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Assessment of microplastic contamination on lakeshores of Lake Lugano

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Abstract: Due to the lack of knowledge on microplastic distribution on lakeshores and their ecological consequences in these ecosystems, the International Commission for the Protection of the Italian-Swiss Waters initiated a study to compare microplastic concentrations on shores of Lake Lugano with those of six Swiss lakes. Therefore, samples were collected on nine shores of Lake Lugano to quantify and identify microplastic particles (0.3-5 mm). After fractionation of the samples, the microplastic particles were manually extracted, quantified and characterized using a Fourier-transform infrared spectrometer (FTIR). Our data from Lake Lugano suggest that the microplastic distribution is heterogeneous among the shores; with the Agno bay being the most contaminated zone, probably due to its proximity to an urban-industrial area and the Vedeggio tributary. The observed microplastic particles were composed up to 89% of polyethylene, polypropylene and polystyrene. The data indicates that Lake Lugano shores have a higher concentration (3'063 ± 2'566 particles/m^2) compared to shores of the six other Swiss lakes, albeit the order of magnitude is the same. Regarding spatial variations in the same lake, the pelagic zones of seven Swiss lakes (including Lake Lugano) are approximately four orders of magnitude less contaminated than their shores. Understanding and managing this environmental issue requires a more detailed knowledge of the microplastic distribution on lakeshores and its possible effects on biota.

Keywords: Freshwater ecosystems, FTIR, microplastic composition, microplastic distribution, Southern Switzerland

Valutazione dell'inquinamento da microplastiche nelle rive del Lago di Lugano

Riassunto esteso

Introduzione: Negli ultimi anni, la consapevolezza pubblica e scientifica dell'inquinamento da microplastiche (MP) nell'ambiente è aumentata significativamente. Tuttavia al momento non esistono ancora molti dati empirici al riguardo. Per questo motivo, la Commissione Internazionale per la Protezione delle Acque Italo-Svizzere (CIPAIS) ha deciso di valutare per la prima volta la contaminazione da MP nelle rive del Lago di Lugano, completando e integrando i dati a una ricerca svolta nel 2004 dal Politecnico Federale di Losanna (EPFL) su sei laghi svizzeri (Faure & De Alencastro 2014).

Materiali e metodi: Dopo aver frazionato i vari campioni di sabbia, le MP da 0.3 a 5 mm sono state estratte e quantificate grazie all'uso di uno stereomicroscopio. Le MP di taglia superiore a 1 mm sono state identificate chimicamente tramite la spettroscopia infrarossa a trasformata di Fourier (FTIR-ATR). Dato che uno degli obiettivi di questo studio era anche quello di sperimentare i diversi metodi di analisi, su alcuni campioni è stata applicata una separazione di densità utilizzando il cloruro di sodio. Questo ulteriore passaggio ha aumentato l'efficacia del metodo di estrazione del 50%, motivo per cui questa pratica è fortemente consigliata in simili studi.

Risultati: Le concentrazioni medie di MP misurate su nove rive del Lago di Lugano sono significativamente diverse tra loro, sia per la frazione da 0.3-1 mm che per quella da 1-5 mm (Fig. 3 e Appendice 4). Tra le nove rive campionate, i valori più alti per le MP da 1-5 mm sono stati osservati ad Agnuzzo (2'056 ± 2'189 MP/m^2) e per le MP da 0.3-1 mm alla foce della Magliasina (6'633 ± 3'625 MP/m^2), nel bacino sud. Le due rive meno inquinate invece si trovano in prossimità di Brusino (67 ± 71 MP/m^2), per le MP di taglia 1-5 mm, e Melano (300 ± 173 MP/m^2), per le MP da 0.3-1 mm. Questa importante variazione in concentrazione di MP è giustificata dal fatto che i due siti più inquinati sono situati in prossimità degli affluenti Vedeggio e Magliasina, oltre a essere vicini ad una zona industriale e popolata come Agno. Per quanto riguarda la distribuzione di MP sulla riva stessa, si è osservata una concentrazione più bassa nella zona sommersa della riva rispetto alla linea di deposizione (Fig. 4). Questo può essere dovuto ad una perdita di MP durante il campionamento o all'azione dell'acqua che impedisce la deposizione di plastica nella regione sommersa. La maggior parte delle MP osservate sulle rive del Lago di Lugano erano composte da polistirene (45%), polietilene (33%) e polipropilene (11%). Queste tre tipologie chimiche di plastica, oltre ad essere tra le più prodotte al mondo (Fig. 5), sono polimeri plastici a bassa densità, caratteristica che permette a queste particelle di MP di galleggiare in acqua, favorendone la mobilità (PlasticsEurope 2020). Le concentrazioni di MP misurate sulle nove rive lacustri erano significativamente più alte, di 4 unità di grandezza, rispetto a quelle osservate nell'acqua superficiale dello stesso lago (Tab. 1). Questo risultato rafforza l'idea che le rive sono un importante compartimento di accumulo e di deposito per le MP, mentre la zona pelagica funge da via di trasporto. Le

concentrazioni di MP misurate sulle rive del Lago di Lugano sono risultate più elevate rispetto ad altre sei rive di laghi svizzeri (Faure & De Alencastro 2014), anche se l'unità di grandezza è complessivamente la stessa (Tab. 1). Questa differenza potrebbe essere spiegata dalle precipitazioni prima del campionamento, dal piccolo volume d'acqua del Lago di Lugano, da una differenza metodologica tra questi due studi o da una reale variabilità tra questi diversi bacini.
Conclusioni: Questo studio è importante in quanto fornisce ulteriori dati riguardo la distribuzione di MP negli ecosistemi d'acqua dolce e può quindi essere il punto di partenza per ulteriori progetti su questo argomento. Benché su questo tema siano stati fatti notevoli passi avanti negli ultimi anni, molte questioni rimangono ancora aperte, in particolare la mancanza di un metodo standardizzato per l'analisi delle MP e gli effetti delle MP sulla fauna e la flora.

