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Microplastic accumulation and biomagnification in a coastal marine reserve situated in a sparsely populated area



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ABSTRACT

Toxic chemicals within and adsorbed to microplastics (0.05–5 mm) have the potential to biomagnify in food webs. However, microplastic concentrations in highly productive, coastal habitats are not well understood. Therefore, we quantified the presence of microplastics in a benthic community and surrounding environment of a remote marine reserve on the open coast of California, USA. Concentrations of microplastic particles in seawater were 36.59 plastics/L and in sediments were 0.227 ± 0.135 plastics/g. Densities of microplastics on the surfaces of two morphologically distinct species of macroalgae were 2.34 ± 2.19 plastics/g (*Pelvetiopsis limitata*) and 8.65 ± 6.44 plastics/g (*Endocladia muricata*). Densities were highest in the herbivorous snail, *Tegula funebralis*, at 9.91 ± 6.31 plastics/g, potentially due to bioaccumulation. This study highlights the need for further investigations of the prevalence and potential harm of microplastics in benthic communities at remote locations as well as human population centers.

1. Introduction

Anthropogenic change in the ocean has altered biogeochemical cycles, degraded marine habitats, and decreased biodiversity (Derraik, 2002; Halpern et al., 2008). Since the onset of the mass production of plastics in the latter half of the 20th century, plastic debris has become a growing environmental concern across ecosystems (Jambeck et al., 2015). Due to the durable nature of plastic, as well as its economic and societal importance as a low-cost manufacturing product, its proliferation could have serious consequences for the marine environment and biota (Laist, 1987; Gregory, 1999). Microplastics, which range from 0.05 mm to 5 mm, are manufactured at small sizes or secondarily formed by the degradation or fragmentation of macroplastics from UVradiation and physical-erosion (Cole et al., 2011). At these smaller sizes, microplastics, potentially pose a risk to marine organisms as they become bioavailable (Derraik, 2002; Andrady, 2003; Barnes et al., 2009; Cole et al., 2013). While marine organisms are directly affected by hazardous leachates seeping from the plastics in the water column, such as plasticizers (phthalates), additives (organotin compounds and

nonylphenols (NP)) and monomers (BPA) (Teuten et al., 2009), that are considered toxic (Cole et al., 2011), additional contamination may occur from contact with persistent organic pollutants (POPs) and pathogens adsorbed to microplastic surfaces (Gregory, 2009; Andrady, 2011; Teuten et al., 2009; Cole et al., 2011; Wright et al., 2013).

Although macroplastics are consumed by species that are at least the size of the plastic, microplastics pose a risk to marine organisms of nearly all sizes from potential biomagnification in trophic interactions (Derraik, 2002; Cole et al., 2011; Farrell and Nelson, 2013; Provencher et al., 2018). Microplastics have been documented to adhere superficially to the surface of primary producers, posing a risk to the macroalgal physiology while also incorporating them into food webs (Bhattacharya et al., 2010; Wright et al., 2013). Consumers are at risk of accumulating microplastics by direct consumption (Wright et al., 2013) via misidentification of plastics for prey (Schuyler et al., 2014), which leads to physiological (Wright et al., 2013; Bour et al., 2013; Browne et al., 2008; Zettler et al., 2013) and reproductive (Green, 2016; Lo and Chan, 2018) consequences that affect overall intertidal community structure through potentially altered biomass in

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the population (Green, 2016). In addition to direct consumption, macroscopic primary producers may also facilitate incidental ingestion by herbivorous grazers (Gutow et al., 2016) or secondary attraction to plastics with epiphytic biofilms in larger predators (Savoca et al., 2016). Ingestion rates of microplastics by filter-feeders (Farrell and Nelson, 2013; Desforges et al., 2015), grazers (Gutow et al., 2016), and deposit-feeders (Setälä et al., 2016) have been quantified in the laboratory, indicating the efficacy for microplastics to enter food webs from multiple trophic levels. However, feeding mode and behavior substantially affected encounter and ingestion rate (Setälä et al., 2016), leading to differences in overall bioaccumulation potential. Microplastics can also be associated to toxic chemicals (e.g. PAHs, PCBs, and PBDEs) and thus, act as facilitators in uptake and bioconcentration within consumers and bioaccumulation in predators (Farrell and Nelson, 2013; Rochman et al., 2013).

