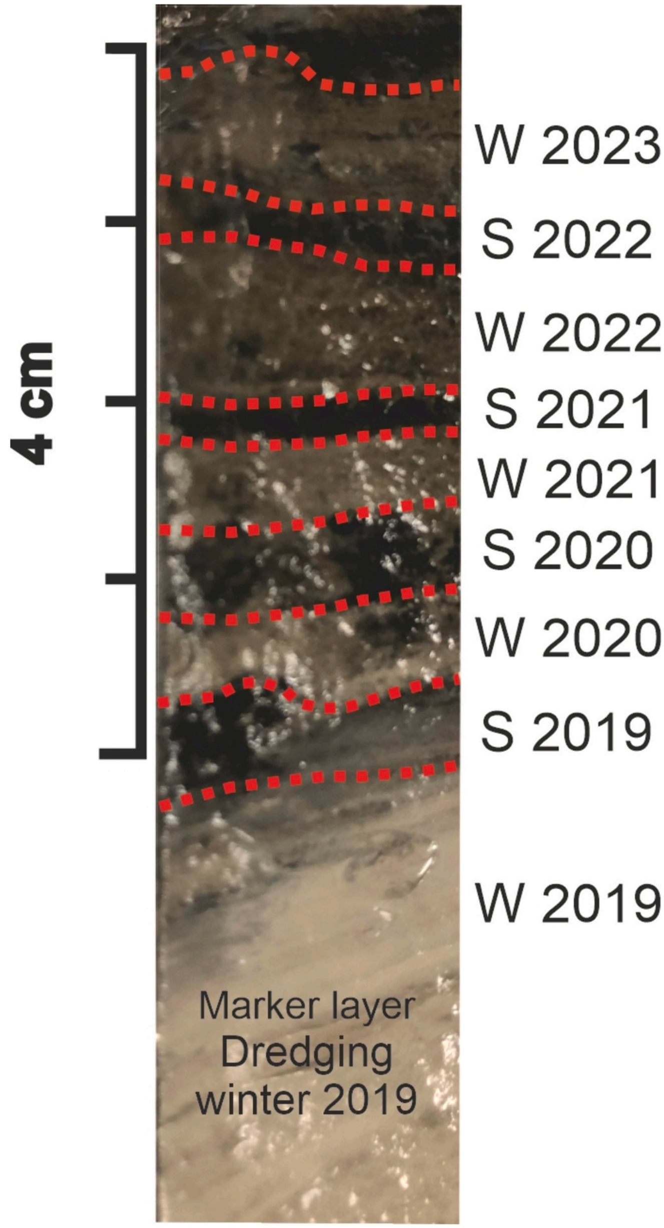


Fig. 2. Sediment varve structure with each seasonal lamina indicated (W, spring flood lamina, S open water season lamina). The 2-cm thick clayey marker layer resulted from the dredging at the harbor area during winter 2019 is used to support the varve chronology.

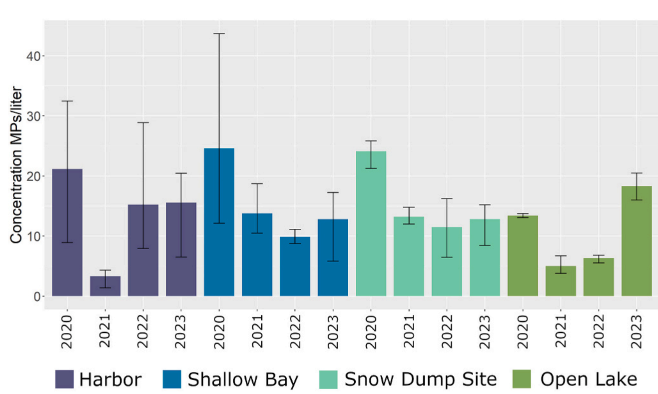


Fig. 3. Mean particle concentrations per sample.