Parole chiave: Composizione di microplastiche, distribuzione di microplastiche, ecosistemi di acqua dolce, FTIR, Svizzera sudalpina

INTRODUCTION

Plastic has revolutionized our lives, improving our wellbeing in every sector, from the food industry to the healthcare system. As Zalasiewicz et al. (2015) suggested, a plausible beginning of the Anthropocene could be placed at the start of the mass production of plastic in 1950, which irrevocably changed the planet. Nowadays, plastic is one of the most employed materials, with a global annual production of 367 million tons in 2020 (PlasticsEurope 2021). The success of this material can be mainly explained by its low production price and its versatile properties (e.g. flame retardancy, plasticity, microbial growth inhibition) gained by the presence of additives (Lambert & Wagner 2018). However, this extraordinary material has also become one of the dominant environmental issues of our times for several reasons (UNEP 2016). First, because plastic contributes to fossil fuels use, and second, because a significant proportion of it is not disposed of correctly and contributes to the pollution of the environment (UNEP 2016). Once in the environment, plastic has shown to be highly persistent to biodegradation. In contrast, it tends to fragment, thus transforming in and accumulating as microplastics (MP), defined as plastic particles with sizes smaller than 5 mm (Rocha-Santos & Duarte 2017). The toxicity of MP particles is mainly due to toxic additives (e.g. phthalates, bisphenol-A) and/or adsorbed substances such as polychlorinated biphenyls (PCBs) and heavy metals (Rocha-Santos & Duarte 2017). However, the consequences of these chemical compounds for the biota are not well known despite the substantial research effort on the topic (Li et al. 2020).

MP contamination in the environment was mainly studied in marine rather than freshwater ecosystems because the former are considered as final sinks of plastics (Li et al. 2020). Nevertheless, freshwater ecosystems are equally concerned since they are the principal pathway of plastic and MP from terrestrial to marine areas and can act as sinks as well (Imhof et al. 2013). Additionally, freshwater ecosystems are important biodiversity hotspots and provide many crucial ecosystem services (e.g. drinking water; GESAMP 2010). Because of these environmental concerns and lack of knowledge on the MP presence and impacts, the Swiss Federal Office for the Environment in 2014 commissioned a study to the Swiss Federal Institute of Technology Lausanne (EPFL) to provide data and to evaluate the MP contamination in the pelagic zone and on the shores of six major Swiss lakes (Faure & De Alencastro 2014). The six investigated lakes are Lake Brienz, Lake Constance, Lake Geneva, Lake Maggiore, Lake Neuchâtel and Lake Zürich. Owing to the fact that Lake Lugano was not included in this study, the International Commission for the Protection of the Italian-Swiss Waters (CIPAIS) commissioned the University of Applied Sciences and Arts of Southern Switzerland (SUPSI) to provide data for the shores of Lake Lugano, which can complement data from the pelagic zone of Lake Lugano (Solcà 2018). Specifically, the aims of this study were (i) to quantify and characterize for the first time small plastic particles (more than 5 mm) and MP particles (0.3 to 5 mm) on nine lakeshores of Lake Lugano (ii) to infer on the causes of plastic and MP particles spatial distribution among sites and within sites, and (iii) to compare obtained data with the results from the pelagic zone of Lake Lugano and from shores and pelagic zones of six different Swiss lakes (Faure & De Alencastro 2014; Solcà 2018). Based on the existing literature (Cable et al. 2017; Li et al. 2020; Zbyszewski et al. 2014), we postulated the following hypotheses: (i) lakeshores have higher MP concentrations than pelagic zones, (ii) shores in proximity to urban-industrial areas and tributaries have higher particle concentrations, (iii) smaller MP particles occur in higher concentrations than bigger particles, and (iv) the concentrations of low-density plastics, such as polyethylene (PE), polypropylene (PP) and polystyrene (PS) are higher on lakeshores than those of high-density plastics.

MATERIALS AND METHODS

Study area

Lake Lugano is a subalpine lake in the southern Prealps on Swiss and Italian territory and has a catchment area of 565.6 km^2 (IST-SUPSI 2020). The lake is divided in three basins with different physical characteristics: the North basin (27.5 km^2), the South basin (20.3 km^2) and the Ponte Tresa basin (1.1 km^2). The main tributaries enter into the South basin, which is richer in nutrients and pollutants compared to the North basin and has much shorter water renewal time (1.4 years compared to 12.4 years of the North basin; Solcà 2018). Nine

