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Microplastic contamination in the San Francisco Bay, California, USA

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ABSTRACT

Despite widespread detection of microplastic pollution in marine environments, data describing microplastic abundance in urban estuaries and microplastic discharge via treated municipal wastewater are limited. This study presents information on abundance, distribution, and composition of microplastic at nine sites in San Francisco Bay, California, USA. Also presented are characterizations of microplastic in final effluent from eight wastewater treatment plants, employing varying treatment technologies, that discharge to the Bay. With an average microplastic abundance of 700,000 particles/km^2, Bay surface water appears to have higher microplastic levels than other urban waterbodies sampled in North America. Moreover, treated wastewater from facilities that discharge into the Bay contains considerable microplastic contamination. Facilities employing tertiary filtration did not show lower levels of contamination than those using secondary treatment. As textile-derived fibers were more abundant in wastewater, higher levels of fragments in surface water suggest additional pathways of microplastic pollution, such as stormwater runoff.

1. Introduction

While plastic pollution of the marine environment has been reported for decades, only recently have estuaries and freshwater systems been a focal point of similar studies (Dubaish and Liebezeit, 2013; Eriksen et al., 2013; Castañeda et al., 2014; Free et al., 2014; Yonkos et al., 2014; Davis and Murphy, 2015). A key component of this pollution, microplastic describes fragments of plastic that are smaller than 5 mm (Thompson et al., 2009; Masura et al., 2015). Sources of microplastic to the environment include microbeads used in personal care products, pre-production pellets used as precursors to manufacture plastic products, fibers derived from clothes and fabrics made with synthetic materials (e.g., polyester and acrylic) or fishing line, fragments from the photodegradation of larger plastic items, and plastic foam particles from polystyrene products or cigarette filters (Fendall and Sewell, 2009; Browne et al., 2011; Eriksen et al., 2013; Free et al., 2014; van Franeker and Law, 2015). Microplastic can enter the aquatic environment through wind advection, stormwater runoff, or illegal dumping of plastic materials (Eriksen et al., 2013). Additionally, both microbeads from personal care products and fibers from synthetic clothing can be washed down the drain and enter wastewater treatment plants, where their small size, buoyancy, and lack of reactivity limits removal, resulting in release via treated wastewater (Browne et al., 2011; NYS OAG, 2015).

Microplastic particles pose risks to wildlife because the particles may be mistaken for food and ingested (Wright et al., 2013). The particles are also small enough that they can be ingested by planktonic organisms and other filter feeders (Browne et al., 2008; Cole et al., 2013). The hydrophobicity and high surface area to volume ratio of microplastic particles leads to sorption of persistent organic pollutants such as polycyclic aromatic hydrocarbons (Teuten et al., 2007). Organisms that ingest microplastic particles may thus receive higher doses of sorbed contaminants, potentially causing additional harm (Wright et al., 2013). Ingestion of microplastic can block the digestive tract, reduce growth rates, block enzyme production, lower steroid hormone levels, affect reproduction, and may lead to greater exposure to plastic additives with toxic properties (Wright et al., 2013).

Despite widespread detection of microplastic pollution in the marine environment, data describing microplastic abundance in urban estuaries and microplastic discharge via treated municipal wastewater are limited. This initial, screening study characterized microplastic in treated wastewater effluent from eight facilities employing a range of treatment technologies and discharging to San Francisco Bay, hereafter referred to as the Bay. Treated wastewater is considered an important

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pathway for microplastic to enter receiving waters, but only a few studies of this matrix are available (Carr et al., 2016; Mason et al., in review). In addition, this study provides data on microplastic in surface waters of the Bay, the largest estuary on the west coast of North America, which is surrounded by a dense urban population and drains roughly 40% of the waters of California.

