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Coastal Lakes as a Buffer Zone for the Accumulation and Redistribution of Plastic Particles from Continental to Marine Environment: A Case Study of the Dishui Lake in Shanghai, China

Yan Liu and Jiasong Fang *

Hanghai Engineering Research Center of Hadal Science and Technology, College of Marine Sciences, Shanghai Ocean University, Shanghai 201306, China; liuyan_shou@126.com

* Correspondence: jsfang@shou.edu.cn

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Abstract: Microplastics, as an emerging environmental contaminant, have attracted increasing attention worldwide. Previous studies have addressed this environmental problem in either the marine or continental environment, but ignored the water bodies in between. Coastal lakes are transitional aquatic systems and may play an important role in transport, reworking and redistribution of plastics across catchment scale. Here, we report results of our investigation of plastic pollution in sediment of a coastal lake, the Dishui Lake, in Shanghai, China. The lake is located in coastal Shanghai and connected to the East China Sea via a 7-km long canal. Sediment samples were collected from around the lake and the canal. Plastic particles were detected in the sediment with various shapes, colors and compositions. The total particle count in the canal sediment was orders of magnitude higher than in the lake sediment. Polypropylene was the dominant polymer in the sediment. Our results suggest that coastal lakes can serve as a reworking zone for accumulation and reworkings of plastic particles, and a buffer zone contributing to plastic pollution in the marine environment. This study addresses the most understudied area of plastic pollution, i.e., reworking and redistribution of plastic debris at catchment scale across the marine and continental environment.

Keywords: microplastics; Dishui Lake; East China Sea; sediment; mesoplastics; macroplastics; buffer zone

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1. Introduction

Plastic is one of the most widely used materials in modern society. The production of plastics has increased annually from 0.5 million tons in 1950 to 330 million tons in 2016 [1]. However, the legacy has now become an intractable problem. The use and abuse of plastics caused serious white pollution worldwide [2,3]. According to the ministerial declaration adopted by the United Nations Environment Assembly, plastic waste entering the ocean from land sources was 4.8–12.7 metric tons annually in 2017 [4]. Plastics, as a new type of emerging contaminant in the marine environment, have attracted ever-increasing attention of the scientific community, environmental policy makers, and the society as a whole [5].

Plastics can be divided to micro-, meso- and macroplastics with diameter, respectively, <5, 5–20 and >20 mm [6,7]. Because of their large specific surface area, it is easy for plastics to adsorb chemical contaminants in water, such as persistent organic pollutants (POPs), metals, etc., and play an important role in contaminant transport across ecosystems [8,9]. Thus, the combined toxicity of plastic particles and the absorbed pollutants is currently a hot research topic [10–14]. Meanwhile, the environmentally harmful additives like plasticizers, UV stabilizers, flame retardant, etc., which are added to improve plastic properties, would release to the environment [15–18]. Furthermore, plastic particles could migrate in the food chain [19]. Thus, plastics can act as a powerful carrier for the transport of chemical contaminants in the environment through the food chain and eventually reach the human body [20–24]. Plastic particles, especially micoplastics, are now found almost everywhere worldwide, from the polar regions to the deepest part of the ocean—the Challenger Deep of the Mariana Trench [25–30], and even in the air that we breathe [31].

At present, most of the research has focused on marine microplastic pollution. In fact, anthropogenic stress, including plastic pollution, has also caused huge irreversible changes in rivers [32]. Research on plastics in continental environments is increasing in recent years [33]. However, most of those studies are directed on large water bodies. Eriksen et al. (2013) studied plastics in the Great Lakes of the United States and found that lake water had a very high concentration of microplastics (average concentration of 43,000 particles per km^{-2}), and lakes in densely populated areas contained higher concentrations of microplastics than in remote areas [34]. Urban rivers, such as the Danube River [35] and the Rhine River [36], had plastics pollution in varying degrees. Furthermore, inland rivers with sparse population density, such as the Qinghai-Tibet Plateau (China), cannot avoid plastic intrusion [37]. The distribution of plastics in inland rivers and lakes is inseparable from the development of urbanization, from sewage discharge, surface runoff, littering, and atmospheric deposition [38,39].