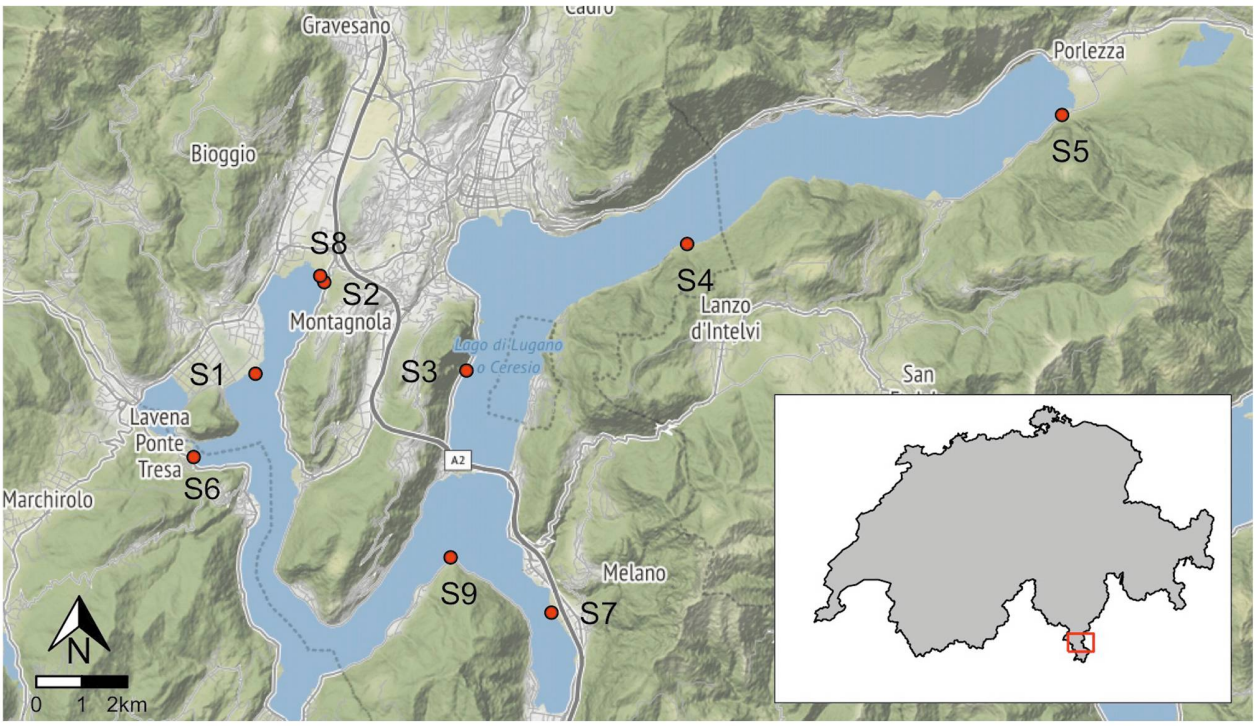

Figure 1: Location of the nine Lake Lugano sampling sites, three in the North basin (S3, S4, S5) and six in the South basin (S1, S2, S6, S7, S8, S9; Map from OpenStreetMap modified in R 3.6.1, 2021).

sites around Lake Lugano (Fig. 1) were selected for this study based on the lakeshore substrate type (favoring sand and gravel) but also to cover a broad range of characteristics of Lake Lugano shores (Appendix 1). Characteristics include different proximities to urban-industrial areas and different environmental and morphological conditions (inclination, aspect, wind conditions, tributary proximity).

Sampling method

As one of the main goals was to complement the study on microplastic contamination of six major Swiss lakes by Faure & De Alencastro (2014), it was essential to maintain a similar sampling method. For this reason, it was decided to focus and collect three samples on the drift line, a line parallel to the waterline on which material accumulates on the shore due to current and wave action (Fig. 2). The drift line is chosen by most published studies because it is where the majority of debris and material accumulates, including plastic and MP (Hanvey et al. 2017). However, to verify and compare the effects of position on the lakeshore for plastic and MP accumulation, three samples were also taken above and below the drift line. A total of nine samples of volumes equal to 0.5 L were collected at each sampling site.

Samples were extracted with a steel corer of 10×10×30 cm, which was inserted 5 cm into the substrate and removed with a small shovel covering the bottom opening. Samples were then transferred and stored in glass jars. This sampling technique resulted in surface samples; consequently, the resulting values are expressed per square meters shore surface area and not per cubic meters. It must be noted, however, that most samples

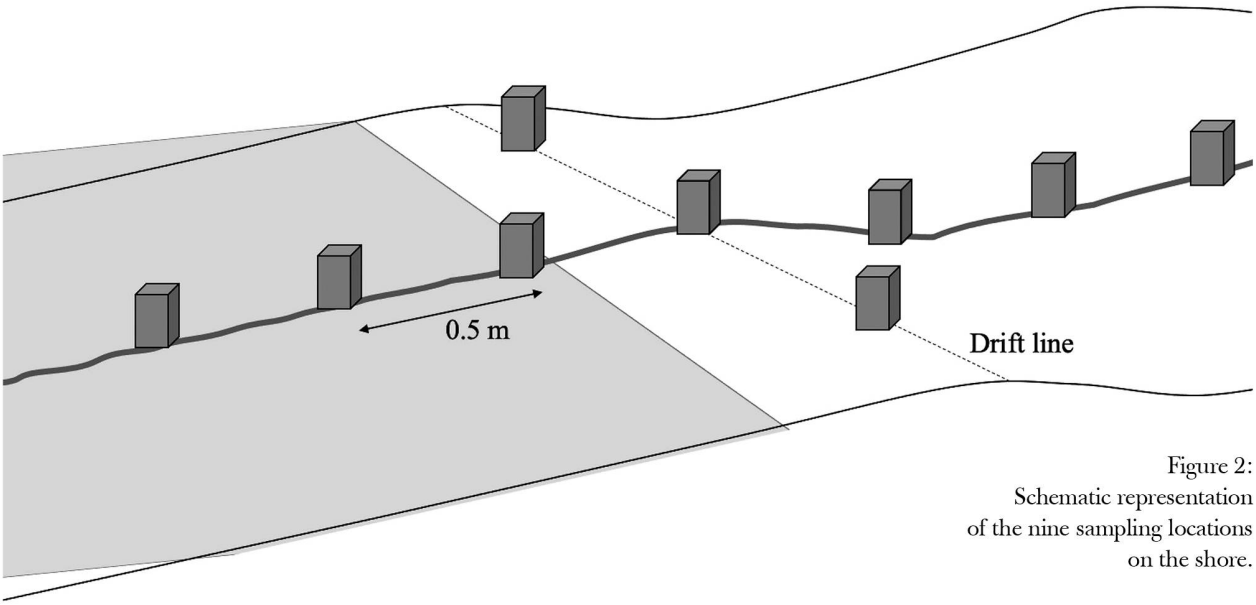

Figure 2: Schematic representation of the nine sampling locations on the shore.

below the drift line were taken from submerged areas of the shore, which complicated the extraction of the sample (washing out of some material during removal) and potentially caused a reduction in the detection rate. Samples were then freeze-dried (FreeZone 2.4, LABCONCO) and stored until further analyses. During sampling and MP extraction and characterization (described below) all unnecessary plastic equipment was avoided to minimize contaminations.

Plastic and microplastic extraction

After weighting, dried samples were fractionated in four size classes using metal sieves of 63 µm, 0.3 mm, 1 mm and 5 mm mesh sizes (ISO 3310, VWR International). Samples were placed at the top of the sieve column and shaken for three minutes. Then the material accumulated in each sieve was collected and stored in a separate glass jar. Small plastic and MP particles were extracted and counted from all samples of the size classes bigger than 1 mm with the help of a stereomicroscope (Leica EZ4). MP particles in the size range 0.3-1 mm were only extracted from samples from the drift line. During extraction, all potential plastic particles were categorized into seven different morphological categories: pellets, microbeads, fragments, fibres, wires, foams and films, i.e. the most common categories employed in similar studies (Free et al. 2014; Laglbauer et al. 2014; Negrete Velasco et al. 2020). As a first identification (i.e. plastic vs. other material) the hot-needle technique was used (Lusher et al. 2020) which consists of placing a hot needle close to the selected particle. The particle was considered as a plastic if it melted.