2. Materials and methods

2.1. Wastewater

Treated wastewater is discharged to San Francisco Bay from more than 30 different discharge locations. Eight facilities, providing approximately 60% of measured wastewater flows directly to the Bay, permitted researcher access to final effluent sinks or other available ports, allowing us to collect samples. Samples of microplastic discharged from wastewater treatment plants were collected by passing flows of final, treated effluent through 8-in. diameter stacked Tyler sieves with 0.355 mm and 0.125 mm stainless steel mesh, typically for 2 hours during each facility's peak flow. The 0.125 mm mesh has been found to be particularly useful for retention of microbeads discharged to the sewer via use of personal care products (Napper et al., 2015; Carr et al., 2016). A single set of two samples, differentiated by sieve mesh size, was collected in the fall of 2014 at each of the eight facilities. Facilities participated voluntarily, and were selected based on multiple factors, including higher discharge levels, geographic diversity, and range of treatment technologies (secondary vs. tertiary filtration; Table 1). Rate of flow at the point of collection was measured before and after each sample was obtained (to ensure consistency), allowing calculation of number of particles per volume of treated wastewater. Each facility provided the 24-h discharge flow rate for the day of sample collection, allowing estimation of the number of particles discharged to the Bay per day.

In order to remove labile organic material, samples were processed via a wet peroxide oxidation (WPO) based upon a National Oceanic and Atmospheric Administration method (Masura et al., 2015), which has been tested to ensure that the most common plastic materials survive. Briefly, samples were reacted with a 30% hydrogen peroxide solution in the presence of an iron (II) catalyst in order to oxidize natural organic material, leaving the synthetic plastic material behind. Wastewater samples were processed as individual samples according to the collected size classification (i.e., 0.125–0.355 mm or >0.355 mm).

After processing, samples were once again filtered though a stacked sieve set (0.355 mm and 0.125 mm) and rinsed using deionized (DI) water into petri dishes. Given their density relative to that of DI water and most natural materials, floating particles within this medium are assumed to be plastic, a common technique within this field of research (Hidalgo-Ruz et al., 2012; Rocha-Santos and Duarte, 2014). Using a dissection microscope, plastic particles were removed, enumerated, and categorized into five classifications: fragment, pellet (spherical particle), fiber/line, film or foam (Free et al., 2014; McCormick et al., 2014). While instrumental analysis methods such as infrared or Raman spectroscopy are necessary for polymeric identification (i.e., polyethylene versus polypropylene), numerous studies have employed only visual identification for microplastic classification (e.g., Bond et al., 2014; Lavers et al., 2014; Devriese et al., 2015; Rochman et al., 2015; Romeo et al., 2015; Fossia et al., 2016; Hammer et al., 2016; Miranda and Carvalho-Souza, 2016; Nicolau et al., 2016; Peters and Bratton, 2016). Given the source (i.e., wastewater), fibers obtained in this processing would presumably be anthropogenic and derived from textiles, though a portion of fibers observed in wastewater may not be plastic, instead derived from other anthropogenic sources (Remy et al., 2015; Nirmela Arsem, personal communication).

2.2. Surface water

Single surface water microplastic samples were collected from each of nine sites in San Francisco Bay over the course of 2 days in January 2015 (Fig. 1). Central and southern portions of the Bay contain higher levels of litter, including macroplastic debris, than northern stretches, and were the focus of this study (Rubissow-Okamoto, 2014). During sample collection, conditions were calm: the sea state on the Beaufort

Table 1
Microplastic particles present in treated wastewater, and estimates of discharge per liter and per day.

				No. plastic particles by type						No. plastic particles	
Wastewater treatment plant	Flow[a] (MLD)	Highest level of treatment	Size category (mm)	Fragment	Pellet	Fiber	Film	Foam	Total	Per liter[b]	Per day[a]
San José-Santa Clara	310	Tertiary filtration	0.125–0.354	0	0	26	0	0	26		
			≥0.355	0	0	33	0	0	33		
			total	0	0	59	0	0	59	0.047	15,000,000
East Bay Municipal Utilities District (EBMUD)	170	Secondary	0.125–0.354	1	0	11	1	0	13		
			≥0.355	7	0	5	3	0	15		
			total	8	0	16	4	0	28	0.071	12,000,000
Palo Alto	76	Tertiary filtration	0.125–0.354	3	0	24	0	0	27		
			≥0.355	8	0	23	2	0	33		
			total	11	0	47	2	0	60	0.13	9,600,000
Central Contra Costa	110	Secondary	0.125–0.354	21	0	28	0	0	49		
			≥0.355	5	0	10	0	0	15		
			total	26	0	38	0	0	64	0.072	8,100,000
Fairfield-Suisun	45	Tertiary Filtration	0.125–0.354	2	0	43	0	0	45		
			≥0.355	2	0	50	2	0	54		
			total	4	0	93	2	0	99	0.092	4,100,000
East Bay Dischargers Association (EBDA)	190	Secondary	0.125–0.354	1	0	11	0	0	12		
			≥0.355	1	0	9	0	0	10		
			total	2	0	20	0	0	22	0.022	4,100,000
San Mateo	31	Tertiary filtration	0.125–0.354	20	0	24	0	3	47		
			≥0.355	7	0	21	3	0	31		
			total	27	0	45	3	3	78	0.064	2,000,000
San Francisco Airport Sanitary (SFO)	2.3	Secondary	0.125–0.354	5	0	49	0	0	54		
			≥0.355	4	0	42	0	1	47		
			total	9	0	91	0	1	101	0.19	460,000
Total count			total	87	0	409	11	4	511		
Percentage by type			total	17%	0%	80%	2%	1%	100%		

