

Distribution and characteristics of microplastics in the sediments of Poyang Lake, China

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ABSTRACT

Microplastics are considered to be a widespread environmental contaminant, posing a serious threat to the aquatic environment. We addressed this issue based on field observations and laboratory analysis of samples from Poyang Lake. We collected sediment samples from 10 sites across Poyang Lake during 2017. Data were analyzed by one-way analysis of variance (ANOVA). Results showed that the abundance of microplastics ranged from 11 to 3,153 items/kg dw in the sediment samples. Except at Nanjishan, the amount of microplastics in different periods decreased in the order: December > April > July. Microplastics with a size <1 mm were the most abundant fraction in sediments, reaching over 50%. Observations under microscope revealed four types of microplastics in Poyang Lake: fragments, films, foams and fibers. Fragments were more common in sediments. Microplastics have complex surface topography, typically including rough surfaces, porous structures, cracks and extensive damage. Energy dispersive X-ray analysis indicated that most microplastics contained Si, Na, Ca, Cl and Al. Overall, the results provided strong evidence of high levels of microplastics in Poyang Lake, suggested that the microplastics pollution status in Poyang Lake should continue to be monitored.

Key words | abundance, microplastics, pollution, Poyang Lake, sediment

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INTRODUCTION

Millions of metric tons of plastic are produced annually, some of which are released to the environment (Yoshida *et al.* 2016). The longevity of plastic is estimated to be hundreds to thousands of years (Barnes *et al.* 2009). Consequently, plastics accumulate continuously in the environment and become prevalent in aquatic ecosystems across the globe (Rocha-Santos & Duarte 2015). Pollution caused by plastic debris is an urgent environmental problem of growing concern due to its environmental persistence and complexity, as well as the potential for microplastics to introduce toxic chemicals into surface waters and the associated threat to marine wildlife (Lwanga *et al.* 2017; Li *et al.* 2018). An increasing number of marine species are directly impaired by plastics, as they can become entangled in ropes and drown, or ingest plastic debris that may clog their digestive systems (Hämer *et al.* 2014). Given the

increasing use of plastics worldwide, the problems associated with plastic pollution of the environment merit continued scientific investigation.

Plastic debris can fragment in the ocean and then form microscopic particles of plastic, termed 'microplastics' (Cole *et al.* 2015). These microplastics originate from successive degradation of larger plastic debris or can be manufactured as small granules and used in many applications (Sruthy & Ramasamy 2017). Microplastics have been confirmed as an emerging pollutant representing a major environmental problem in recent years (Dehaut *et al.* 2016). Many studies have demonstrated how microplastics have ubiquitously permeated the marine ecosystem, and this issue has received increased attention (Welden & Cowie 2016). Microplastics (<5 mm in size) possess physico-chemical properties (e.g. size, density, color or chemical composition) that promote their bioavailability to aquatic organisms (Rocha-Santos & Duarte 2015): this is one of the primary environmental risks of microplastics (Li *et al.* 2016). A range of marine organisms have been demonstrated to ingest microplastics in mistake for a food source, resulting

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in loss of nutritional value of diet, physical damage, exposure to pathogens and transport of alien species (Cole *et al.* 2015; Sruthy & Ramasamy 2017). In addition, microplastics can adsorb toxic hydrophobic organic contaminants, leading to the question of what risk of chemical exposure is faced by aquatic biota from microplastic-associated contaminants (Beckingham & Ghosh 2017). Moreover, the presence of marine microplastics in seafood could pose a threat to food safety (Cauwenberghe & Janssen 2014). Hence, understanding the sources, abundance, types and composition of microplastics present in the environment is important.

Microplastics have the capability to accumulate in rivers, lakes and the marine environment all over the world, due to properties such as buoyancy and extreme durability (Jungnickel *et al.* 2016). While many studies on microplastics in the marine environment have been carried out, few have considered the freshwater environment (Wang *et al.* 2017a; Li *et al.* 2018), even though freshwater may be an important transport pathway for microplastics (Talvitie *et al.* 2015). So far, only a few studies have provided evidence for the presence of microplastics in rivers and lakes, such that data on their abundance are sparse. Likewise, sources of microplastics and their environmental fate remain to be investigated (Dubaiish & Liebezeit 2013). Numerous peer-reviewed papers have quantified the ingestion of microplastics by marine vertebrates, yet relatively few studies have focused on microplastic ingestion by freshwater organisms (Peters & Bratton 2016). Despite the rising concern about the pollution of freshwater by microplastics, studies of microplastic pollution in the inland freshwaters of China remain insufficient (Wang *et al.* 2017b). Therefore, research on the microplastics pollution status of lakes can address the poorly quantified levels of microplastics pollution in rivers and lakes in China.

Poyang Lake is the largest freshwater lake in China. Five large rivers carry sediments into the lake (Guo *et al.* 2008). In recent years, human activities such as land-use changes have impacted on the freshwater system, resulting in a series of ecological-environmental problems (Ye *et al.* 2013). Large changes in the water level in Poyang lake prolong the sediment discharge time, increasing the risk of pollutant release (Zhao *et al.* 2010). At present, increasing attention is focusing on the ecological security of Poyang Lake; however, microplastics in Poyang Lake have not been studied. Therefore, accurate data on the spatial/temporal distribution of microplastics is an important first step to understand how microplastics might be affecting Poyang Lake.

Based on the current research status of microplastics pollution and the importance of Poyang Lake, this study intended to combine field surveys with laboratory analysis to investigate the microplastics distribution and pollution level in sediments of Poyang Lake. Our results will aid understanding of the scale of the potential effects of microplastics on the environment and organisms. Furthermore, the study provides basic data and information relevant to further investigation of microplastics pollution and its ecological effects.