Since no standardized method exists yet for the analysis of MP, an important part of this study was also to evaluate the methods used. An additional extraction step of density separation with NaCl was tested on samples composed principally by sand in the size range from 0.3 to 5 mm. In this study, a systematic density separation was excluded initially because it was believed to cause an important loss of plastic particles without increasing the extraction efficiency. Regarding the density separation experiments, it was chosen to use NaCl because it is cheap and easy to use (i.e. non-toxic compared to other salts). A downside of using a NaCl solution is that it has a relatively low density of about 1.2 g/cm^3 and is therefore inefficient to separate denser plastics such as polyvinylchloride (PVC) (Faure & De Alencastro 2014). NaI or $ZnCl_2$ solutions have higher densities but are expensive and potentially toxic (Hanvey et al. 2017). The results showed that density separation increased MP extraction efficiency by about 50%. It is therefore highly recommended for projects with similar goals.

Chemical identification

A total of eight small plastic particles larger than 5 mm and 398 MP particles in the size range from 1 to 5 mm were chemically characterized using FTIR in the ATR mode (Gemini Analyzer, Thermo Fisher Scientific). This device has a size limitation of 1 mm. Since fibres were usually thinner than 1 mm, it was impossible to chemically characterize this MP category in this study.

Statistical analysis

All statistical analyses and graphic representations were generated in R (version 3.6.1). An analysis of variance (ANOVA) was performed to test whether the MP concentrations (1-5 mm) were significantly different among the nine sampled lakeshores (Appendix 2). A two-way ANOVA was performed to test if the MP concentrations on the drift line for the two size fractions, 0.3-1 mm and 1-5 mm, were significantly different (Appendix 3). In order to meet the ANOVA assumptions of equal variances and normal distribution, the MP concentration variable was transformed to a decadic logarithmic scale and a constant was added. Finally, a two-way nested ANOVA was performed to determine whether the MP concentrations differed significantly among sites and different positions within lakeshores. In this case as well, values of MP concentration were transformed to a decadic logarithmic scale and a constant was added.

The graphs have been generated using the ggplot2 (version 3.3.2), dplyr (version 1.0.2) and ggpubr (version 0.4.0) packages. The maps in figure 1 and figure 3 were created on the base of multiples packages: ggplot2, dplyr, ggpubr, ggmap (version 3.0.0.901), maps (version 3.3.0), mapdata (version 2.3.0), cowplot (version 1.1.0) and devtools (version 2.3.2).

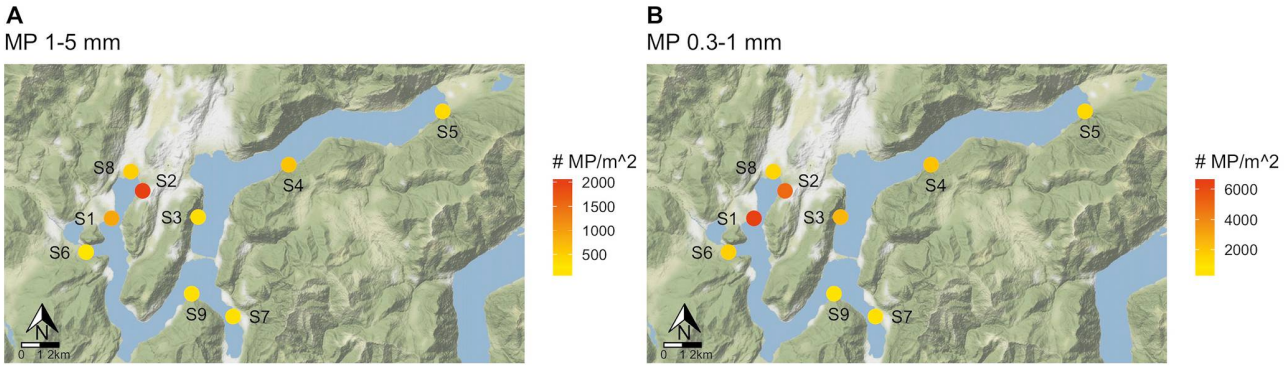

Figure 3: Concentrations of MP particles represented as a gradient from yellow (low concentration) to red (high concentration) as detected on the sampled shores (S1 to S9): A) Particle size range 1-5 mm. B) Particle size range 0.3-1 mm.

RESULTS

Microplastic particles concentrations on shores of Lake Lugano

Concentrations of MP particles differed significantly among the nine sampled shores (p-values < 0.05, Appendix 2 and Appendix 3) for both size ranges, i.e. 0.3-1 mm and 1-5 mm (Fig. 3). Concentrations of MP particles of 0.3-1 mm ranged from 0 to 2'000 particles/m^2, whereas those for MP particles of 1-5 mm ranged from 0 to 6'500 particles/m^2. The most contaminated sites for these two size fractions were in the Agno bay in the South basin of the lake: S1 with a MP (0.3-1 mm) concentration of 6'633 ± 3'625 particles/m^2 and S2 with a MP (0.3-1 mm) concentration of 5'000 ± 5'197 particles/m^2. The least contaminated sites for these two size fractions were also in the South basin: Lavena (S7) with a MP (0.3-1 mm) concentration of 300 ± 173 particles/m^2 and Ponte Poiana (S9) with a MP (0.3-1 mm) concentration of 667 ± 473 particles/m^2. The MP concentrations are reported in Appendix 4.

Distribution of microplastic particles within nine shores of Lake Lugano

The small-scale MP distribution within lakeshores differ significantly for particles in sizes between 0.3-1 mm (p-value < 0.05; Appendix 5). More precisely, lower MP concentrations were observed beneath the drift line, in the submerged region of the shore, compared to the drift line and above it (Fig. 4). However, no difference was observed in concentrations measured on the drift line and above it.