[a] Measured discharge on day of sample collection, used to calculate plant discharge per day.

[b] Calculated using average flow rate at point of sample collection, see Supplementary Content.

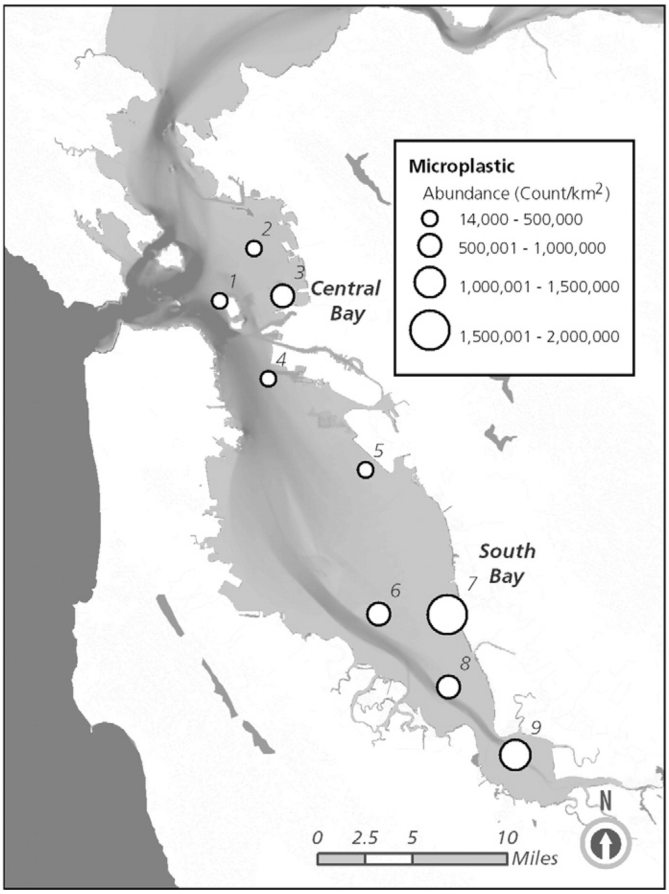

Fig. 1. Estimated abundance of microplastic particles in surface water at nine sites in San Francisco Bay. Site numbers correspond to those listed in Table 2; circles are located at trawl midpoints.

Scale remained between 0 and 2 for all sites. Samples were collected using a Manta Trawl with a rectangular opening 16 cm high by 61 cm wide, and a 3 m long 333 μm mesh net with a 30 × 10 cm^2 collecting bag, a sample collection technique now in common use (e.g., Eriksen et al., 2013; Free et al., 2014; Masura et al., 2015). Sampling took place over the course of 30 min at each site, with tow speeds from 2 to 4 knots and the vessel maintaining a consistent heading. Coordinates were recorded at the start and finish of each trawl to establish tow length; this length, multiplied by the width of the trawl, provided the surface area sampled, allowing calculation of standardized values per square kilometer.

Most samples were collected during flood tides, with two samples, at sites 5 and 9, collected during slack tides. For the central Bay, where tidal exchanges are significant, flood tides may result in reduction of microplastic abundance due to the addition of ocean water with lower levels of urban contaminants; therefore, microplastic abundances measured in the central Bay should be considered lower-bound estimates. Abundances measured in southern stretches of the Bay, where oceanic exchange is significantly reduced, are not expected to be significantly affected by tidal flushing. All samples were placed in sample jars and preserved with 70% isopropyl alcohol.

Nine small fish were collected as accidental by-catch at one site (6). Although fish collection was not planned, the abundance of microplastic in these fish was determined after thorough rinsing to remove external contaminants; results are provided in Supplementary Content.