Nearly all marine habitats are exposed to plastic pollution, (Panti et al., 2015; Chiba et al., 2018; Provencher et al., 2018) indicating that the majority of sea life is at risk to its effects (Gall and Thompson, 2015). Although there is widespread evidence of microplastic pollution globally (Provencher et al., 2018), whether proliferating microplastics have penetrated marine protected areas (MPAs) has yet to be investigated. As these areas aim to reduce degradation of habitats and limit exploitation of resources (Agardy et al., 2011), it is important to determine the infiltration of microplastics into the food webs of coastal MPAs located far from cities and point-source polluters. While prior sampling within the California Current System indicates that microplastics have been present in both nearshore and offshore seawater samples for at least the last 35 years (Gilfillan et al., 2009), a follow-up assessment on deposition and incorporation into intertidal food webs, specifically locations within MPAs, has yet to be published.

Our goal was to determine whether microplastics were prevalent in a reserve located along a sparsely developed stretch of coastline. Therefore, we quantified ambient levels of microplastics in abiotic and biotic environments of the Bodega Marine Reserve (BMR), situated along the coast of northern California, with San Francisco being the closest large population center located ~82 km to the south. We chose a wave-exposed and a sheltered site to target both the abiotic environment, consisting of sand and seawater, and biotic environment, consisting two species of macroalgae with different morphologies and an herbivore (Fig. 1). Abiotic heterogeneity within ecosystems leads to variations in the residence time of sand, water and potentially microplastics in an ecosystem. In addition, the morphology of the two species



Fig. 1. Representation of response variable predictions categorized by the variable tested and concentration of microplastics. Variable categories (site, species, and bioaccumulation potential) are the uppermost nodes with tested variable branching vertically. Magnitude of concentration of microplastics within each variable category is relative to its category, and positioning of variables among categories is not intended for cross-category comparisons.

of macroalgae differs considerably, potentially affecting the magnitude of attachment of microplastics to their surfaces. Therefore, we expected that microplastics would be more likely to settle and accumulate at the sheltered site where there should be less turbulence from wave action. Similarly, because one species of macroalga, *Pelvetiopsis limitata*, has smooth branching fronds, and the other, *Endocladia muricata*, is a bushy turf alga, we expected the latter would collect more microplastics as water flow slows passing through it. We selected the abundant snail, *Tegula funebralis*, because it grazes both species of macroalgae potentially bioaccumulating microplastics. A more extensive survey would be needed to better establish the concentrations of microplastics in the reserve and bioaccumulation as well as to rigorously test our hypotheses.

2. Materials and methods

2.1. Study system

This study was conducted in the Bodega Marine Reserve (BMR) in Sonoma County, California. The reserve is unique in that it contains both terrestrial and marine habitats. Damage or take of all marine resources (living, geologic, or cultural) is prohibited, protecting a wide range of marine habitats including subtidal, rocky intertidal, mudflat, sandy beach, fresh and saltwater marsh, coastal grassland and dune communities. Established in the mid 1960s (concurrent with the establishment of the Bodega Marine Laboratory), the BMR manages over 600 acres and is adjacent to the Bodega Marine Life Refuge extending 1000 ft. from the shore. The larger Bodega Head State Marine Reserve was established in 2010 as part of the coordinated network of state MPAs and extends 3 nautical miles from shore in state waters and along the outer coast of Bodega Head. BMR is located in one of four highly productive upwelling regions that support some of the world's most important fisheries (Chavez and Messié, 2009). We selected three distinct sites within BMR: a wave-exposed rocky shore as well as a sheltered rocky-shore and sand beach in Horseshoe Cove (Fig. 2), to represent most habitat characteristics and exposure potentials.