Although results of these past studies have increased our understanding of microplastics in the marine and continental environments, knowledge gaps remain as to the role of aquatic systems in the transitional zone between the two environments, in the accumulation, reworking, redistribution, and transport of plastics to the marine environment. Currently, there is limited understanding on fate and behavior of plastic particles across the freshwater-saltwater bodies and their potential contribution of plastic debris to the marine environment. We hypothesize that coastal lakes, located between and connected with the continental and marine environments, can act as a buffer zone in reprocessing and redistribution of plastic particles at catchment scale across ecosystems. In this study, we sampled a coastal lake in southeast Shanghai—the Dishui Lake. The lake is an ideal aquatic system to test our hypothesis as it is located in coastal Shanghai, with the Dazhi River emptying into it on the north and the Chifenggang Canal on the south, connecting the lake and East China Sea (ECS). We determined the abundance and characteristics of plastics in surface sediment of the lake and the canal. The lake as a source, a sink, and a buffer zone for reworking and redistribution of all three sizes of plastics is discussed.

2. Methods

2.1. Sampling Area

The Dishui Lake is located in the southeast corner of Shanghai, China (Figure 1). It is the central lake of the Nanhui New Town, a population center in the area. The lake plays an important role in the development of this area [40]. The lake is an artificial lake, connected to the East China Sea (ECS) by a 7-km canal, the Chifenggang Canal. This canal is cut off from the East China Sea by the Nanhuizui Gate, which is regularly opened to release lake water into the East China Sea. The lake has a total area of about 5.56 km^2 and a water storage capacity of approximately 16.2 million m^3 (https://baike.so.com/doc/5337898-5573337.html). The Dazhi River, a tributary of the Huangpu River which runs through the center of Shanghai, discharges into the lake in the north (Figure 1). The lake is 2.6 km in diameter and has a maximum depth of approximately 6.2 m. At present, the southwest side of the lake is more populated than the other sides, which are either cultivated areas or under urban constructions.

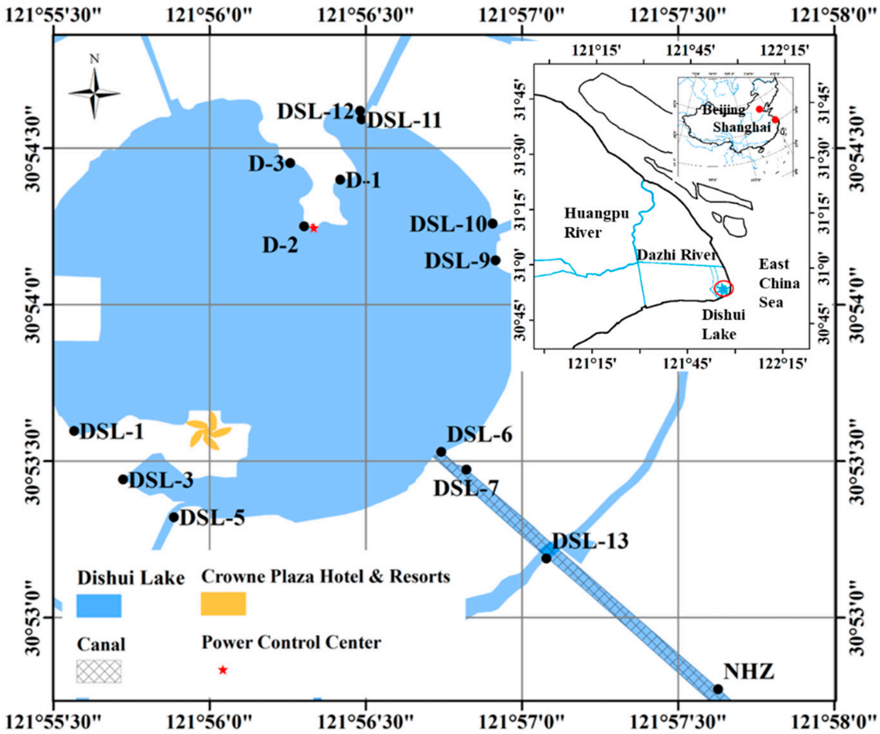

Figure 1. Map showing sampling sites in the Dishui Lake.