Surface water samples then went through a pre-processing stage where each sample was visually inspected to remove any obvious larger (i.e., >1 mm) plastic debris, as well as any larger vegetative debris (such as leaves, twigs, seeds, feathers, and insects), which would be difficult to chemically process (as described below). All materials were thoroughly rinsed prior to removal and vegetative debris was discarded. Samples were then subjected to the WPO treatment to remove seston and other labile organic matter, sieved into three different size classifications using 8-in. diameter stacked Tyler sieves of 0.355 mm, 1.00 mm and 4.75 mm stainless steel mesh, and rinsed thoroughly with deionized (DI) water. After processing, all samples and all size classifications were analyzed using a dissection microscope and plastic particles within were removed, enumerated, and categorized as described above.

A single field blank sample, created by rinsing sieves employed during both Bay and wastewater sample collection, and four lab blank samples in which DI water was stored within sample containers for periods of 1–14 days, were processed in the same manner as all other samples. While the field blank sample revealed the presence of four fibers measuring less than 1 mm, the lab blank samples were not found to have any microplastic contamination. The fibers within the field blank are thus most likely derived from sample cross-contamination (e.g., particles that adhered to the mesh bag or the sieves themselves), as lab blank samples would indicate that contamination from the containers, lab or processing was negligible. Nevertheless, field blank contents were subtracted from all sample counts.

3. Results

3.1. Wastewater

The eight San Francisco Bay wastewater treatment plants discharged an average of 0.086 microplastic particles per liter (or 0.33 particles per gallon) and 7 million microplastic particles per day (Table 1). These levels were higher than those found in effluent from nine municipal wastewater treatment facilities in the Midwest and Northeast U.S. analyzed using the same method (0.050 particles per liter and 2 million particles per day; Mason et al., in review), as well as eight southern California facilities analyzed with a different analytical method (all facilities discharged <0.001 particles per liter; Carr et al., 2016). In total, the eight Bay facilities, representing approximately 60% of treated wastewater flows to San Francisco Bay, discharged 56 million microplastic particles per day. If levels of microplastic in effluent from these eight facilities are assumed to be generally representative of the region, an estimated 90 million microplastic particles per day may be discharged into San Francisco Bay. This estimate does not include contributions of microplastic discharged by treatment plants into the Sacramento-San Joaquin River Delta, which ultimately drains to the Bay.

Fibers were the dominant form of particulate pollution in effluent, followed by fragments (Table 1). The San José-Santa Clara Regional Wastewater Facility, which employs tertiary granular filtration, discharged only fibers during sample collection. However, overall there were no consistent differences between the proportions of fibers and fragments discharged by facilities employing secondary treatment only (EBMUD, Central Contra Costa, EBDA, SFO) versus those that included tertiary filtration as well (San José-Santa Clara, Palo Alto, Fairfield-Suisun, San Mateo). Likewise, plants employing tertiary granular filtration did not display consistently lower concentrations of overall microplastic per liter than those employing only secondary treatment technologies.

Comparable numbers of smaller (0.125–0.355 mm) and larger (>0.355 mm) microplastic particles were discharged by most facilities (Table 1). The Central Contra Costa Sanitary District facility was an exception, discharging three times more smaller particles than larger ones.

3.2. Surface water

All nine surface water samples contained microplastic pollution (Table 2). Average abundance for Bay samples was 700,000 ± 600,000 particles/km^2 (range: 15,000–2,000,000 particles/km^2), higher than average measurements from the Great Lakes (Eriksen et al., 2013),

Table 2
Count, tow length, and abundance of microplastic particles in surface waters at nine sites within San Francisco Bay.

Site	Total count	Tow length, meters	Abundance, particles/km^2
Central San Francisco Bay			
1	26	2855	15,000
2	107	1708	100,000
3	994	1776	920,000
4	188	1655	190,000
Southern San Francisco Bay			
5	438	2302	310,000
6	1192	2017	970,000
7*	3641	2959	2,000,000
8*	1247	2799	730,000
9*	1665	2643	1,000,000

* Samples included considerable bulky vegetation.

the Chesapeake Bay (Yonkos et al., 2014), and the Salish Sea (Davis and Murphy, 2015). All samples contained fragments, fibers, and to a lesser extent pellets in the smallest (0.355–0.999 mm) size class (see Supplementary Content). One site (1) lacked foamed microplastic particles in the smallest size class, while another (site 2) lacked films in the smallest size class. Larger size classes were most often dominated by fragments and fibers (Table 3). Preliminary data from nine small, prey fish obtained as accidental by-catch suggested high levels of microplastic contamination, particularly by particles in the 0.355–0.999 mm size class (see Supplementary Content).