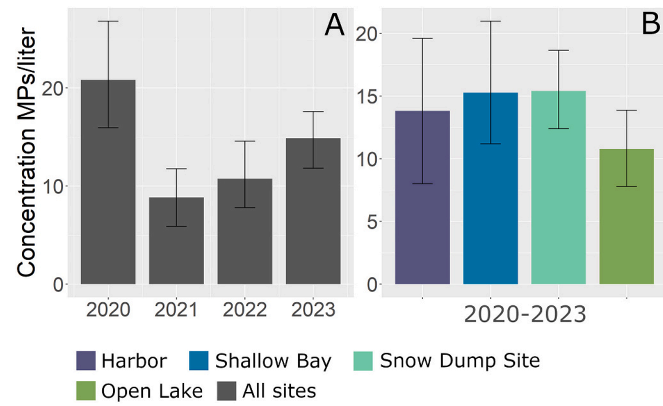


Fig. 4. Mean particle concentrations for each year (A) and site (B).

data points.

Concentrations found from ice far exceed those measured from water on the same locations. Uurasjärvi et al. (2020) found highest MP concentrations in water to be 0.25 MPs/L, which is one to two orders of magnitude lower than the concentrations found in this study from ice. This is intuitive as two of the most common polymer types detected (PE and PP) have lower density than water. In theory, these particles float on top of the water column and are frozen into the ice layer. However, this does not explain the high concentrations of PET in the ice samples. This could be studied further if it was feasible to sample the whole ice layer in different vertical sections to see if the concentrations of different polymers vary from layer to layer. In this study however, the sampling circumstances and composition of the ice layer made this unfeasible with the methods used (Fig. S3). Geilfus et al. (2019) and Karnaukhov et al. (2022) found in their studies from sea ice and lake ice respectively, that MPs are distributed quite homogenously within the ice layer. Geilfus et al. (2019) discuss that homogenous distribution might be a result of relatively slow freezing process, where MPs have time to be distributed evenly in the water column. Hence, the fact that we only sampled bottom part of the ice layer, might not be pivotal.

The particles found in fish from the same area (Uurasjärvi et al., 2021) were smaller compared to ice; 66 ± 63 μm in vendace and 81 ± 69 μm in perch compared to 142 ± 177 in ice. However, the polymer types were similar: PP, PE and PET being the most common also in fish. This implies that fish ingest smaller particles but probably from the same sources.

The sediments of Maljalahti basin are annually laminated, or so called varved sediments (Kwiecien et al., 2022; Zolitschka et al., 2015). The composition of varves is dictated by the annual cycle of seasonal conditions. In boreal context, such structures are previously well described and understood (Ojala et al., 2013; Saarni et al., 2017; Salminen et al., 2023). It is previously shown that accumulation underneath the ice is very limited (Johansson et al., 2019) and hence the minerogenic lamina and the microplastic incorporated within it, are accumulated rapidly during spring floods. The light materials, such as PP and PE were also most frequently detected in the sediment samples. While generally biofouling is suggested as a factor causing negative buoyancy of light particles, the fact that these materials are also dominating the spring flood layer, at time of likely reduced biofouling, suggest, that these particles can become accumulated rapidly, likely through heteroaggregation.

In sediment record the MP concentrations are likely controlled by the intensity of the spring floods. The winter samples 2022 and 2023 with the highest snow accumulation (Table 1) coincide with highest MP concentrations (Table 2). This highlights the importance of catchment erosion and, especially in boreal urban locations, the transport of MPs through storm waters. It also suggests, that much of the MPs transported by the flood waters become rapidly accumulated and incorporated in the