2.2. Sampling Sites and Methods

Fourteen sediment samples were collected in March and May 2019, at sites in the southwest side, the north side where the Dazhi River empties into the lake, and the southeast side along the Chifenggang canal which connects the lake to the ECS (Figure 1). At each site, the top 1–2 cm of sediment was collected, carefully wrapped with aluminum foil, and kept in polyethylene bags. The aluminum foil was pre-combusted in a muffle furnace at 450 °C for 4 h. All samples were taken to the lab and stored at −20 °C until analysis.

2.3. Density Separation of Plastic Particles

The method of extracting plastic particles from the sediment was adopted from Thompson et al. (2004) [6] with modifications. The sediment samples were first dried using a freeze-dryer. Then the dried sediment samples were poured into a porcelain mortar and mixed with a pestle. About 100 g of each sample were taken and passed through a 10-mesh metal sieve to remove mesoplastics and macroplastics for separate analysis. The sieved sediment was used for extracting microplastic particles as described below.

At the present, the common practice is to digest sediment samples to remove organic matter before extracting microplastics. Sediment is typically treated with acids (HNO_3, HCl, HNO_3, $HClO_4$) or hydrogen peroxide (H_2O_2, 30%). According to previous studies, these treatments could cause plastic fading and digestion and may underestimate the abundance of plastics [41,42]. Therefore, we utilized a floatation method for extracting plastics from the sediment. However, it must be noticed that certain plastics with a density higher than that of the saturated NaCl solution would hardly be suspended and extracted by this method.

For floatation, we first prepared a saturated solution of sodium chloride (NaCl, Sangon Biotech, China). The saturated NaCl solution was filtered through a glass fiber filter. The solution (1.2 g mL^{-1}) was poured into beakers that contained sediments and then stirred manually with a clean glass rod for 2 min. The volume of the floatation solution was more than 3 times that of the sediment. The mixture was allowed to stand for 24 h at room temperature on a super clean bench. The supernatant was transferred to a beaker (pre-combusted at 450 °C for 4 h). This procedure was repeated 3 times. Eventually, the supernatant collected was filtered through a Whatman GF/A filter under vacuum. The microplastics retained on the filters were collected.

2.4. Identification of Plastics

Plastic particles retained on filters were observed by a microscope (Nikon, SMZ25/SMZ18, Tokyo, Japan). Each filter was observed at least 3 times. Microplastic items were identified based on size, color, and shape, and recorded. Some relatively large microplastics (>1 mm) can be distinguished [43] if (1) no visible cellular or organic structures were seen on the microplastics, (2) the entire fiber had equal thickness, and (3) the particles had clear and homogeneous colors.

All plastic particles were photographed by a microscope and then classified by size, color, and shape. The composition and polymer type of all collected particles including micro-, meso- and macroplastic were identified by a Fourier Transform Infrared Spectrometer (FT-IR, Thermo Fisher Nicolet^{TM} In^{TM}10, Madison, WI, USA) and the transmission mode was used. The test result with more than 70% confidence matching with the FT-IR library was considered to be a plastic polymer [44].

2.5. Quality Assurance and Control

The sample-takers wore cotton clothes when they were taking samples from the lake. Plastic tools were avoided during experiments. The glass containers and glass fiber filters were combusted at 450 °C for 4 h prior to use. All the liquids, including nanopure water and the prepared NaCl solutions, were filtered before use (Whatman GF/A, $\varphi = 1.6$ μm). All the tools that could not be pre-combusted at 450 °C were rinsed three times with filtered nanopure water. A blank control was set in every batch of samples (5 samples per batch). All experiments were performed on a clean bench.

3. Results

3.1. Composition, Abundance, and Distribution of Microplastics in the Lake Sediment

No plastic particles were found in procedure blanks, suggesting that the detected plastic debris were all from the sediment samples. Microplastics were found at all sites except at sites DSL-9, DSL-11, DSL-12, D-1, and D-3. The abundance and distribution of microplastics is shown in Figure 2. The sampling sites were grouped as around the lake sites (ALS, 11 sites) and the canal sites (TCS, 3 sites). Average microplastic concentration at the TCS sites (230 items kg^{-1} d.w.s., dry weight sediment) was much higher than at the ALS sites (46 items kg^{-1} d.w.s.). The three ALS sampling sites (DSL-1, DSL-3, DSL-5) close to the populated towns on the west of the lake had higher concentrations of microplastics than sites on the eastern and northern sides of the lake. Site D-2, located close to a power supply control center on the north side of the lake, had the highest level among all the ALS sites, 221 items kg^{-1} d.w.s. At the TCS sites, the highest concentration was detected at site DSL-13 in the middle of the canal, 340 items kg^{-1} d.w.s., followed by site NHZ at the junction point between the canal and ECS, 280 items kg^{-1} d.w.s.