Characteristic of plastic and microplastic particles: concentrations depending on the MP size, chemical and morphological composition

Microplastics were observed on every shore but small plastic particles larger than 5 mm were detected only in three sites (S1, S2 and S8). Mean MP concentrations of the nine samples from all sites combined increased with decreasing particle size: 10 ± 22 particles/m^2 > 5 mm, 585 ± 609 particles/m^2 1-5 mm, and 2'396 ± 2'085 particles/m^2 0.3-1 mm. From the 398 MP particles in the size range 1-5 mm that were chemically identified (Fig. 5A), 45% were composed of polystyrene (PS), 33% of polyethylene (PE), 11% of polypropylene (PP), 2.3% of thermoplastic rubber (TR), and 8% could not be identified with the available databases (no_match). From the 473 MP particles of 0.3 to 5 mm that were morphologically identified, 37% were fibres, 30% fragments, 24% foams, 6% films, 2% pellets and 1% wires (Fig. 5B). Some pictures of the observed MP particles are shown in Appendix 6.

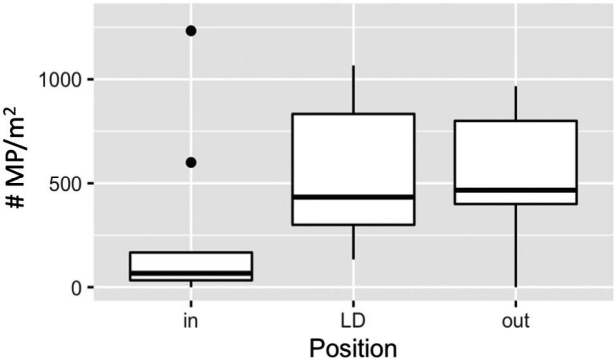

Figure 4: MP concentrations (particles/m^2) and distributions for the three sampling positions (beneath the drift line: in, drift line: LD, above the drift line: out) within lakeshores.

Comparison of microplastic concentrations between seven Swiss lakeshores with their pelagic zones

For Lake Lugano, the mean MP concentration on lakeshores (drift line) was 3'063 ± 2'566 particles/m^2 compared to 0.21 ± 0.16 particles/m^2 on the surface of the pelagic zone (Solcà 2018). This difference (i.e. about four orders of magnitude) was also found similar for the other six Swiss lakes for which comparable data is available (Tab. 1). No small plastic particles larger than 5 mm were collected on the drift line in the nine sampling sites, resulting in a near zero mean concentration for the Lake Lugano, which is lower compared to the other Swiss lakeshores (Tab. 1). Mean concentration of

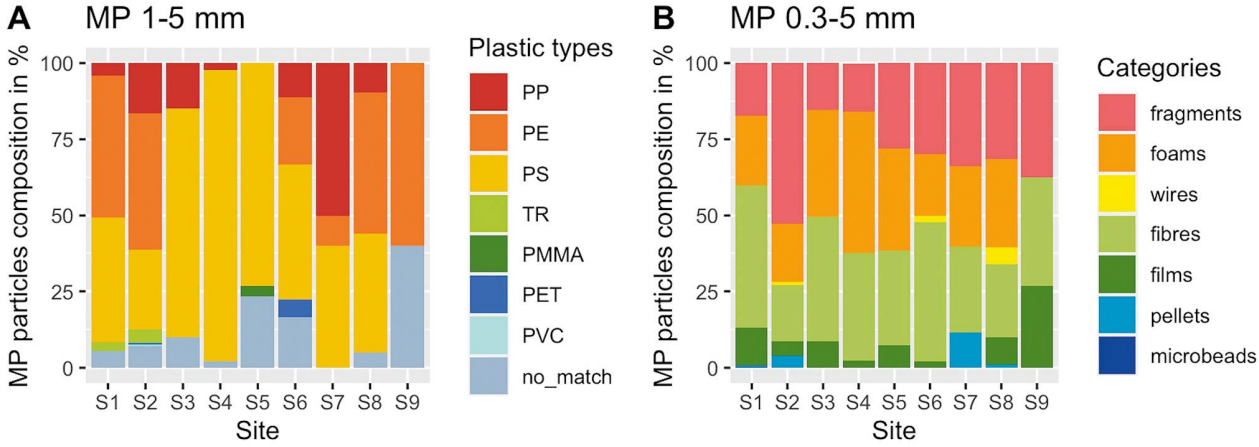

Figure 5: A) Chemical composition of MP particles (1-5 mm) for the different sites (S1 to S9). Plastic types: polypropylene (PP), polyethylene (PE), polystyrene (PS), thermoplastic rubber (TR), polymethyl methacrylate (PMMA), polyethylene terephthalate (PET), polyvinyl chloride (PVC) and non-identifiable particles (no_match). B) Morphological categories of MP particles (0.3-5 mm) for each site (S1 to S9).

Table 1: Mean concentrations (particles/m² ± 1SD) of small plastic particles (> 5 mm) and MP particles (0.3-5 mm) for seven Swiss lakes for lakeshores and pelagic zones. The data from pelagic zones of Lake Lugano is from Solcà (2018), whereas that of the other Swiss lakes is from Faure & De Alencastro (2014).

Site	Lakeshores (particles/m²)		Pelagic zones (particles/m²)	
	> 5 mm	0.3-5 mm	> 5 mm	0.3-5 mm
Lake Lugano	0 ± 0	3'063 ± 2'566	$5\times10^{-3} \pm 5\times10^{-3}$	0.21 ± 0.16
Lake Maggiore	28 ± 42	1'110 ± 2'330	$7\times10^{-3} \pm 6\times10^{-3}$	0.22 ± 0.15
Lake Geneva	35 ± 65	2'100 ± 2'000	$2\times10^{-3} \pm 2\times10^{-3}$	0.22 ± 0.16
Lake Constance	8 ± 11	320 ± 220	$1\times10^{-3} \pm 1\times10^{-3}$	0.06 ± 0.01
Lake Neuchâtel	17 ± 26	700 ± 1'100	$3\times10^{-4} \pm 5\times10^{-4}$	0.06 ± 0.02
Lake Zürich	3 ± 6	460 ± 350	$1\times10^{-3} \pm 1\times10^{-3}$	0.01 ± 0.003
Lake Brienz	400 ± 510	2'500 ± 3'000	$1\times10^{-3} \pm 1\times10^{-3}$	0.04 ± 0.02

MP particles in the range of 0.3-5 mm (3'063 ± 2'566 particles/m²) was higher for Lake Lugano shores than for other Swiss lakeshores, although the order of magnitude is the same.