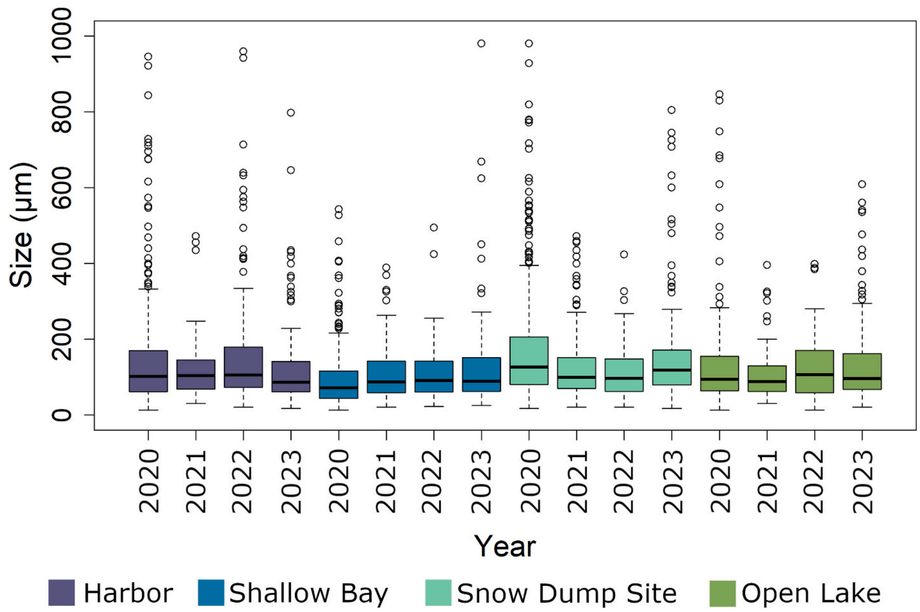


Fig. 5. Particle sizes from each year and site. In total 2597 particles were detected, from which 13 were longer than 1000 μm (longest dimension).

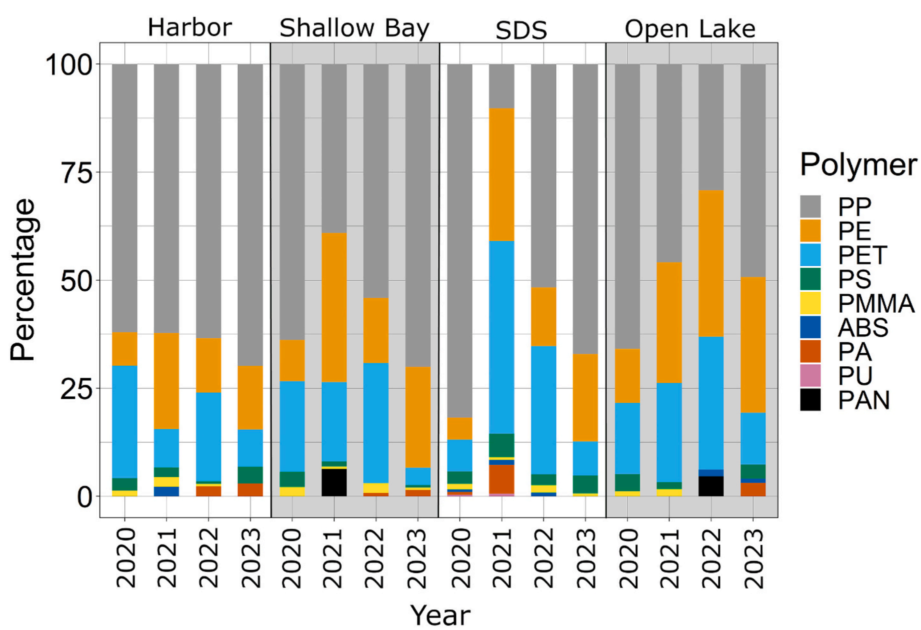


Fig. 6. Portions of polymer types per site and year. SDS = Snow Dump Site.

flood layers of the sediment record. The MP concentration during the open water season shows much less variability. However, highest concentrations of MPs coincide with the highest detected precipitation (May–October, 459 mm; FMI), hence increased surface run off and storm water input could explain the observation.

In ice, mean MP concentrations between sites was slightly lower on Open lake site than on the other three sites. Similar observation has previously reported from the sediment traps (Saarni et al., 2023) and surface water samples (Uurasjärvi et al., 2020) from the same lake system, suggesting that much of the MPs released from the urban area seem to be accumulated relatively close to their source. However, it is noteworthy, that based on the available data, it is not possible to evaluate the proportion of the near shore accumulating share of MPs.