MATERIALS AND METHODS

Study area and sample collection

Poyang Lake (28°22'–29°45'N and 115°47'–116°45'E) has an average water depth of 8.4 m and a storage capacity of 27.6 billion m³ (Guo *et al.* 2008). Located in the north of Jiangxi Province, Poyang Lake drains through a narrow outlet into the Changjiang (Yangtze River), which is the longest river in China. The five major rivers in Jiangxi flowing into the Poyang Lake are the Xuishui, Ganjiang, Fuhe, Xinjiang, and Raohe. Poyang Lake is well known for its ecological and economic importance as well as its rapid changes in lake surface area throughout the year (Shankman *et al.* 2006). The lake's inundation area often increases between July and September, the so-called flood period, and usually shrinks to form a narrow meandering channel of 1000 km² during the dry period from October to March. The remainder of the year is called the 'normal period'.

In December 2016, samples were collected from 10 locations, chosen for their potential pollution level and geographic region (Figure 1). These sites are representative of the five large rivers that carry sediments into the lake. Site 1 was at the tributary of Xuishui; Sites 2–4 were at the tributary of three branches of Ganjiang; Site 7 was located at the source of Raohe; Site 8 was located in the upstream reaches of Raohe, at the Dexing Copper Mine; Sites 5, 6 and 9 were the tributaries of Fuhe, Xinjiang and Raohe. Site 10 was located in the Najishan National Nature Reserve. In April and July 2018, Sites 1–2, 5–6 and 9–10 were sampled again. Sites 1–10 are referred to as S1–S10 hereon in.

At each site, three 50 cm × 50 cm quadrants were randomly selected along the river bank and the sediments were collected from the top 2 cm using a shovel. The sediments were kept in a plastic bag as one complete sample from each site and brought to the laboratory as soon as

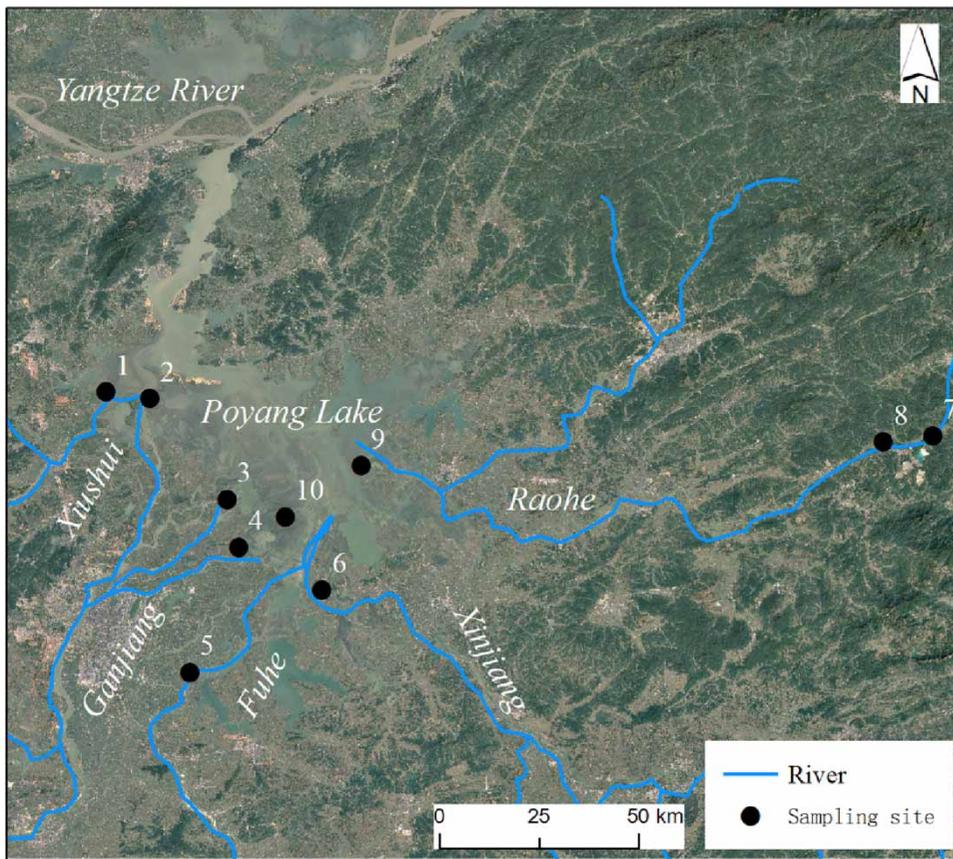


Figure 1 | Field sampling sites in Poyang Lake.

possible, where they were then air dried in white dissecting trays until analysis, with covers to avoid contamination. Sampling containers used in the field were plastic; however, precautions were taken so that all equipment was rinsed three times with filtered tap water.

Microplastics extraction and measurement

In the laboratory, extraction of plastic particles was achieved by density separation using a saturated NaCl (1.5 g cm^{-3}) solution as the density-controlled liquid (Kunz et al. 2016). The dry samples were transferred to a glass beaker for density separation, then the salt solution was added and the sample was magnetically stirred for 2 min. After the sediment had settled, the supernatant was carefully poured through a sieve with $2 \mu\text{m}$ mesh size. The sediment samples were separated into the size fractions of 4.0–5.0, 3.0–4.0, 2.0–3.0, 1.0–2.0 and <1.0 mm. Materials retained on the mesh were examined by naked eye for potential microplastics or under a stereomicroscope to select suspected microplastics (0.002–5 mm in size).