Pelvetiopsus limitata and E. muricata are abundant along rocky shores, occurring from the low- to mid-tidal zone, and have different morphologies, geographic locations and interactions with T. funebralis. Pelvetiopsus limitata is a common brown algal species that extends from Vancouver Island, British Columbia to Cambria, California and occurs primarily in the mid-intertidal zone. This branching 4-8 cm tall fucoid species is a primary source of food for T. funebralis (Steinberg, 1985) and a potential pathway for indirectly ingesting microplastics. Fucus vesiculosus, a similar species to P. limitata, was determined to accumulate microplastics that adhere to algal tissue (Gutow et al., 2016), suggesting that our fucoid species may also do so given similar morphological and physical characteristics. In contrast, E. muricata is a stout, bushy red alga that is eaten less by T. funebralis (Morgan et al., 2016). This alga occurs in the middle and high-intertidal zone. Its dense, bushy morphology collects sediments and moisture and provides refuge for grazers (Glynn, 1965), such as T. funebralis. Therefore, E. muricata probably also traps microplastics where they may be consumed by grazers. Tegula funebralis is abundant on exposed rock and in tidepools throughout the intertidal zone during low tide (Gravem and Morgan, 2017). As a consequence, it may encounter sand, seawater and the two algal species throughout the day through locomotion, grazing, and refuge seeking behaviors. It is eaten by crabs and seastars (Gravem and Morgan, 2017) providing a pathway for microplastics to accumulate at higher trophic levels, as documented for species in other marine communities (Farrell and Nelson, 2013; Setälä et al., 2014; Watts et al., 2014).

2.2. Collection and processing

Samples were collected on April 22, 2018 during the morning low



Fig. 2. (A) Sampling location (red star) is positioned ~82 km north of San Francisco, CA (yellow star), the closest large population center. (B) Samples were collected from sites (wave-exposed, sheltered, and sandy beach) all located within the Bodega Marine Reserve in Bodega Bay, California on April 22, 2018. (C &D) Samples were taken from wave-exposed (orange) and sheltered (purple) sites in transects that best covered the area of the site that contained all species. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tide. For the exposed rocky site, we established two 30-m transects parallel to the coastline and 10-m apart to represent both mid-high and mid-intertidal zones, respectively. At the sheltered rocky site, *P. limitata* was not present at the mid-intertidal range, so one 60-m transect was established in the high intertidal zone instead. Biotic samples were taken from 6, $1-m^2$ quadrats from each site by estimating the percent cover of macroalgae, macroinvertebrates, and bare rock.

From each of the rocky sites, we obtained two samples of water from 4 tidepools near the transects. Water was collected from the top 10 cm of each tidepool, taking care not to disturb the sediment on the bottom, and filtered through two sieves ($180 \,\mu\text{m}$ and $63 \,\mu\text{m}$ mesh) rinsing the contents of the latter sieve into a sterile collection jar. The sample in each jar was preserved with 95% ethanol to prevent any further growth of phytoplankton species within the sample.

Sand samples were collected from both intertidal rocky sites and a supratidal sand beach following procedures from Lippiatt et al. (2013). From the beach site, one sample was collected every 20-m from a 100-m transect across the uppermost wrack line. Additional samples were collected from the intertidal, both in tide pools and sandy beaches in the exposed and sheltered sites. Sand samples in the exposed site were pooled into two samples, due to the sparse amounts of sand found in individual tide pools. The sheltered zone had enough sand for six samples. Following collection, samples were homogenized and dried at 60 °C for 4 weeks. Prior to analysis, each sample was weighed and quartered for subsampling.