The concentrations in ice were substantially higher in 2020 than any other year. This contradicts with the sediment record, showing lowest MP concentration on winter 2020. The reasons behind this are still lacking. One major factor seems to be the snow cover on top of the ice. Snow could shield the ice layer from atmospheric MP deposition, and thus we observe less particles during snowy winters in ice (Fig. 7). The MPs from snow are quickly released into meltwaters in spring. However, one contributing factor is also the portion of ice we sampled each year. Every year we sampled only the clear ice layer, which is the undermost part of the ice. During spring 2020 however, there was basically only the clear ice layer present. Consequently, we sampled almost the whole thickness of the ice. Other years (2021, 2022 and 2023) there were many soft ice layers with water and slush layers in between them, on top of the clear layer. Most important variable appears to be the mean winter temperature, as during warm winters the MP concentrations are higher. The amount of in-flowing water in the catchment is higher during warm winters. Sediment pulses are detected underneath the ice related to

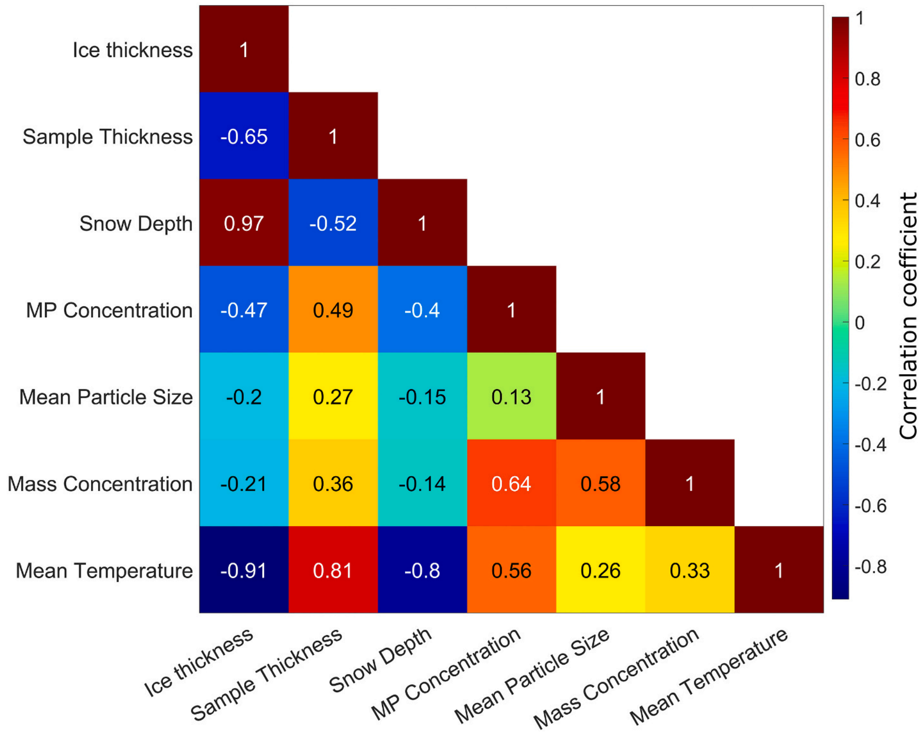


Fig. 7. Correlation coefficient for different environmental and ice sample variables. Ice thickness and snow depth are official values from the closest measuring points. Mean temperature is measured as the mean temperature of the winter season.

Table 2
Seasonal sediment samples (W winter season, S summer season), the linear sedimentation rate (LSR), total number of microplastics in each sediment layer, and microplastic concentration in each seasonal layer.

Sample	LSR (mm)	MP total	MP conc n g^{-1}
W20	4.60	592	89
S20	5.17	619	124
W21	4.19	1200	182
S21	2.68	1324	298
W22	7.73	2160	371
S22	2.40	1327	296
W23	8.06	3560	526

small thawing episodes during winter (Johansson et al., 2019). It is possible the thaw waters resulting periods of warm temperatures in winter, transport MPs from the city area into the lake, and become trapped in the ice when the temperatures turn back to freezing.