DISCUSSION

This study was carried out to assess the microplastic distribution of lakeshores, which are expected to play key roles as accumulation compartments for microplastic particles. The main goals of this study were to quantify the spatial variability of the concentrations on nine lakeshores of Lake Lugano and to compare pelagic and lakeshores concentrations detected in Lake Lugano with those of six other Swiss lakes. Our results suggest that MP concentrations differ substantially among shores of the same lake (this study; Imhof et al. 2013; Faure & De Alencastro 2014). Therefore, comparing a single mean value of MP concentrations among lakes is a gross simplification and makes estimates extremely dependent on the selection and number of sampling sites. This is also the case for Lake Lugano, where more than 50% of the MP particles were observed in two lakeshores out of nine (Fig. 3). It is therefore relevant to study the variability of MP concentrations among shores of the same lake and to identify factors that control this variability.

Our study suggests that the proximity of a shore to tributaries draining urban-industrial areas contributes substantially to high MP concentrations as has been suggested by other studies (Li et al. 2020; Imhof et al. 2013; Akdogan & Guven 2019). For Lake Lugano, the most contaminated sites (S1 and S2) are located in the Agno bay, an urban and industrial region where the Vedeggio river, a main tributary of Lake Lugano, enters the lake (Fig. 3). Site 8, also located in the Agno bay seems to represent an exception to this interpretation, as the observed MP concentrations were not particularly high. This is probably due to the presence of reeds that on one hand reduce the arrival of MP particles from the lake and on the other hand, limit the potential for recreational activities on this site and reduce littering and direct inputs of plastic particles. The least contaminated shores (S7 and S9) were in areas with minor anthropogenic activities in the catchment and with no major tributary.

Another factor explaining differences in MP concentrations among shores is their substrate composition, i.e. whether it is principally composed of sand or gravel (note that due to methodological reasons we did not study MP concentrations in shores with larger-grained substrates like cobbles and boulders). Previous studies have shown that MP concentrations tend to be higher on sandy shores compared to shores with gravel (Li et al. 2020). MP particles may preferentially deposit and accumulate on sandy shores, whereas they are washed out from gravel shores or transported to deeper layers of the shores due to the large space between the grains. Substrate grain size may also explain differences among shores of Lake Lugano. The sites with the highest concentrations (S1 and S2) are sandy shores, whereas the least contaminated sites (S7 and S9) were mainly composed of gravel. Additionally, factors such as prevalent wind conditions, lake currents and the influence of wastewater treatments plants may also affect MP concentrations on nearby lakeshores (Fischer et al. 2016; Li et al. 2020).

Regarding the small-scale MP distribution within lakeshores, our data suggests a higher accumulation propensity on the drift line and above it, compared to the area of the shore submerged in water (Fig. 4). Two reasons could potentially explain this difference. The first is linked to the mechanical action of the water that prevents accumulation and deposition of MP in the submerged area. The second reason could be linked to a partial loss of MP particles during the extraction of the substrate from the water.

Based on our results, a difference in MP distribution is evident also between shores and pelagic zones of the same lake. Data from seven large Swiss lakes (including Lake Lugano), indicate that the amount of MP particles observed on shores is about four orders of magnitude higher than in the pelagic zones of the same lake (Tab. 1). These results suggest that pelagic zones are a transitory compartment for MP and represent mainly a pathway for MP in lakes whereas lakeshores are zones of MP accumulation and deposition (Li et al. 2020).

As expected, MP concentrations differ substantially among different lakes as well (Tab. 1), probably mainly due to the high variability in MP concentrations depending on the chosen shores for sampling, differences

in catchment land use, and in the ratio of lake surface area to catchment surface area (Xu et al. 2020). For example, on the shores of Lake Chiusi (Italy), a small eutrophic lake in Tuscany (surface area: 3.9 km^2), a mean concentration of 2'117 ± 695 MP particles/m^2 was measured (Fischer et al. 2016). On the shores of the Lake Sétubal instead, a floodplain lake alongside Santa Fe in Argentina (surface area: 32 km^2), 720 MP particles/m^2 were observed (Blettler et al. 2017). Or again, 5.43 ± 12.62 MP particles/m^2 were observed on the shores of Lake Huron (surface area: 81'340 km^2), one of the Great lakes located in an industrial and touristic area in the USA (Zbyszewski et al. 2014). From these data it becomes clear that the MP concentration on lakeshores is lake specific since factors influencing the MP distribution are more or less relevant depending on the lake.

Mean MP concentrations on the shores of Lake Lugano (3'063 ± 2'566 particles/m^2) seem to be higher than those on the shores of the other six Swiss lakes for which data are available, albeit in the same order of magnitude (Tab. 1). Three main factors could have contributed to these differences observed among Swiss lakes: lake sizes, precipitation amounts and methodological choices. First, lakes with small surface areas seem to have higher MP concentrations than larger lakes (Free et al. 2014). Because even if the same amount of MP reaches a small lake, the concentration can be higher because the surface area is smaller compared to a bigger lake. The surface area of Lake Lugano (48.7 km^2) is relatively small but in the range of that of Lake Brienz (29.8 km^2) and Lake Zürich (88.7 km^2). Whereas the other Swiss lakes for which comparable data is available, i.e., Lake Constance, Lake Geneva, Lake Maggiore and Lake Neuchâtel, have a substantially larger surface area of around 500 km^2. Second, heavy precipitation events can increase the amount of MP entering a lake (Fischer et al. 2016). In our study, heavy precipitations (> 36 mm per day; MeteoSvizzera 2019) on four days in the two weeks prior to sampling in Lake Lugano may have increased the MP concentrations detected on the shores of Lake Lugano. Heavy precipitation events occurred also before sampling on the shores of Lake Maggiore in Faure & De Alencastro (2014), which makes the data between these lakes comparable for this specific factor. Third, methodological choices have an important influence on the results. Although methods were chosen as similar as possible as the ones in Faure & De Alencastro (2014), some methodological differences were unavoidable. Notably, Faure & De Alencastro (2014) did a density separation of sand samples using NaCl, but not of gravel samples. Then a fractionation was performed on all types of samples and finally a digestion with H_2O_2 was applied to samples of the range 0.3 to 1 mm. In our study however, a simple fractionation and a visual sorting was conducted. Moreover, comparisons with Faure & De Alencastro (2014) can only be done based on samples collected on the drift line because they focused solely on this part of the shore.