Sites in the southern portion of San Francisco Bay had higher average microplastic abundance, 1,000,000 particles/km^2, than sites in the central Bay, which averaged 310,000 particles/km^2. Flood tides occurring during sampling in the central Bay could contribute to reduced abundances measured at these sites. Southern sites typically contained higher levels of small fragments (Table 3); three of these samples also included large amounts of bulky vegetation (Table 2).

4. Discussion

Overall levels of microplastic pollution measured in this initial, screening study were greater than comparable measurements available for other urbanized areas of the U.S., including treated wastewater from municipal wastewater treatment facilities located in other parts of the U.S. (Carr et al., 2016; Mason et al., in review) and surface waters of the Great Lakes, Chesapeake Bay, and the Salish Sea (Eriksen et al., 2013; Yonkos et al., 2014; Davis and Murphy, 2015). Bay Area wastewater facilities investigated here typically serve large populations that have implemented significant water conservation measures due to severe drought, in contrast to the facilities from other regions for which consistently measured data are available (Mason et al., in review); these differences provide a potential explanation for the increased concentrations of microplastic particles in Bay Area wastewater, as the same overall amounts of urban contaminants would be more concentrated if released with lesser amounts of water. The apparent elevation of San Francisco Bay surface water microplastic pollution can be at least partially explained by a dense urban population surrounding a small body of water with limited interchange with the Pacific Ocean.

Table 3
Average abundance and type of particles in three size classes in central and southern San Francisco Bay surface water samples.

Central San Francisco Bay	0.355–0.999 mm	1.000–4.749 mm	≥4.75 mm	% of Total
Fragment	68,000	35,000	2100	34%
Pellet	3100	970	0	1%
Fiber	80,000	67,000	1200	48%
Film	8200	22,000	3500	1%
Foam	2300	12,000	460	5%
Total Count/km^2	160,000	140,000	7200	
% of Total	53%	45%	2%	

Southern San Francisco Bay	0.355–0.999 mm	1.000–4.749 mm	≥4.75 mm	% of Total
Fragment	450,000	150,000	5400	60%
Pellet	17,000	2500	0	2%
Fiber/ine	140,000	86,000	2800	22%
Film	25,000	37,000	6700	7%
Foam	35,000	52,000	2300	9%
Total Count/km^2	670,000	330,000	17,000	
% of Total	66%	32%	2%	

Southern Bay levels of microplastic were generally higher than those of the central San Francisco Bay. A similar regional pattern has been observed for a number of contaminants derived largely from treated wastewater (e.g., Klosterhaus et al., 2013). Surface waters in the southern Bay receive a large volume of treated wastewater and urban stormwater, have the highest hydraulic residence time relative to other portions of the Bay, and experience the least amount of dilution.

However, the observation that small fragments drove the higher microplastic levels measured at southern Bay sites, while wastewater discharges were primarily composed of fibers, suggests that treated wastewater was not the only source of microplastic pollution for southern stretches of the Bay. Instead, microplastic from other pollution pathways, such as stormwater, and in situ processes including the fragmentation of larger plastic debris, in combination with the long residence times, may have contributed to higher levels of microplastic contamination.

An additional qualitative observation was that some of the largest counts of plastic were associated with Bay samples containing substantial quantities of vegetation (Table 2). The potential for vegetation to entrain microplastic merits exploration in future studies. Of particular concern, the presence of surface vegetation can result in more concentrated feeding activity nearby. If microplastic levels are higher in these zones, wildlife may be more likely to ingest these particles.

Comparison of wastewater treatment plants employing typical secondary treatment versus those equipped with additional tertiary filtration did not indicate a significant effect on microplastic particle discharge or distribution of particle types. Additional monitoring is needed to explore this finding, which is consistent with observations from a study of New York State treatment facilities focusing exclusively on plastic pellets (NYS OAG, 2015). Assessment of microplastic content in associated influent and biosolids would better elucidate the impacts of different treatment types on microplastic particles in wastewater. A study exploring microplastic levels at different points in the wastewater treatment train found considerable removal via skimming during initial stages of treatment (Carr et al., 2016). Nevertheless, the limited data currently available suggest that granular tertiary filtration may not be an effective means of controlling microplastic pollution.