The correlation coefficient of −0.47 between ice thickness and MPs concentration (Fig. 7) indicates that the bottom layer of ice might in fact contain a lower concentration of MPs, which contradicts the findings made by Karnaukhov et al. (2022). However, all the samples were collected relatively late into the winter season (March to April), and the snow on top of the ice had already formed new cloudy ice. Hereby, the ice layer is substantially thicker, but the concentration of plastics on the bottom of the ice stays the same. This would also back up the theory that snow on top of the ice catches most of the atmospheric deposition of MPs. Moreover, the warmer the winter, the thicker the sampled clear ice layer is, and the higher the concentration of MPs found (correlation coefficients 0.56 and 0.49, respectively). The size of MPs did not seem to correlate with the other parameters in this experiment.

This study shows that one-year freshwater ice is a temporal deposit for MPs. Similar conclusions have been derived from studies of sea ice (Caruso et al., 2023; Kim et al., 2021; Obbard et al., 2014). However, comparing these results to other studies is not straightforward because studies focusing on freshwater ice layers and MPs are scarce. Ice studied in marine environments show similar results with concentrations of 8 to 41 MPs/L (Geilfus et al., 2019). There are, to our knowledge, only two studies considering ice of freshwater lakes. Studies include ice at Lake Baikal (Karnaukhov et al., 2022) and Lake Vesijärvi (Scopetani et al., 2019). Karnaukhov et al. (2022) found the MP fiber concentrations to be on average 55.5 MPs/L in the upper ice layer and 65 MPs/L in the lower layer. Scopetani et al. (2019) reported concentrations of 7.8 ± 1.2 MPs/L of ice and 117.1 ± 18.4 MPs/L of snow. Order of magnitude higher concentrations found in snow suggest that atmospheric deposition is indeed an important source for MPs in ice. This is further backed up by the −0.4-correlation coefficient between snow depth and MP concentration in our present study.

As global warming increases the winter temperatures in the arctic and sub-arctic regions, also the time that MPs are trapped in ice is decreasing; hence, the MP fluxes are undergoing a substantial change in these forementioned regions. With the knowledge gained from this work we can give suggestions for the next steps of MP monitoring in sub-arctic (urban) aquatic environments. Ice samples should be taken at different times during the winter alongside with snow samples. This way one could explore if atmospheric deposition or accumulation from water is the main route of MP accumulation to ice. Sampling should also include sample division into different layers of ice when possible. Sediment trapping could be a viable addition for monitoring the MP accumulation at the studied sites to determine the sedimentation rate of MPs on a longer timeframe. Moreover, the probable MP sources, for example runoff water streams, should be monitored to assess the origin of MPs.

5. Conclusions

One-year freshwater ice is a temporal deposit for microplastics. Microplastic concentrations in ice are one to two orders of magnitude higher than in lake water. Furthermore, microplastics seem to concentrate in sediment imminently after the ice melts; highest microplastic concentrations in sediments are found in layers before growing season. Analysis of MPs in the ice cover completes the overview of MP burden in the environment when connected with data from other sample matrices. Even though weather conditions and annual MP concentrations in ice vary significantly, it seems that the concentrations remain quite stable as their moving average is studied. Thus, the moving average of the monitoring data would provide a tool to analyze trends in MP concentration. The present study combines results from different environmental compartments and sheds light on the winter dynamics of microplastics in an urban freshwater environment.

CRediT authorship contribution statement

Tuomo Soininen: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Emilia Uurasjärvi:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Jouni Sorvari:** Validation, Supervision, Resources, Methodology, Investigation, Conceptualization. **Saija Saarni:** Writing – original draft, Validation, Resources, Methodology, Investigation. **Arto Koistinen:** Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Funding

The sediment research in this article was funded by AXA (2021-AXA-THEME 1-066).

Declaration of competing interest

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

Acknowledgements

We would like to thank Eetu Niiranen from Snowchange cooperative for support on graphical aspects of the paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.177602.

Data availability

Data will be made available on request.

References

Allen, S., Allen, D., Phoenix, V.R., Galop, D., 2019. Microplastics in a remote mountain catchment. Nat. Geosci. 12 (May). https://doi.org/10.1038/s41561-019-0335-5.

Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P.W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W.W.L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., et al., 2023. In: Core Writing Team, Lee, H., Romero, J. (Eds.), IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, pp. 35–115. https://doi.org/10.59327/IPCC/AR6-9789291691647 (IPCC, 13(3)).

Caruso, G., Iannilli, V., Vitale, G., Vardè, M., Oliverio, M., Bogialli, S., Litti, L., Setini, A., Rosso, B., Corami, F., 2023. Small microplastics: a yet unknown threat in the Svalbard (Norway) region. Journal of Marine Science and Engineering 11 (12), 1–10. https://doi.org/10.3390/jmse11122330.

Chen, L., Liao, Y., Zeng, K., Wu, Y., Li, Y., Wang, H., 2024. Microplastic occurrence characteristics and ecological risk assessment of Urban River in cold regions during ice-covered periods. Sustainability (Switzerland) 16 (7). https://doi.org/10.3390/su16072731.

Chubarenko, I., Lazaryuk, A., Orlova, T., Lobchuk, O., Raguso, C., Zyubin, A., Lasagni, M., Saliu, F., 2022. Microplastics in the first-year sea ice of the Novik Bay, Sea of Japan. Mar. Pollut. Bull. 185 (October). https://doi.org/10.1016/j.marpolbul.2022.114236.

Dimante-Deimantovica, I., Suhareva, N., Barone, M., Putna-Nimane, I., Aigars, J., 2022. Hide-and-seek: threshold values and contribution towards better understanding of recovery rate in microplastic research. MethodsX 9, 101603. https://doi.org/10.1016/j.mex.2021.101603.

Geilfus, N.X., Munson, K.M., 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.

GESAMP, 2016. Sources, fate and effects of microplastics in the marine environment: part two of a global assessment. Rep.Stud. GESAMP No. 93, 220.

Goßmann, I., Herzke, D., Held, A., Schulz, J., Nikiforov, V., Georgi, C., Evangeliou, N., Eckhardt, S., Gerdts, G., Wurl, O., Scholz-Böttcher, B.M., 2023. Occurrence and backtracking of microplastic mass loads including tire wear particles in northern Atlantic air. Nat. Commun. 14 (1). https://doi.org/10.1038/s41467-023-39340-5.

Hartmann, N.B., Hüffer, T., Thompson, R.C., Hassellöv, M., Verschoor, A., Daugaard, A. E., Rist, S., Karlsson, T., Brennholt, N., Cole, M., Herrling, M.P., Hess, M.C., Ivleva, N. P., Lusher, A.L., Wagner, M., 2019. Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. Environ. Sci. Tech. 53 (3), 1039–1047. https://doi.org/10.1021/acs.est.8b05297.

Järvi-Meri wiki. Kallavesi (yhd.) [WWW document]. (2022). https://www.jarviwiki.fi/wiki/Kallavesi_(yhd.) (Accessed: 19.6.2024).

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 (2). https://doi.org/10.3390/quat2020018.

Karnaukhov, D., Biritskaya, S., Dolinskaya, E., Teplykh, M., Ermolaeva, Y., Pushnica, V., Bukhaeva, L., Kuznetsova, I., Okholina, A., Silow, E., 2022. Distribution features of microplastic particles in the Bolshiye Koty Bay (Lake Baikal, Russia) in winter. Pollution 8 (2), 435–446. https://doi.org/10.22059/POLL.2021.328762.1159.

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 (April), 125971. https://doi.org/10.1016/j.jhazmat.2021.125971.

Kwiecien, O., Braun, T., Brunello, C.F., Faulkner, P., Hausmann, N., Helle, G., Hoggarth, J.A., Ionita, M., Jazwa, C.S., Kelmelis, S., Marwan, N., Nava-Fernandez, C., Nehme, C., Opel, T., Oster, J.L., Perşoiu, A., Petrie, C., Prufer, K., Saarni, S.M., Breitenbach, S.F.M., 2022. What we talk about when we talk about seasonality – a transdisciplinary review. Earth Sci. Rev. 225 (October 2021). https://doi.org/10.1016/j.earscirev.2021.103843.