Concerning MP concentrations of the different particles sizes, the exponentially increasing concentration of particles as their size decreases observed in our study corroborates studies from Lake Geneva (Faure & De Alencastro 2014), from Lake Garda (Imhof et al. 2018) and from the Great lakes (Cable et al. 2017). The reason probably lies in the fact that MP are transported and accumulate as larger particles and then broken down on the shores into many smaller particles as a consequence of wave action and UV-radiation (Rocha-Santos & Duarte 2017).

The morphological composition of the observed MP particles in sizes 0.3 to 5 mm was very similar to that observed on the shores of other Swiss lakes (Faure & De Alencastro 2014; Filella & Turner 2018). The most frequent categories observed on Swiss lakeshores were fibres, fragments and foams. The source of fibres are principally textiles whereas fragments are formed by the fragmentation of bigger plastic objects, and foams derive mainly from construction sites (PlasticsEurope 2020). Most particles detected on the shores of Lake Lugano (i.e. 89%) were composed of PE, PP and PS (Fig. 5A). These three plastic types are among the most used worldwide (PlasticsEurope 2020). Moreover, their density is lower than that of water, which facilitates their transport and distribution in the environment. The same plastic types were also dominant on other Swiss lakeshores, where 62% were composed of PE, 15% PP and 12% PS (Faure & De Alencastro 2014).

CONCLUSION

Public awareness of the environmental issues associated with plastic contamination in the environment has increased worldwide. Available studies on diverse aspects of the plastic cycle contribute to the increasing understanding of the impacts on the environment and organisms. Nevertheless, understanding and managing this issue is still hampered by the lack of data on MP concentration and distribution in freshwater ecosystems. The knowledge on the effects of MP on flora, fauna, and microorganisms is also still very limited and hinders effective policy and management actions as well. However, probably the biggest challenge to advance knowledge in this field is the lack of standardized methods for the extraction and identification of MP. This limits our ability to compare data among studies and regions. The scientific community has now recognized this issue and started to address this lack of standardization (SAPEA 2019). While it is important to understand MP distribution in the environment and the biota, it is even more important to mitigate this environmental issue at the source, i.e., reducing inputs to ecosystems. Nowadays, the use of most plastic types in Switzerland is still largely organized as a linear end-pipe system in which 90% of plastic is incinerated instead of being recycled (McLellan 2021), although some progress is made at the communal level. It would seem efficient to take inspiration from and coordinate with large-scale political initiatives addressing this environmental issue as currently undertaken in the European Union, for example by banning single-use plastics (European Commission 2021). At the same time, small-scale actions, such as organizing municipal recycling of most

plastic types, installing garbage bins on the shores, and organizing clean-up days, could contribute to sensibilizing the general public and reducing littering.

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APPENDIX

Appendix 1: Background data for each sampling site (S1 to S9): substrate type (sand or gravel), coordinates (CH1903+/LV95), aspect in °, inclination in °, vegetation cover in % and the fetch value (Oikos 2000 2016).

Site	Substrate	Longitude	Latitude	Aspect	Inclination	Vegetation cover	Fetch
S1	sand	2'712'666	1'092'246	193	14	54	3
S2	sand	2'714'151	1'094'297	249	14	79	2
S3	gravel	2'717'318	1'092'405	110	13	74	5
S4	gravel	2'722'123	1'095'293	5	10	41	4
S5	gravel	2'730'315	1'098'312	278	14	24	5
S6	sand	2'711'343	1'090'380	72	8	39	1
S7	gravel	2'719'291	1'087'083	219	16	28	3
S8	sand	2'714'058	1'094'434	249	13	12	2
S9	gravel	2'717'049	1'088'260	324	14	9	3