The physical characteristics of the microplastics are shown in Figure 3. The color, shape, and its composition are important factors in pinpointing the source of the plastic. Among the detected microplastic debris, white microplastics accounted for the majority (54%), followed by blue (30%) and green pieces (13%). In addition, small amounts of yellow (2%) and orange (1%) pieces were also detected in the sediments. Line microplastics (22%) were most widely distributed, in all 10 sampling sites except site D-2. Some of the line microplastics can be identified as fishing line. However, the highest concentration was observed for sheet microplastics (53%), particularly DSL-13 and site D-2. The foam microplastics (12%) ranked third, and then pellet (8%) and film microplastics (5%). For size distribution, microplastics in the Dishui Lake were mostly in the range of 1–5 mm, 91%. Particles in sizes between 0.1–0.5 mm and 0.5–1 mm accounted for 3% and 6%, respectively.

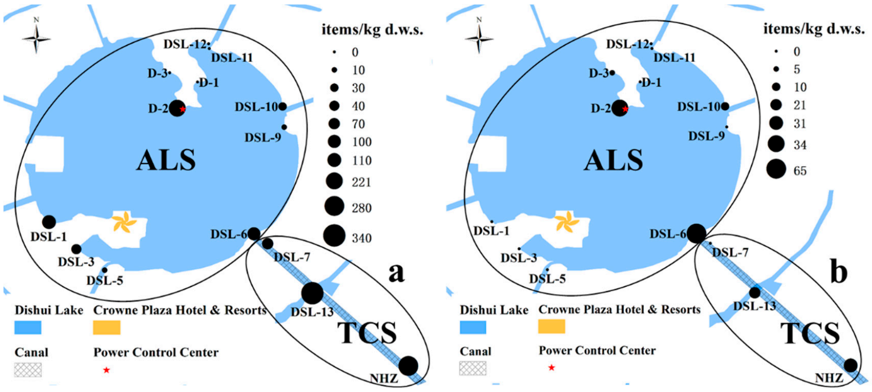

Figure 2. Abundance and distribution of microplastics (**a**), mesoplastic and macroplastic (**b**) in Dishui Lake sediment. ALS: Sampling sites around the Dishui Lake, including sites in the north (D1, D2, D3, DSL-11, and DSL-12), the east (DSL-9 and DSL-10), and the south (DSL-1, DSL-3, and DSL-5). TCS: Sampling sites int the canal connecting the lake to the East China Sea (DSL-6, DSL-13 and NHZ).