We collected one 10-cm^2 algal sample of *P. limitata* and *E. muricata* from each quadrat in the exposed (n = 6) and sheltered sites (n = 6). Neither algal species was present on the beach site. To isolate microplastics potentially adhered to the surface and trapped within bushy clusters, we rinsed each sample with deionized water through a 500 µm and subsequent 38 µm sieve. Contents from the latter sieve were transferred to a 50-mL Falcon tube containing 95% ethanol. Wet and dry tissue weights were recorded after rinsing and oven drying (60 °C for 4 weeks), respectively.

Because *T. funebralis* mostly resides in tidepools during low tides, we collected individuals within 1-m of each quadrat at both exposed and rocky sites. There were no individuals observed at the beach site. Each snail was relaxed in ethanol and then euthanized in a boiling water bath. To dissolve the visceral mass, snails were dissolved in 10% KOH solution with ultrapure water following Rochman et al. (2015), for

4 weeks.

We used dissecting microscopes and hand-held, metal dissecting tools to quantify the abundance and specific types of microplastics, following images from Rochman et al. (2015), in all of the samples (water, sand, algae, and grazer). Dried algal tissue was also inspected for microplastics to control our rinse technique. Results are reported as total microplastics per L ($TM\cdot L^{-1}$) of seawater; for sediments and biota, results are reported as total microplastic per gram ($TM\cdot g^{-1}$).

2.3. Quality control

In order to control for microplastic contamination from sources other than the environment, we included samples of deionized water (DI) along with each batch of seawater, algae, and biota. All blank samples were processed using the same materials and methods as environmental samples. Specifically, for seawater, an in-situ blank sample was generated by pouring 1 L of deionized water (DI) into a sampling jar at the time of seawater collection. For algal samples, we quantified microplastics in a sample of DI water following the same methods described above. For invertebrates, a blank sample containing only KOH solution and ultrapure water were processed in the same batch as *T. funebralis* samples.

2.4. Data analysis

Statistical procedures were performed using RStudio Software (R Core Team, 2017). Student t and ANOVA tests were used to compare microplastic densities in sand samples among sites within the reserve and to compare microplastic accumulation among abiotic (e.g. sand and water) and biotic (e.g. algae and invertebrates) compartments. To conform with parametric test assumptions, microplastic density data in *E. muricate* and *P. limitata* were natural-log transformed and tested for normality using Shapiro-Wilk test. Post-hoc Tukey test was performed to identify differences in microplastic densities among algae and invertebrate species. Welch's test was used to compare differences in microplastic densities between wave exposed and sheltered sites within the reserve. Pearson's correlation test was performed to explore the relationship between microplastic accumulation with size and weight in *T. funebralis*. All tests of significance were made at an alpha level of 0.05.



Fig. 3. Total density of microplastics (TM·g⁻¹) from abiotic (sand) and biotic (two species of macroalgae and the black turban snail) compartments within exposed and sheltered rocky locations combined in the Bodega Marine Reserve in Bodega Bay, California on April 22, 2018. Different letters above the bars indicate significant differences by a one-way ANOVA followed by a Tukey test at p < 0.05).

3. Results

There was an average of 36.59 $\text{TM}\cdot\text{L}^{-1}$ of seawater in samples collected from the BMR [CI_{95%} 5.70, 67.70]. The average microplastic content across the reserve differed, where the exposed rocky shore site had an average of 26.125 $\text{TM}\cdot\text{L}^{-1}$ seawater and the sheltered site had an average of 47.05 $\text{TM}\cdot\text{L}^{-1}$ seawater.

Sediment grain size from all three sites (sheltered and exposed rocky shore, sandy beach) was large, varying from 1-mm to 5-mm in diameter. Sand particles were subangular to round and moderately sorted. The average reserve density of microplastics was 0.227 ± 0.135 TM·g⁻¹ and was significantly different from zero ($t_{1,5} = 4.121$, p < 0.01; 95% CI [0.08, 0.37]). Plastic densities among sites were similar ($F_{2,7} = 0.648$, p = 0.55). Higher densities in sediments than in seawater samples suggest deposition of microplastic particles.