Appendix 2: ANOVA to test the differences in the MP concentrations (1-5 mm) among the nine shores of Lake Lugano.

```
> MPsiti <- aov(log(m2+10) ~ site, data = cat1_pos)
> summary(MPsiti)
            Df Sum Sq Mean Sq F value   Pr(>F)
site         8   93.2  11.650   4.037 0.000526 ***
Residuals   72  207.8   2.886
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Appendix 3: Two-way ANOVA to test the differences in the MP concentrations on the drift line for the size categories 0.3-1 mm and 1-5 mm on the nine sampled shores of Lake Lugano.

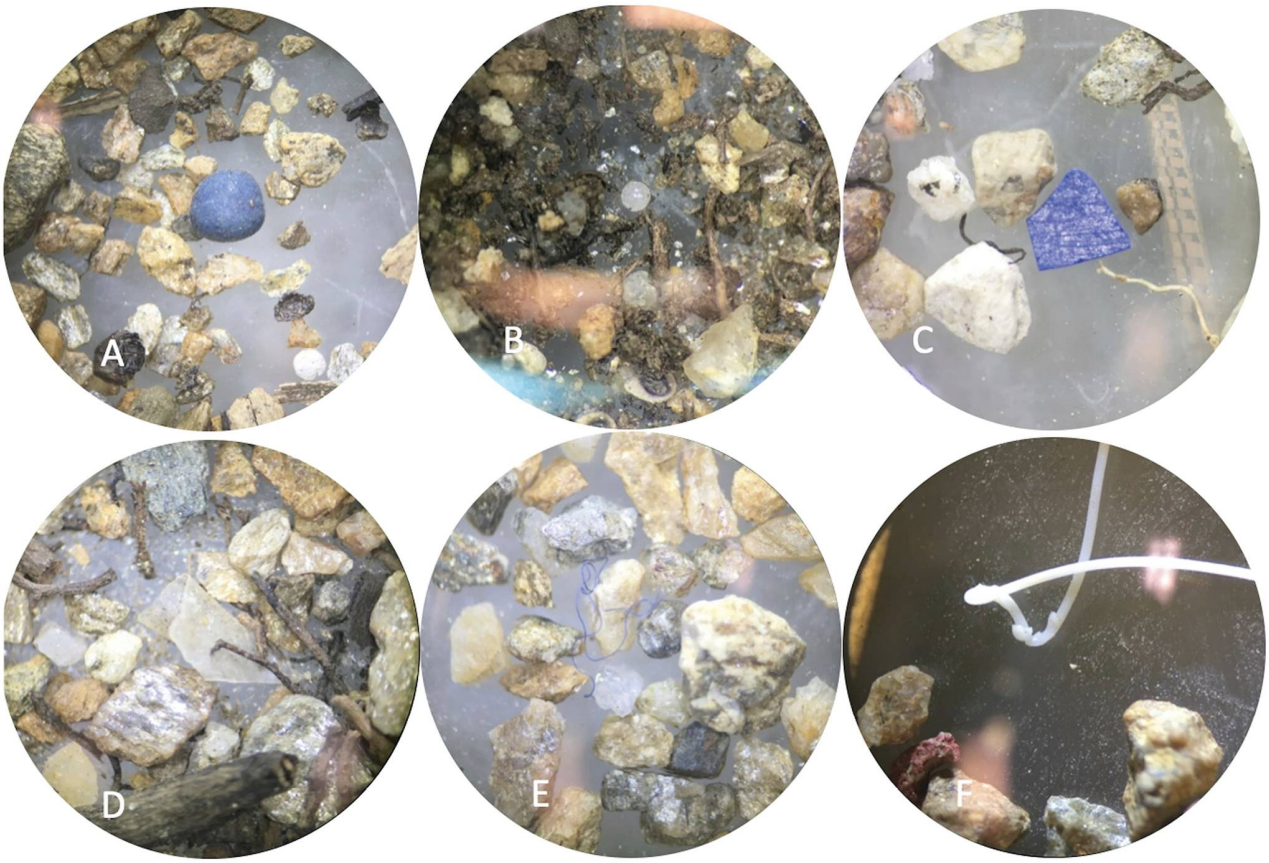
```
> ld13<-aov(m2 ~ site+fraction, data = solo_LD13)
> summary(ld13)
            Df    Sum Sq  Mean Sq F value   Pr(>F)
site         8  81023704 10127963   3.647 0.002458 **
fraction     1  39526667 39526667  14.235 0.000479 ***
Residuals   44 122180000  2776818
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Appendix 4: MP concentrations for size fractions > 5 mm, 1-5 mm and 0.3-1 mm. The mean and standard deviation (SD) are indicated in square meters and kilograms.

Site	Name	Value	>5 mm	1-5 mm	0.3-1 mm
			n=9	n=9	n=3
S1	Foce Magliasina	mean ± 1SD [#/m²]	11 ± 33	922 ± 574	6'633 ± 3'625
S1	Foce Magliasina	mean ± 1SD [#/kg]	0 ± 1	16 ± 10	114 ± 62
S2	Agnuzzo	mean ± 1SD [#/m²]	67 ± 87	2'056 ± 2'189	5'000 ± 5'197
S2	Agnuzzo	mean ± 1SD [#/kg]	1 ± 2	42 ± 44	101 ± 105
S3	Capo San Martino	mean ± 1SD [#/m²]	0	322 ± 421	2'433 ± 551
S3	Capo San Martino	mean ± 1SD [#/kg]	0	4 ± 5	31 ± 7
S4	Caprino	mean ± 1SD [#/m²]	0	622 ± 652	2'100 ± 794
S4	Caprino	mean ± 1SD [#/kg]	0	8 ± 8	27 ± 10
S5	Porlezza	mean ± 1SD [#/m²]	0	378 ± 606	1'333 ± 153
S5	Porlezza	mean ± 1SD [#/m²]	0	5 ± 9	19 ± 2
S6	Lavena	mean ± 1SD [#/kg]	0	256 ± 251	1'633 ± 208
S6	Lavena	mean ± 1SD [#/m²]	0	4 ± 4	25 ± 3
S7	Melano	mean ± 1SD [#/kg]	0	144 ± 224	300 ± 173
S7	Melano	mean ± 1SD [#/m²]	0	2 ± 3	4 ± 2
S8	Agnuzzo canneti	mean ± 1SD [#/kg]	11 ± 33	500 ± 433	1'467 ± 493
S8	Agnuzzo canneti	mean ± 1SD [#/m²]	0 ± 1	8 ± 7	23 ± 8
S9	Brusino	mean ± 1SD [#/kg]	0	67 ± 71	667 ± 473
S9	Brusino	mean ± 1SD [#/m²]	0	1 ± 1	10 ± 7
	Mean	mean ± 1SD [#/kg]	10 ± 22	585 ± 609	2'396 ± 2'085
	Mean	mean ± 1SD [#/m²]	0	10 ± 13	39 ± 40

Appendix 5: Nested two-way ANOVA to test the differences in the MP concentrations (1-5 mm) among different sites (S1 to S9) and positions (above the drift line, on the drift line and beneath the drift line) within lakeshores of Lake Lugano.

```
> cat_nestaov <- aov(log(m2+10) ~ site / factor(position), data = cat1_pos)
> summary(cat_nestaov)
                     Df Sum Sq Mean Sq F value   Pr(>F)
site                  8   93.2  11.650   6.144 1.27e-05 ***
site:factor(position) 18  105.4   5.856   3.088 0.000703 ***
Residuals             54  102.4   1.896
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```



Appendix 6: MP particles extracted from the samples. A) Pellet B) Microbead. C) Fragment. D) Film. E) Fibre. F) Wire.