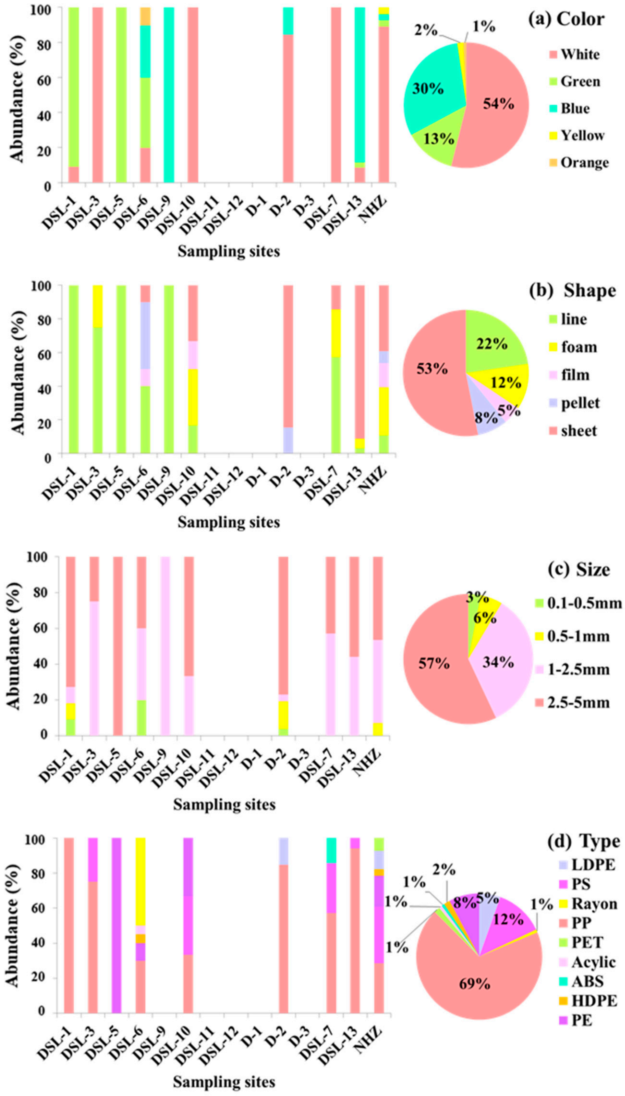

Figure 3. Color (**a**), shape (**b**), size (**c**), and polymer type (**d**) distribution of microplastics in sediment of the Dishui Lake.

The microplastic particles were further examined by FT-IR to determine their composition and polymer type. A total of seven polymer types were identified in the Dishui Lake sediment, including polypropylene (PP), polystyrene (PS), polyethylene (PE), acrylic, high density polyethylene (HDPE), low density polyethylene (LDPE), acrylonitrile, acrylonitrile butadiene styrene (ABS), and polyethylene terephthalate (PET) (Figure 3d). PP was the most abundant polymer type (69%). PP microplastics in Dishui Lake sediment had various shapes, including sheets, pellets, and lines. The second most abundant polymer type was PS (12%), all of which were foam fragments. The PE microplastic account for 8% of the total, then LDPE and HDPE, which were 5% and 2%. PE microplastics were mainly films. HDPE and LDPE were mainly pellet shaped.

3.2. Mesoplastics and Macroplastics in Dishui Lake Sediment

In addition to microplastics, we also detected mesoplastics and macroplastics in the lake sediment (Figure 2b). The highest concentration of large plastic debris was detected at DSL-6, followed by D-2, NHZ, DSL-13, DSL-10, and D-3. In most of the sites, not all three sizes of plastics were detected concurrently. It is interesting to note that the concentrations of the plastics followed the sizes of the particles; that is, microplastics were the most abundant, followed by mesoplastics and macroplastics. It is also important to note that the polymer type, color, and shape of the large sized particles was similar to that of the smaller sized particles found in the sediments.

4. Discussion

4.1. Sources of Microplastics in Dishui Lake Sediment

The Dishui Lake is surrounded by developing towns. Previous studies have shown that urban rivers, hyporheic zone of rivers, the river bed, and inland lakes accumulated large amounts of microplastics, such as the Beijiang River (China), River Rhine, and the Main River (Germany), rivers in Northern England, and Lake Winnipeg (Canada) [33,45–48]. Our results showed that the distribution of microplastics in the Dishui Lake sediment is affected by human activities. The sampling sites on the north side of the lake (DSL-1, DSL-3, DSL-5), which is relatively densely populated, had higher concentrations of microplastics than the eastern side, which is mostly farmland (DSL-9, DSL-10, DSL-11, DSL-12, D-1). This conclusion is also supported by the elevated concentrations of microplastics detected at site D-2. This sampling site is close to a power supply control center, where various anthropogenic activities take place daily, such as inspection and repair work. Our finding is consistent with observations in previous studies. Eriksen et al. (2013) found that, among the five Great Lakes, Lake Erie, which is near the most populated cities, had consistently higher amounts of microplastics than Lake Superior and Lake Huron [34]. Xiong et al. (2019) showed evidence that human activities affect the abundance of microplastics in the middle and lower reaches of the Yangtze River [49]. Similarly, a recent study by Peng et al. (2018) indicated that population density and quantities of industrial waste were important sources for plastic accumulation in fluvial sediment [44]. The concentration of microplastics in lakes of Wuhan also exhibited a decreasing trend away from urban centers [50].