Löder, M.G.J., Imhof, H.K., Ladehoff, M., Löschel, L.A., Lorenz, C., Mintenig, S., Piehl, S., Primpke, S., Schrank, I., Laforsch, C., Gerdts, G., 2017. Enzymatic purification of microplastics in environmental samples. Environ. Sci. Tech. 51 (24), 14283–14292. https://doi.org/10.1021/acs.est.7b03055.

Obbard, R.W., Sadri, S., Wong, Y.Q., Khitun, A.A., Baker, I., Thompson, R.C., 2014. Global warming releases microplastic legacy frozen in Arctic Sea ice. Earth's Future 2 (6), 315–320. https://doi.org/10.1002/2014ef000240.

Ojala, A.E.K., Kosonen, E., Weckström, J., Korkonen, S., Korhola, A., 2013. Seasonal formation of clastic-biogenic varves: the potential for palaeoenvironmental interpretations. Gff 135 (3–4), 237–247. https://doi.org/10.1080/11035897.2013.801925.

Peeken, I., Primpke, S., Beyer, B., Gütermann, J., Katlein, C., Krumpen, T., Bergmann, M., Hehemann, L., Gerdts, G., 2018. Arctic sea ice is an important temporal sink and means of transport for microplastic. Nat. Commun. 9 (1). https://doi.org/10.1038/s41467-018-03825-5.

Primpke, S., Cross, R.K., Mintenig, S.M., Simon, M., Vianello, A., Gerdts, G., Vollertsen, J., 2020. Toward the systematic identification of microplastics in the environment: evaluation of a new independent software tool (siMPle) for spectroscopic analysis. Appl. Spectrosc. 74 (9). https://doi.org/10.1177/0003702820917760.

Saarni, S., Soininen, T., Uurasjärvi, E., Hartikainen, S., Meronen, S., Saarinen, T., Koistinen, A., 2023. Seasonal variation observed in microplastic deposition rates in boreal lake sediments. J. Soil. Sediment. 23 (4), 1960–1970. https://doi.org/10.1007/s11368-023-03465-3.

Saarni, Saija, Lensu, A., Tammelin, M., Haltia, E., Saarinen, T., 2017. Winter climate signal in boreal clastic-biogenic varves: a comprehensive analysis of three varved records from 1890 to 1990 AD with meteorological and hydrological data from Eastern Finland. Gff 139 (4), 314–326. https://doi.org/10.1080/11035897.2017.1389984.

Saarni, Saija, 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. https://doi.org/10.1016/j.envpol.2021.116568.

Salminen, S., Saarni, S., Saarinen, T., 2023. Sensitivity of varve biogenic component to climate in eastern and central Finland. J. Paleolimnol. 70 (2), 113–130. https://doi.org/10.1007/s10933-023-00287-8.

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 (11). https://doi.org/10.1007/s10661-019-7843-z.

Soininen, T., Uurasjärvi, E., Hämäläinen, L., Huusari, N., Feodoroff, J., Moshnikoff, J., Niiranen, E., Feodoroff, P., Mustonen, T., Koistinen, A., 2024. Microplastics in Arctic waters of the Finnish Sámi area. Sci. Total Environ. 940. https://doi.org/10.1016/j.scitotenv.2024.173666.

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 (1), 149–156. https://doi.org/10.1002/wer.1229.

Uurasjärvi, E., Sainio, E., Setälä, O., Lehtiniemi, M., Koistinen, A., 2021. Validation of an imaging FTIR spectroscopic method for analyzing microplastics ingestion by Finnish lake fish (Perca fluviatilis and Coregonus albula). Environ. Pollut. 288 (November 2020). https://doi.org/10.1016/j.envpol.2021.117780.

Zhao, S., Shi, X., Li, C., Zhang, H., Wu, Y., 2014. Seasonal variation of heavy metals in sediment of Lake Ulansuhai, China. Chem. Ecol. 30 (1), 1–14. https://doi.org/10.1080/02757540.2013.841894.

Zolitschka, B., Francus, P., Ojala, A.E.K., 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.