At present, combinations of physical (e.g. microscopy) and chemical (e.g. spectroscopy) analyses are widely used (Shim et al. 2017). The membrane and the material retained on the sieves were dried and observed under Metallographic microscope (Shanghai Precision Instrument Company) to select plastic fragments. All particles were photographed using a Nikon digital camera DXM1200F connected to the microscope. A desktop scanning microscope (S-3400N, Hitachi Electronics, Japan) with 5–3000 \times magnification was used to observe the morphology of microplastics.

Data analysis

We used the PROC UNIVARIATE procedure to test the normality of the data and PROC TTEST procedure to test for homogeneity in the variances. Duncan's multiple-range test was used to perform multiple comparisons and evaluate whether the microplastics abundance significantly differed between different sites and seasons. The level of significance was set to $P < 0.05$. All statistical analyses were performed in SPSS v.20.

RESULTS AND DISCUSSION

The distribution of microplastics in sediment of Poyang Lake

Spatial distribution of microplastics in sediment

The spatial distribution of microplastics in Poyang Lake sediment showed marked spatial variability (Figure 2(a)). Microplastics abundance at Nanjishan and Wucheng were significantly lower than those at other sites. The abundance of microplastics had an average of 1134 items/kg dw (dry weight) and ranged from 11 items/kg dw (where Ganjiang

and Xiushui reach Poyang Lake) to 3153 items/kg dw (in the upper Raohe near the Dexing copper mines) (Figure 2(b)).

Previous studies have found microplastics in sediments with mean abundances varying from 112 (Lake Bolsena) to 234 particles/kg dw (Lake Chiusi) in central Italy (Fischer *et al.* 2016). Microplastic particles are present at up to 4000 particles/kg dw in river shore sediments of the rivers Rhine and Main in the Rhine-Main area in Germany (Klein *et al.* 2015). Esiukova (2017) showed that microplastics content ranged between 1.3 and 36.3 items/kg dw in sediment along the Russian coast. The average abundance of microplastics in local coastal sediments respectively ranged from 49 to 279 particles/kg dw in Hong Kong coastal regions (Tsang *et al.* 2017). Microplastic particles were found in all samples of bottom sediments of the Russian part of the Baltic Sea, with an average concentration of 34 ± 10 items/kg dw (Zobkov & Esiukova 2017). The abundances of microplastics reached 11.0–234.6 items/kg dw in sediments in Taihu Lake (Lei *et al.* 2016). These results demonstrate that microplastics pollution is a global issue. We found that the average abundance of microplastics ranged from 11 to 3153 items/kg dw in sediment from Poyang Lake, thereby demonstrating that microplastics pollution in Poyang Lake merits our attention. The wide variability in sediment microplastics abundances between different studies may be due to the different sampling depths, sampling locations, number of repeat extractions, and settling times (Besley *et al.* 2016).

We found the most abundant microplastics (3,153 items/kg dw) near the Dexing Copper mines, which was consistent with the higher content of toxic elements. Previous research has revealed a relatively strong, significant linear relationship between microplastic quantities and potentially toxic element/polycyclic aromatic hydrocarbon concentrations in coastal sediments (Akhbarizadeh *et al.* 2017). Ongoing studies are continuing to address this relationship. We found less abundant microplastics in Nanjishan and Wucheng, probably due to their lower levels of human activity. Nanjishan and Wucheng are well known national nature reserves, and as such are less disturbed by human activity. Many studies have found that that microplastics abundance is related to the proximity of densely populated areas and inputs from river estuaries (Frias *et al.* 2014; Lima *et al.* 2015; Alomar *et al.* 2016; Nel *et al.* 2017; Wang *et al.* 2017b).

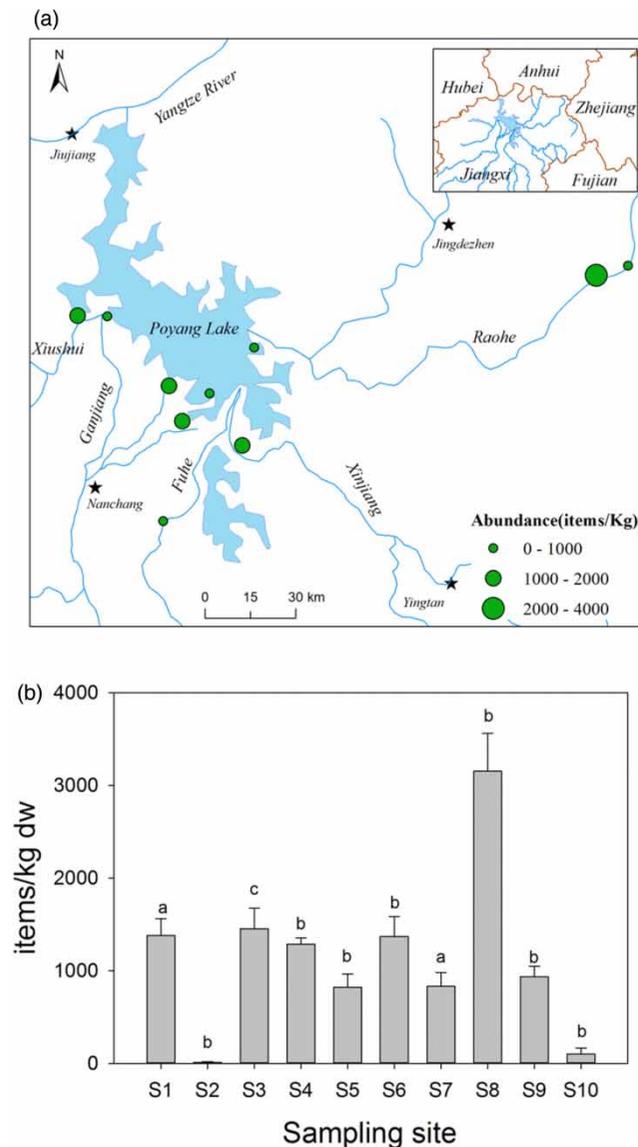


Figure 2 | Spatial distribution of microplastics in sediment samples collected from Poyang Lake in December 2016.