There was an average of 8.65 \pm 6.44 TM·g⁻¹ in *E. muricata* and 2.34 \pm 2.19 TM·g⁻¹ of *P. limitata*. Total plastics from both species were not correlated with dry weight (Pearson's t₂₀ = 1.5, *p* = 0.14). Microplastic density data were natural-log transformed to meet assumptions of parametric tests (Shapiro-Wilk W = 0.98, *p* = 0.67). Microplastic density differed among sand and biotic compartments (Fig. 3, ANOVA, F(Andrady, 2011; Provencher et al., 2018) = 44, *p* < 0.001). *E. muricata* harbored more microplastics per gram than *P. limitata* (Tukey post hoc, *p* = 0.001) but there was no difference in density with *T. funebralis* (Tukey post hoc, *p* = 0.85). Microplastic density in *P. limitata* was greater than that in sand (Tukey post hoc, *p* < 0.001). Further, there was no significant interaction between species and site (ANOVA F(Besseling et al., 2015; Panti et al., 2015) = 15.84, *p* = 0.44).

There was an average of 9.91 \pm 6.31 TM·g⁻¹ of *T. funebralis* in the BMR. Total plastics in *T. funebralis* were not correlated with snail size (Pearson's t_{1,10} = 0.648, *p* = 0.532) or weight (Pearson's t_{1,10} = 0.500, *p* = 0.628). Total concentration of microplastics was similar between the wave exposed and sheltered sites (Welch t_{1,7} = 1.092, *p* = 0.31).

Quality control blank samples presented very low microplastic contamination in DI water, with average of 0.006 $\text{TM}\cdot\text{L}^{-1}$. We found microplastic contamination in DI blank sample processed in-situ with seawater, with average of 0.043 $\text{TM}\cdot\text{L}^{-1}$.

3.1. Heterogeneity in community composition

Percent cover of macroalgae, invertebrates and bare rock was heterogeneous among plots with mussels and barnacles dominating (> 40% cover combined) in three of six quadrats (both high and low tide lines) on the exposed rocky shore and four out of six quadrats in the sheltered area. Algae dominated (> 50% cover) one quadrat at the high tide line in the exposed area and covered from 10% to 53% of each quadrat in the exposed and sheltered areas. One quadrat at the high tide line of the exposed site had 75% cover of bare rock. *E. muricata* had greater percent coverage than *P. limitata* in seven of 12 quadrats. *Pelvetiopsis limitata* dominated the two quadrats from the high tide line at the exposed site and one quadrat from the sheltered site. One quadrat at each exposed and sheltered site had similar algal coverage overall. Regardless of the percent coverage of the two species of algae, *E. muricata* had higher microplastic densities than *P. limitata* in all plots at both exposed and sheltered sites.

4. Discussion

This is the first attempt to describe the abundance of microplastics in biota and the abiotic environment within a remote coastal marine reserve, far from large city inputs of potential pollutants. Previous studies quantifying the relative abundance of microplastics in marine biota differ in that targeted aquatic locations sat adjacent to or nearby highly developed landscapes. BMR is unique in that it sits nested within a network of protected marine sites, all of which hold regulations for preserving the natural system. Thus, any infiltration of microplastic pollution into remote, protected areas would illustrate the efficacy for transport and inspire more research to quantify microplastic pollution in vulnerable habitats around the world. Our results demonstrated the presence of foreign, plastic pollutants in both the abiotic environment and various biota. From this first look into a protected area, we have highlighted effective transport within the abiotic environment and also potential for uptake in both primary producers and primary grazers in an intertidal ecosystem.