Microplastics in the environment come from two main sources—the primary source and the secondary source. The primary source refers to those that directly contribute plastics to the environment, such as urban rubbish, industrial waste, and fishing waste, etc. [51–53]. Once released into the environment, macroplastic, mesoplastics, and microplastics can be fragmented into smaller pieces under the effects of physical, chemical, and biological processes [38,54,55]. These constitute the secondary source of microplastics in the environment. In previous studies, line or fiber microplastics were found to be important plastic components in rivers and coastal waters and were suspected to come from laundering [56,57]. Our results showed that sheet microplastics were the most abundant microplastics in the Dishui Lake sediment, suggesting that laundry wastewater discharging was not the main source. In addition, we found that PP microplastics were the most abundant type of microplastics. PP is widely used in woven products, food packaging, and pipes. The detection of PS foams in the Dishui Lake sediment further suggests that food packaging plastic material is likely the primary source of plastic particles in the lake. It is interesting to note that macroplastics, mesoplastics, and microplastics all exhibited similar characteristics in color, shape, and polymer type, suggesting that the different sizes of plastic particles found in the lake sediment were from the same sources.

4.2. Coastal Lakes as a Buffer Zone between the Continental and Marine Environment

Coastal lakes, commonly connected directly with the ocean and also having water discharged from inland rivers, can serve as a repository and reworking zone for plastics sourced from the continental environment. Thus, plastic debris from the drainage area of rivers can be transported to coastal lakes and reprocessed there. The Dishui Lake is a typifying example of this type of lake. The lake connects with the East China Sea via a canal on the southeast. The Dazhi River, a tributary of the Huangpu River which runs through the center of Shanghai, enters the lake on the north. We call such lakes as buffer zones for plastics (PBZ), which can act as a sink for plastics from the continental environment and, at the same time, as a source contributing plastics to the marine environment. Specifically, coastal lakes like the Dishui can serve as a reworking zone for plastics entering them, which can be further fragmented by physical, chemical and biological processes [55,58]. Plastics entering such lakes can be from direct sources, i.e., human activities around the lake, or from indirect sources, e.g., by riverine transport from continental environment.

Recent studies have shown that size distribution of plastic debris can be used to indicate the source and transport pathways [59]. The average abundance at ALS and TCS sites were, respectively, 47.1 and 230 items kg^{-1} d.w.s. The concentrations of microplastics in the canal sites DSL-13 and NHZ are orders of magnitude higher than that at the lake sites (DSL-6, DSL-10 and D-2). At the ALS sites, microplastics accounted for 86.8% of all size plastics. However, the ratio at the TCS sites was 93.0%. This indicated that plastics were more severely fragmented in the canal than in the lake. Combining the fact that the Nanhuizui gate is periodically opened to release water to the ESC, we infer that during the closing of the Nanhuizui gate, the plastic debris entering the lake are broken into smaller pieces by physical, chemical, and biological processes. Our observations suggest that Dishui Lake served as a PBZ, contributing plastic particles to the Eastern China Sea.

5. Conclusions & Perspectives

In this study we examined the composition, abundance, and distribution of macro-, meso-, and microplastics in sediment of a coastal lake, the Dishui Lake in Shanghai, China and of the canal connecting the lake to the East China Sea. Our results show that human activities are a major contributing factor to the accumulation of plastic debris in the lake. Our results further suggest that coastal lakes, exemplified by the Dishui Lake, can be a reworking zone for plastics derived from continental sources, and a buffer zone contributing plastic debris to the marine environment. This study addressed one of the most understudied research areas on plastic pollution in the environment—that is, studying transport, reworking, and redistribution of plastic debris at catchment scale across the marine and continental environment. It is important and useful for future research to focus on the sources, sinks, reworking, and redistribution of all three sizes of plastics at catchment scale, both in the surface water bodies and in groundwater [33,38,60]. We hope that our study will stimulate more hypotheses in future research to determine the extent and potential impact of coastal transitional aquatic ecosystems in transport and the reworking and redistribution of plastic particles across ecosystems. Furthermore, studying the dynamic interactions between plastic particles and water/sediment in coastal lakes affected by properties of plastics (size, shape, density, and surface properties) and the hydrodynamic conditions of the water bodies is another field that needs to be expanded to understand the fate and transport of plastics across the ecosystems.

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Conflicts of Interest: The authors declare no conflicts of interest.

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