Temporal changes in microplastics in sediment

The microplastics' abundance during the dry period was significantly higher than those of the normal and flood periods

Table 1 | Microplastics abundance in sediment of different sampling sites and seasons

Sampling period	Sampling sites					
	Nanji	Xiushui	Ganjiang (middle tributary)	Fuhe	Xinjiang	Raohe
April	14 ± 24 ^a	843 ± 50 ^a	1396 ± 286 ^{a,b}	659 ± 103 ^a	842 ± 206 ^a	624 ± 62 ^a
July	48 ± 18 ^a	746 ± 126 ^a	1033 ± 247 ^a	512 ± 75 ^a	776 ± 67 ^a	478 ± 64 ^a
December	102 ± 65 ^a	1452 ± 221 ^b	1936 ± 88 ^b	821 ± 142 ^a	882 ± 375 ^a	937 ± 112 ^b

Data are indicated by the mean ± s.d of microplastics abundance. Different letters (a and b) in the same column indicate significant differences among different sampling periods (Duncan's test, $P < 0.05$).

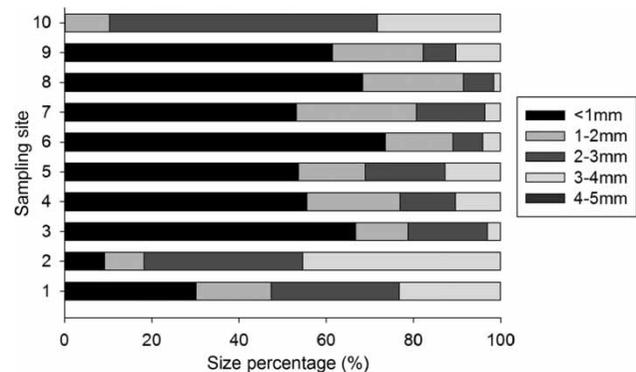
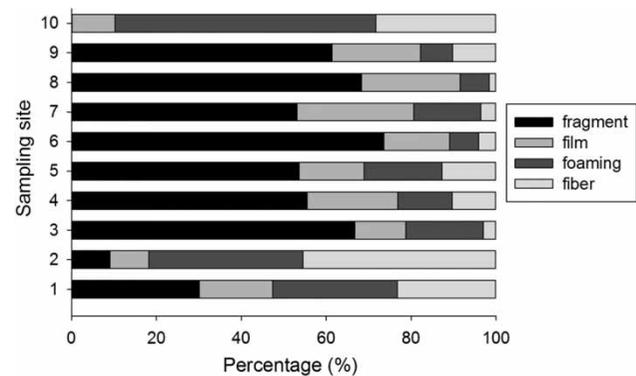
in Xiushui, Ganjiang and Raohe ($P < 0.05$). The other three sites also showed higher microplastics abundance during the dry period, but the differences were not significant. Except at Nanjishan, the microplastics abundances decreased in the order: dry period > normal period > flood period (Table 1). Our study showed that the microplastics abundance in Poyang Lake was higher in December than in April or July. Similarly, Aytan *et al.* (2016) reported that the average microplastics concentration in the Black Sea in November was higher than in February. Veerasingam *et al.* (2016) showed that the abundance of microplastics in November 2015 was threefold higher than that in March 2015. The highest abundance of microplastics was observed during the late rainy season, when large quantities of fresh microplastics were washed into rivers from the land during floods (Lima *et al.* 2015).

Grain size and types of microplastics in Poyang Lake sediments

Microplastics had grain sizes >1 mm in Nanjishan. At the other sampling sites, microplastics of size <1 mm were the most abundant, and exceeded 50%. The 1–2 mm fraction was the second most abundant. Overall, the microplastics abundance decreased with increasing grain size, except at Nanjishan (Figure 3).

Observations under the microscope revealed four types of microplastics in Poyang Lake: fragments, films, fibers and foam. Fragments were the most common type, except at Nanjishan, accounting for 30–74% of microplastics. In Nanjishan, foam was the most dominant component with a proportion of 61% (Figure 4).

Our results showed that fragments were the most common particle type in the sediments of Poyang Lake, and that particle sizes <1 mm were the most common size fraction. Lei *et al.* (2016) showed that the microplastics were dominated by fibers, of 0.01–1 mm in size in Taihu Lake. Fragment type microplastics were more common in Marine Protected Areas and microplastics were always

**Figure 3** | Composition of microplastics grain sizes at different sampling sites of Poyang Lake.**Figure 4** | Composition of microplastics shape in different sampling sites of Poyang Lake.

present from 0.5 mm to 2 mm (Alomar *et al.* 2016). The prevalent type was foamed plastic (range 0.5–5 mm) along the Russian coast (Esiukova 2017). The most frequent microplastics dimensions ranged from 0.1 to 2.0 mm, and transparent fibers were predominant in beach sediments of the Southern Baltic Sea (Graca *et al.* 2017). The microplastic particles were primarily fibers and fragments <2 mm in size in Canadian Lake Ontario (Ballent *et al.* 2016). Evidently, different types of microplastics were found in different areas, and were most commonly in the size fraction <2 mm. Fragments were the most abundant types of microplastics identified in the Poyang Lake, indicating that the

main source of microplastics was from secondary sources included broken down plastic litter and debris.