Particle concentrations differed between the biotic and abiotic components (Fig. 3). Microplastic concentration in seawater was close to 40 TM·L⁻¹ on average and as high as 71 TM·L⁻¹ at sites sheltered from large waves. Elsewhere in the Northeastern Pacific Ocean, microplastic concentration was extremely variable, ranging from 0.086 particles·L⁻¹ in San Francisco Bay (Sutton et al., 2016) to 2000 particles·m³ near Vancouver Island (Desforges et al., 2015). Microplastics are present in relatively low concentrations in the sediment collected inside the BMR ranging from 0 to 1.1 particles·g⁻¹. Across the Baja California Peninsula in Mexico, the average concentration of microplastics was 0.135 particles·g⁻¹ of sediment, and the most polluted areas were three times greater on average (Piñon-Colin et al., 2018). On the Atlantic coast of Canada, the average microplastic concentration ranged from 2 to 8 particles per gram of sediment (Mathalon and Hill, 2014).

The organisms surveyed in the BMR had remarkably higher concentrations of microplastic particles than the environmental samples (Fig. 3). The gastropod T. funebralis had approximately 10 to 24 microplastics g^{-1} of tissue, which is consistent with values in intertidal snails from the Persian Gulf (9–20 particles g^{-1} (Naji et al., 2018). Intertidal mollusks are common model organisms to assess microplastic ingestion in coastal ecosystems. Microplastics in bivalves, such as the blue mussel Mytilus edulis, have been more extensively studied than gastropods because they are filter-feeders and commercial important (Browne et al., 2008; Mathalon and Hill, 2014). Mussels concentrate microplastics (0.2 \pm 0.3 particles g⁻¹; Van Cauwenberghe et al., 2015) and transfer microplastic particles to higher trophic levels (Farrell and Nelson, 2013). Although evidence indicating that snails transfer microplastic particles has not yet been documented, we believe they may serve as vectors of transport to larger predators, as snails have historically served as vectors for parasites introduced by direct consumption of prey. Although gastropods are one of the main representatives of the mesograzer trophic level in intertidal communities, historically, few studies have illustrated their potential for microplastic ingestion. The

common periwinkle, *Littorina littorea*, ingests microplastics by grazing fucoid macroalgae on rocky shores (Gutow et al., 2016). Thus, both macroalgae and snails, such as *T. funebralis*, may serve as vectors for transporting microplastics to higher levels in the food web.

We found concentrations of microplastics on primary producers ranging from 0.5 to 24.3 microplastics g^{-1} depending on the species. Concentrations associated with the turf alga E. muricata (2.5-24.3 microplastics g⁻¹) were significantly higher than those found on the fucoid *P. limitata* (0.5–8.0 microplastics g^{-1}). This finding is consistent with our hypothesis (Fig. 1) that algal types with different morphologies contain different densities of microplastics. The intricate, dense branching of *E. muricata* traps sediment and is likely to be responsible for higher levels of microplastic retention (Glvnn, 1965). Each branch of E. muricata is longer and wider than the microplastics characterized in this study passively filtering microplastics suspended in seawater. In contrast, the blades of P. limitata are much flatter and wider than that of E. muricata so that microplastics adhering to the surface of P. limitata blades, are more likely to be resuspended and swept away from the algae (Gutow et al., 2016). Previous laboratory experiments have confirmed that microplastics readily adhere to algal surfaces, but only after exposure to microplastic concentrations much higher than found in nature (Bhattacharya et al., 2010; Wright et al., 2013; Gutow et al., 2016). However, our field study showed that high concentrations of microplastics occurred on intertidal algae even when exposed to low levels in the natural environment. No other studies have described the ambient concentration of microplastics on macroalgae collected from the field (Yokota et al., 2017).