Fibers were the dominant particle type found in treated wastewater from Bay Area facilities, a finding common in similar microplastic analyses of wastewater in other locations (e.g., Browne et al., 2011; Mason et al., in review). An alternative study, which utilized a different method for effluent processing and analysis, did not detect anthropogenic fibers, only microbially derived detritus (Carr et al., 2016). A recent examination of artificial fibers found in the digestive tracts of aquatic invertebrates suggests some portion of these fibers may be derived from cellulose rather than plastic (Remy et al., 2015). Some cellulose-derived fibers can survive the wet peroxide oxidation process that all samples were subjected to in this study (Nirmela Arsem, personal communication); as fibers were not subjected to Raman nor FTIR spectroscopy to confirm their identity, it is possible that the presence of anthropogenic, cellulose-derived fibers resulted in overestimates of the overall levels of plastic fibers in these samples. However, given previous studies indicating high levels of plastic fibers in synthetic clothing wash water as well as in wastewater samples subjected to greater levels of spectroscopic examination (Browne et al., 2011), synthetic plastic is likely to be a dominant source of fibers in the wastewater examined in this study.

Of note, fibers are more reliably identified through visual inspection as plastic than fragments (Lenz et al., 2015).

Multi-colored, spherical plastic pellets in the size class < 1 mm, likely derived from rinse-off personal care products, were detected at low levels in all Bay sites, but in none of the treated wastewater samples. While the absence of these clearly identifiable pellets in treated wastewater was somewhat unexpected, it does not indicate a lack of personal care product-derived contamination. Most of the microplastic particles in personal care products are rough and irregular in shape and therefore classified as fragments (Napper et al., 2015; Carr et al., 2016), with less than 10% consisting of spherical pellets (unpublished data, S.A. Mason). It is likely that a significant portion of the microplastic fragments detected in treated wastewater samples in this study were derived from personal care products containing microbeads.

5. Conclusion

The results of this initial, screening study indicate that microplastic contamination, a global concern, may be higher in San Francisco Bay than in other urban areas in North America for which data are available, including the Great Lakes (Eriksen et al., 2013), the Chesapeake Bay (Yonkos et al., 2014), and the Salish Sea (Davis and Murphy, 2015). Effluent samples from Bay Area treatment facilities also showed higher levels of contamination than seen in other facilities in the U.S. (Carr et al., 2016; Mason et al., in review).

Results from this study indicate the need for method development and standardization to assess microplastic found in common pollution pathways. The increased proportion of fragments over fibers in Bay water samples relative to treated wastewater suggested that other pathways, such as stormwater, may be important contributors to microplastic pollution in the Bay. As yet, there are no established methods for measuring microplastic in stormwater discharges; until such methods are developed, a hypothesis about the relative contributions of stormwater versus wastewater to overall microplastic pollution in receiving waters cannot be tested. The method employed in this study to characterize effluent was originally developed for ambient receiving waters and could be further refined, particularly given the wide range of anthropogenic fibers that may be found at higher concentrations in wastewater. In addition, 24-hour effluent samples could provide a more comprehensive picture of microplastic pollution in treated wastewater, in particular because peak personal care product use follows distinct diurnal patterns.

Ultimately, concerns about microplastic pollution are driven by potential impacts to wildlife or humans. Recent detection of microplastic, including fibers, within sport fish from coastal California as well as Indonesia (Rochman et al., 2015) indicates exposure is occurring; at this time, studies linking microplastic exposure to adverse impacts in controlled laboratory settings have not resulted in development of specific aquatic or tissue-based toxicity thresholds. By-catch prey fish collected at a single site in this study also contained microplastic, especially fibers (Supplementary Content). Of note, most microplastic monitoring in wildlife focuses on microorganisms, invertebrates, or sport fish (e.g., Wright et al., 2013; Rochman et al., 2015), with relatively few data available for smaller, prey fish such as those examined here. Additional study of small, prey fish species is recommended to develop an understanding of microplastic exposure and potential impacts throughout the food web.

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Appendix A. Supplementary content

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