Microstructure of microplastics in Poyang Lake sediments

Scanning electron microscopy (SEM) coupled with an energy dispersive X-ray (EDX) unit was used to investigate the surface

morphology and oxidative and mechanical weathering textures of collected microplastics. SEM images revealed different surface roughness in different microplastics, showing that the microplastics have complex surface topography characteristics generally characterized as rough, porous, cracked or badly damaged. Fragmented microplastics were observed with various colors and morphological diversity; surfaces were rough or uneven with obvious wear marks at the ends (Figure 5(a)).

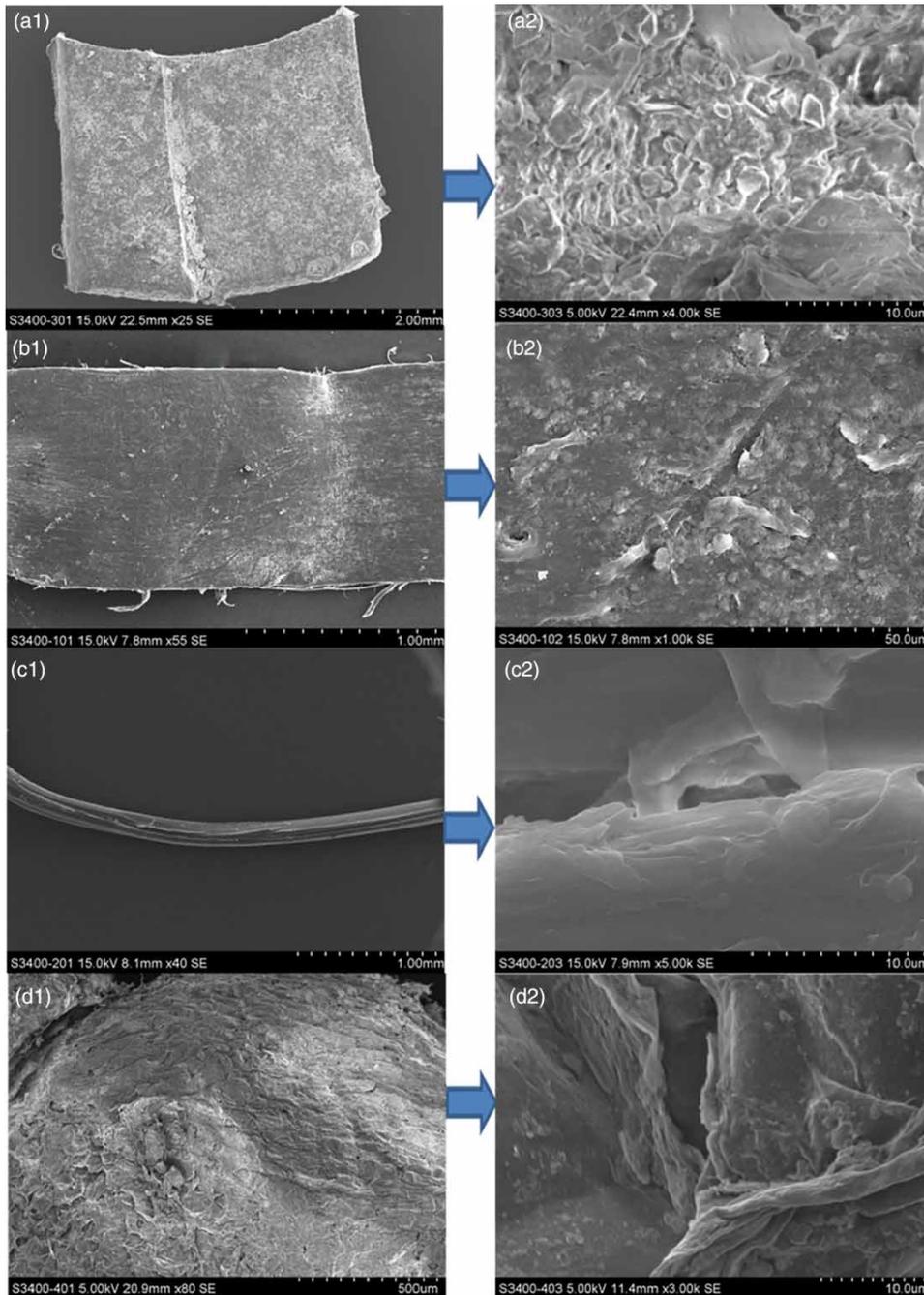


Figure 5 | SEM images of four collected types of microplastics (a: fragments, b: films, c: fibers, d: foam). Please refer to the online version of this paper to see this figure in color: <http://dx.doi.org/10.2166/wst.2019.185>.