Microplastic density increased with trophic level. It was higher in the primary consumer, T. funebralis, than on the primary producers, which is consistent with the biomagnification of contaminants from lower to higher trophic levels by the ingestion of contaminated food (Farrell and Nelson, 2013). Each trophic level concentrates microplastics in different ways. Microplastics in seawater accumulate passively at oceanographic features, such as eddies, but are also found concentrated along coastlines with high human population-densities and industrial centers (Wright et al., 2013). In contrast, microplastics can accumulate in sediments by being buried beneath sand or rocks after settling from the water column as they become less buoyant over time or are submerged by fouling organisms (Barnes et al., 2009; Cole et al., 2011; Bour et al., 2018). Again, microplastics adhere to the surface of macroalgae (Bhattacharya et al., 2010; Gutow et al., 2016) or can be deposited within dense clusters at low flow. Both increase the availability of microplastics to primary grazers; either directly from fleshy tissue or in association with sediment within clusters of bushy algae. Finally, consumers accumulate microplastics by ingesting plants, animals or sediment (Wright et al., 2013).

In the intertidal community at BMR, the species composition of macroalgae within the sampling quadrat was not significantly correlated with microplastic density on *E. muricata* or *P. limitata*. Hence, higher densities of plastic-harboring *E. muricata* did not enhance the deposition of microplastics on either species of macroalgae, indicating that filtering of microplastics is limited to the scale of individual plants. Similarly, the microplastic concentration in *T. funebralis* was much more similar to that of *E. muricata* even though the snail prefers to eat *P. limitata* in the laboratory. Hence, the snail may consume more *E. muricata* in the field, where it prefers to reside, than in the laboratory where a snail is simply offered fragments of choice species.

Although our results are consistent with the literature there is a potential for contamination in our seawater samples, as the quality control samples were slightly contaminated with microplastics (0.043 TM·L⁻¹). However, slight contamination also has occurred in other studies (Mathalon and Hill, 2014) which highlights the challenge of quantifying microplastics in the environment (Rochman et al., 2019). Nevertheless, there were no microplastics in the quality control gastropod samples and these organisms had the highest particle concentration. Further investigations should include a more rigorous

environmental collection protocol as well as a greater number of replicates and volume of samples to accurately survey microplastics. Although this assessment is limited by only one round of sampling, the consequences of microplastic accumulation is concerning. Thus, a follow up to this project should include multiple sampling events throughout the year and greater sampling diversity within and across trophic feeding levels to truly understand potential trophic transfer within the community.

The adherence of microplastics to the surface of macroalgae can inhibit photosynthesis and trigger an oxidative stress response, though this was recorded under microplastic concentrations much higher than those observed in nature (Bhattacharya et al., 2010; Wright et al., 2013). The ingestion or digestion of microplastic leads to a wide range of physiological consequences for herbivorous grazers including decreases in energy reserves (Bour et al., 2018), physical blockages of the gastrointestinal system (Wright et al., 2013), intoxication by persistent organic pollutants (Rochman et al., 2013), translocation into the circulatory system (Browne et al., 2007, 2008), and disruption of the microbiome (Zettler et al., 2013). Grazers can also suffer reductions in recruitment (Green, 2016) and juvenile growth rates (Lo and Chan, 2018), leading to decreased population biomass that may change the structure of the intertidal community (Green, 2016).

Plastic production is increasing at a rate of over 8% per year, and the vast majority of plastic waste accumulates in the natural environment (Geyer et al., 2017). Our study shows that microplastic pollution is prevalent in the environment and two basal trophic levels of an intertidal community located in a sparsely populated area. We add to the long list of marine organisms and environments impacted by microplastic ecotoxicity, including bivalves and fishes that are marketed for human consumption (Rochman et al., 2015) as well as large pelagic animals like tuna (Romeo et al., 2015) and whales (Lusher et al., 2013; Besseling et al., 2015). Combating microplastic pollution likely requires intervention to protect organisms and ecosystems that may be particularly vulnerable. However, many of the current management schemes for protecting biodiversity and ecosystem function in our oceans, including MPAs, can do nothing to protect against microscopic pollutants (Boersma and Parrish, 1999; Agardy et al., 2011). Therefore, addressing the widespread threat that microplastics pose to global marine communities will demand innovative solutions to address the continued production and waste of plastics around the world.

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