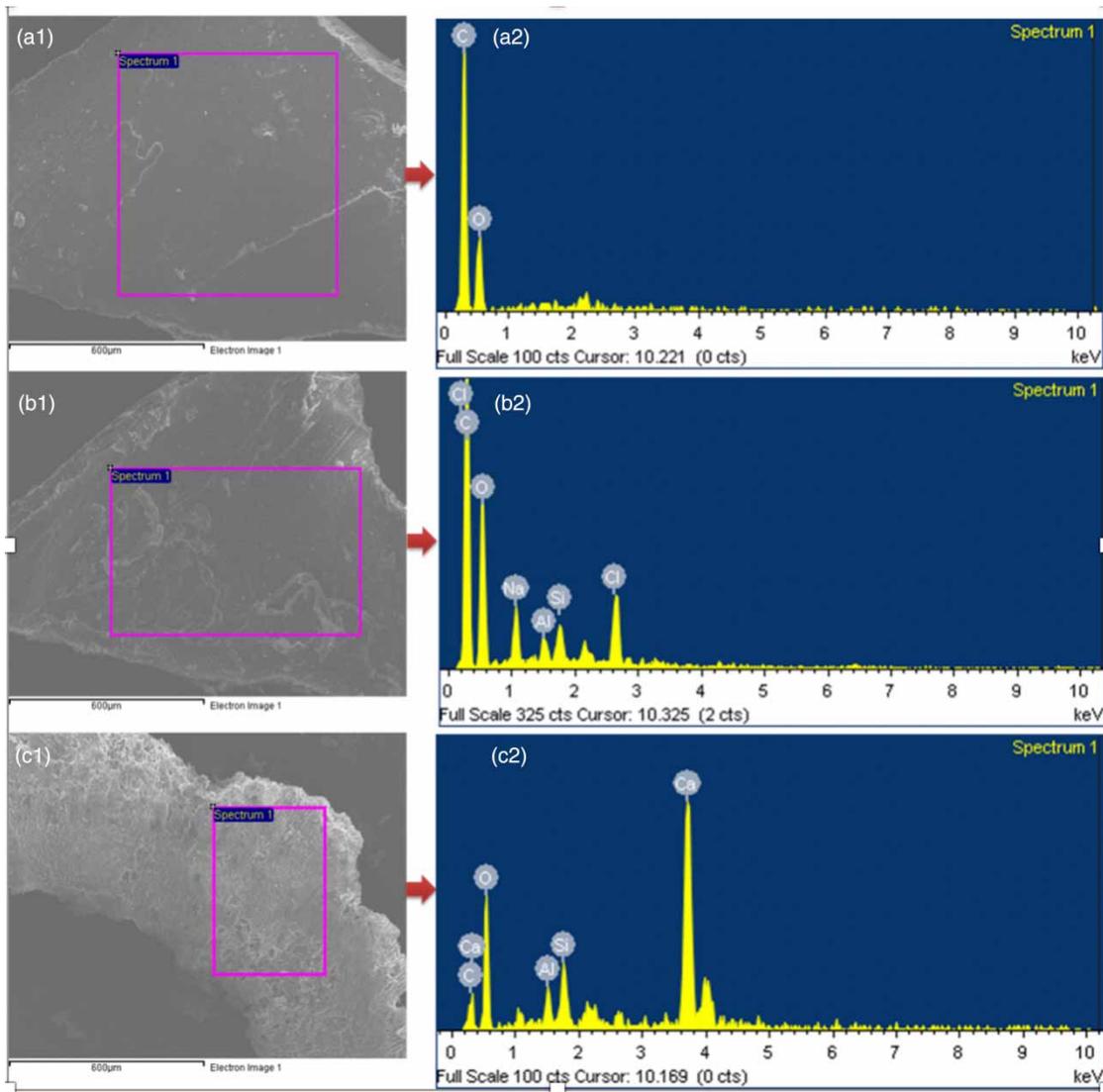


Figure 6 | EDX of collected fragment microplastics damaged to different degrees (a: smooth, b: slightly damaged, c: severely damaged).

Film microplastics comprised irregular films with light and soft textures (Figure 5(b)). Most fibers displayed a smooth surface, linear shape, and were blue in color (Figure 5(c)). Foam microplastics were white and had various shapes (Figure 5(d)).

The EDX analysis indicated that most microplastics contained Si, Na, Ca, Cl and Al. Silicon was mainly present in the form of SiO_2 , and other detected trace elements were probably adsorbed to the microplastics. The plastic fragments with smooth surfaces have weak adhesion ability, while those with serious damage have stronger adhesion ability (Figure 6).

Our results showed that the microplastics have complex surface topography characteristics, and are generally

characterised by rough, porous, cracked and badly damaged surfaces. These images were due to weathering degradation of plastics on the banks, which results in embrittlement of their surfaces and microcracking, yielding microparticles that are carried into the water by wind or wave action (Andrady 2011). Morphological features suggest that microplastics are derived from the breakdown of typical plastic products in daily application.

The EDX analysis indicated that some elements carried by microplastics were not inherent but were derived from the environment. Moreover, microplastics pose a threat to coastal environments due to their capacity to adsorb metal elements. Several metals (Ni, Cd, Pb, Cu, Zn and Ti) have been found in microplastics even after ultrasonic cleaning

(Wang *et al.* 2017a). Therefore, these particles are potentially dangerous to marine species due to their risk of magnification up the food chain. These will be further studied in our future work.

Outlook of microplastics pollution

Annual plastic production has surpassed the 300 million tons mark and the global presence of microplastics in the aquatic ecosystems has emerged as a high-profile contaminant issue (Mintenig *et al.* 2017). To date, recycling has largely failed as a viable solution for the disposal of plastic waste. Environmental conservation agencies are gaining a better understanding of the issue and are beginning to implement strategies to reduce microplastic contamination (Helm 2017). The results have many applications, including informing clean-up efforts, helping to target pollution prevention, and understanding the inter-state or international flows of plastic pollution. Furthermore, an important contribution to reducing entanglements can be the development of education programs promoting effective communication. Replacement of the current materials used in daily life with biodegradable materials could also be a recommended mitigation measure.

CONCLUSIONS

Microplastics pollution has become an urgent problem that may have significant and long-term effects on the environment; in particular, on aquatic ecosystems. This study was designed to investigate the characteristics of microplastics pollution in sediment in Poyang Lake. By analysing sediment samples from 10 sites in the lake, we revealed serious microplastics pollution in some parts of Poyang Lake. These results suggest that reducing human activities could aid remediation of the microplastics pollution in Poyang Lake. This work has established a database of microplastics in the Poyang Lake, and its findings are important for better informing researchers in future studies and as a basis for managerial actions. Further studies are required to investigate the effects of microplastics pollution on heavy metals in Poyang Lake.

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REFERENCES

- Akhbarizadeh, R., Moore, F., Keshavarzi, B. & Moeinpour, A. 2017 Microplastics and potentially toxic elements in coastal sediments of Iran's main oil terminal (Khark Island). *Environmental Pollution* **220**, 720–731.
- Alomar, C., Estarellas, F. & Deudero, S. 2016 Microplastics in the Mediterranean Sea: deposition in coastal shallow sediments, spatial variation and preferential grain size. *Marine Environmental Research* **115**, 1–10.
- Andrady, A. L. 2011 Microplastics in the marine environment. *Marine Pollution Bulletin* **62** (8), 1596–1605.
- Aytan, U., Valente, A., Senturk, Y., Usta, R., Sahin, F. B. E., Mazlum, R. E. & Agirbas, E. 2016 First evaluation of neustonic microplastics in Black Sea waters. *Marine Environmental Research* **119**, 22–30.
- Ballent, A., Corcoran, P. L., Madden, O., Helm, P. A. & Longstaffe, F. J. 2016 Sources and sinks of microplastics in Canadian Lake Ontario nearshore, tributary and beach sediments. *Marine Pollution Bulletin* **110** (1), 383–395.
- Barnes, D. K. A., Galgani, F., Thompson, R. C. & Barlaz, M. 2009 Accumulation and fragmentation of plastic debris in global environments. *Philosophical Transactions of the Royal Society of London* **364** (1526), 1985–1998.
- Beckingham, B. & Ghosh, U. 2017 Differential bioavailability of polychlorinated biphenyls associated with environmental particles: microplastic in comparison to wood, coal and biochar. *Environmental Pollution* **220**, 150–158.
- Besley, A., Vijver, M. G., Behrens, P. & Bosker, T. 2016 A standardized method for sampling and extraction methods for quantifying microplastics in beach sand. *Marine Pollution Bulletin* **114**, 77–83.
- Cauwenberghe, L. V. & Janssen, C. R. 2014 Microplastics in bivalves cultured for human consumption. *Environmental Pollution* **193C**, 65–70.
- Cole, M., Lindeque, P., Fileman, E., Halsband, C. & Galloway, T. S. 2015 The impact of polystyrene microplastics on feeding, function and fecundity in the marine copepod *Calanus helgolandicus*. *Environmental Science & Technology* **49** (2), 1130.
- Dehaut, A., Cassone, A. L., Frère, L., Hermabessiere, L., Himber, C., Rinnert, E., Rivière, G., Lambert, C., Soudant, P. & Huvet, A. 2016 Microplastics in seafood: benchmark protocol for their extraction and characterization. *Environmental Pollution* **215**, 223–233.
- Dubaish, F. & Liebezeit, G. 2013 Suspended microplastics and black carbon particles in the jade system, Southern North Sea. *Water Air & Soil Pollution* **224** (2), 1–8.
- Esiukova, E. 2017 Plastic pollution on the Baltic beaches of Kaliningrad region, Russia. *Marine Pollution Bulletin* **114** (2), 1072–1080.

- Fischer, E. K., Paglialonga, L., Czech, E. & Tamminga, M. 2016 Microplastic pollution in lakes and lake shoreline sediments - a case study on Lake Bolsena and Lake Chiusi (central Italy). *Environmental Pollution* **213**, 648–657.
- Frias, J. P. G. L., Otero, V. & Sobral, P. 2014 Evidence of microplastics in samples of zooplankton from Portuguese coastal waters. *Marine Environmental Research* **95** (4), 89–95.
- Graca, B., Szewc, K., Zakrzewska, D., Dolega, A. & Szczerbowska-Boruchowska, M. 2017 Sources and fate of microplastics in marine and beach sediments of the Southern Baltic Sea – a preliminary study. *Environmental Science and Pollution Research* **24** (8), 7650–7661.
- Guo, H., Hu, Q. & Jiang, T. 2008 Annual and seasonal streamflow responses to climate and land-cover changes in the Poyang Lake basin, China. *Journal of Hydrology* **355** (1–4), 106–122.
- Hämer, J., Gutow, L., Köhler, A. & Saborowski, R. 2014 Fate of microplastics in the marine isopod *Idotea emarginata*. *Environmental Science & Technology* **48** (22), 13451–13458.
- Helm, P. A. 2017 Improving microplastics source apportionment: a role for microplastic morphology and taxonomy? *Analytical Methods* **9** (9), 1328–1331.
- Jungnickel, H., Pund, R., Tentschert, J., Reichardt, P., Laux, P., Harbach, H. & Luch, A. 2016 Time-of-flight secondary ion mass spectrometry (ToF-SIMS)-based analysis and imaging of polyethylene microplastics formation during sea surf simulation. *Science of the Total Environment* **563–564**, 261–266.
- Klein, S., Worch, E. & Knepper, T. P. 2015 Occurrence and spatial distribution of microplastics in river shore sediments of the Rhine-Main Area in Germany. *Environmental Science & Technology* **49** (10), 6070–6076.
- Kunz, A., Walther, B. A., Löwemark, L. & Lee, Y. C. 2016 Distribution and quantity of microplastic on sandy beaches along the northern coast of Taiwan. *Marine Pollution Bulletin* **111**, 126–135.
- Lei, S., Xue, Y., Li, L., Yang, D., Kolandhasamy, P., Li, D. & Shi, H. H. 2016 Microplastics in Taihu Lake, China. *Environmental Pollution* **216**, 711–719.
- Li, J., Qu, X., Lei, S., Zhang, W., Yang, D., Kolandhasamy, P., Li, D. J. & Shi, H. H. 2016 Microplastics in mussels along the coastal waters of China. *Environmental Pollution* **214**, 177–184.
- Li, J., Liu, H. & Chen, J. 2018 Microplastics in freshwater systems: a review on occurrence, environmental effects, and methods for microplastics detection. *Water Research* **137**, 362–374.
- Lima, A. R. A., Barletta, M. & Costa, M. F. 2015 Seasonal distribution and interactions between plankton and microplastics in a tropical estuary. *Estuarine Coastal & Shelf Science* **165**, 213–225.
- Lwanga, E. H., Gertsen, H., Gooren, H., Peters, P., Salanki, T., van der Ploeg, M., Besseling, E., Koelmans, A. A. & Geissen, V. 2017 Incorporation of microplastics from litter into burrows of *Lumbricus terrestris*. *Environmental Pollution* **220**, 523–531.
- Mintinig, S. M., Int-Veen, I., Loder, M. G. J., Primpke, S. & Gerdtts, G. 2017 Identification of microplastic in effluents of waste water treatment plants using focal plane array-based micro-Fourier-transform infrared imaging. *Water Research* **108**, 365–372.
- Nel, H. A., Hean, J. W., Noundou, X. S. & Froneman, P. W. 2017 Do microplastic loads reflect the population demographics along the southern African coastline? *Marine Pollution Bulletin* **115** (1–2), 115–119.
- Peters, C. A. & Bratton, S. P. 2016 Urbanization is a major influence on microplastic ingestion by sunfish in the Brazos River Basin, Central Texas, USA. *Environmental Pollution* **210**, 380–387.
- Rocha-Santos, T. & Duarte, A. C. 2015 A critical overview of the analytical approaches to the occurrence, the fate and the behavior of microplastics in the environment. *TrAC Trends in Analytical Chemistry* **65** (3), 47–53.
- Shankman, D., Keim, B. D. & Song, J. 2006 Flood frequency in China's Poyang Lake region: trends and teleconnections. *International Journal of Climatology* **26** (9), 1255–1266.
- Shim, W. J., Hong, S. H. & Eo, S. E. 2017 Identification methods in microplastic analysis: a review. *Analytical Methods* **9** (9), 1384–1391.
- Sruthy, S. & Ramasamy, E. V. 2017 Microplastic pollution in Vembanad Lake, Kerala, India: the first report of microplastics in lake and estuarine sediments in India. *Environmental Pollution* **222**, 315–322.
- 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 Science & Technology A Journal of the International Association on Water Pollution Research* **72**, 1495–1504.
- Tsang, Y. Y., Mak, C. W., Liebich, C., Lam, S. W., Sze, E. T. P. & Chan, K. M. 2017 Microplastic pollution in the marine waters and sediments of Hong Kong. *Marine Pollution Bulletin* **115** (1–2), 20–28.
- Veerasingam, S., Mugilarasan, M., Venkatachalapathy, R. & Vethamony, P. 2016 Influence of 2015 flood on the distribution and occurrence of microplastic pellets along the Chennai coast, India. *Marine Pollution Bulletin* **109** (1), 196–204.
- Wang, J. D., Peng, J. P., Tan, Z., Gao, Y. F., Zhan, Z. W., Chen, Q. Q. & Cai, L. Q. 2017a Microplastics in the surface sediments from the Beijiang River littoral zone: composition, abundance, surface textures and interaction with heavy metals. *Chemosphere* **171**, 248–258.
- Wang, W. F., Ndungu, A. W., Li, Z. & Wang, J. 2017b Microplastics pollution in inland freshwaters of China: a case study in urban surface waters of Wuhan, China. *Science of the Total Environment* **575**, 1369–1374.
- Welden, N. A. & Cowie, P. R. 2016 Environment and gut morphology influence microplastic retention in langoustine, *Nephrops norvegicus*. *Environmental Pollution* **214**, 859–865.
- Ye, X., Zhang, Q., Liu, J., Li, X. & Xu, C. 2013 Distinguishing the relative impacts of climate change and human activities on variation of streamflow in the Poyang Lake catchment, China. *Journal of Hydrology* **494**, 83–95.

- Yoshida, S., Hiraga, K., Takehana, T., Taniguchi, I., Yamaji, H., Maeda, Y., Toyohara, K., Miyamoto, K., Kimura, Y. & Oda, K. 2016 [A bacterium that degrades and assimilates poly\(ethylene terephthalate\)](#). *Science* **351** (6278), 1196–1199.
- Zhao, G., Hörmann, G., Fohrer, N., Zhang, Z. & Zhai, J. 2010 [Streamflow trends and climate variability impacts in Poyang Lake Basin, China](#). *Water Resources Management* **24** (4), 689–706.
- Zobkov, M. & Esiukova, E. 2017 [Microplastics in Baltic bottom sediments: quantification procedures and first results](#). *Marine Pollution Bulletin* **114** (2), 724–732.

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