



Microplastics are ubiquitous on California beaches and enter the coastal food web through consumption by Pacific mole crabs

Dorothy Horn*, Michaela Miller, Sean Anderson, Clare Steele

Environmental Science and Resource Management Program, California State University Channel Islands, United States of America



ARTICLE INFO

Keywords:

Microplastic
Emerita analoga
Marine food web
Pollution

ABSTRACT

Microplastics are commonly found in marine ecosystems, but their distribution, prevalence, and impacts on resident fauna are still not well understood. Microplastics in coastal sediments expose invertebrate infauna to the risk of ingestion of plastic debris and associated toxicants. We assessed the prevalence of microplastics in beach sediments and ingested by Pacific mole crabs (*Emerita analoga*) at sandy beaches spanning > 900 km of the California coast. Microplastics were present in sediments of every one of 51 beaches sampled. At a subset of 38 beaches Pacific mole crabs were collected and crabs at every beach had ingested microplastics. Across all beaches sampled, an average of 35% of Pacific mole crabs examined had microplastics in their guts. Our study demonstrates that microplastics are ubiquitous in sediments on California beaches and they are frequently consumed by a filter-feeding crustacean that is a common prey item in the diet of a wide variety of taxa, including fishes and birds.

1. Introduction

Several million tons of plastic debris enters the marine environment every year (Jambeck et al., 2015). Plastic litter in the ocean varies in size from meters to micrometers (Barnes et al., 2009). Some plastics enter the marine environment as primary microplastics, including resin pellets associated with industrial spills (EPA, 1992), engineered microbeads (used in toothpaste, facial washes, and related personal care products: Fendall and Sewell, 2009), and synthetic fibers shed from clothing. A single article of synthetic clothing can shed up to 1900 microfibrils per wash cycle (Browne et al., 2011). Secondary microplastics are formed when plastic flotsam, exposed to sun and wave action, breaks down into increasingly smaller pieces (Barnes et al., 2009; Cole et al., 2011), eventually becoming “microplastics” (< 5 mm in diameter: Masura et al., 2015).

The spatial distribution of marine microplastics is poorly characterized. Macroscopic marine debris is heterogeneously distributed at the scale of kilometers (Browne, 2015) to ocean basins (Pham et al., 2014) in both pelagic and littoral regions. The spatial distribution of microplastics may be more uniform than that of larger particles (Van Sebille et al., 2015) because they may behave more like idealized particles. However, recent investigations into microdebris, which have emphasized floating particles in distant pelagic regions of the world ocean such as the Great Pacific Garbage Patch (Browne, 2015), have

found general congruence between patterns of distribution of macro- and micro-debris. Microplastics have been commonly reported from littoral environments, including sandy beaches and nearshore sediments (Van Cauwenberghe et al., 2015), particularly near terrestrial sources such as urban cores (Reisser et al., 2015) and coastal river mouths (Van Sebille et al., 2015), however, factors governing the deposition and accumulation of microplastics are not well understood.

The Pacific coast of California can be divided into distinct littoral cells, typically characterized by inputs of sediment from creeks and rivers and eroding coastal bluffs, transport of sediment along the shoreline and losses from the system (e.g. into a submarine canyon) (Patsch and Griggs, 2007). Within each littoral cell, features like rivers, streams, in addition to providing sand to the cell (Patsch and Griggs, 2007), are likely inputs of macro- and micro-debris to coastal systems (Claessens et al., 2011). Because of this spatial structure of the California coastline, it would be valuable to know whether there are differences in the accumulation of microplastics among littoral cells.

Growing evidence from field studies reveals that microplastics are ingested by a variety of marine organisms from polar regions (Kühn et al., 2018), temperate seas (Murray and Cowie, 2011), to pelagic fishes adjacent to the North Pacific Subtropical Gyre (Davison and Asch, 2011; Choy and Drazen, 2013). In laboratory studies, Setälä et al. (2014) found that mysid shrimp, copepods, cladocerans, rotifers, polychaete larvae, and ciliates all ingested fluorescent polystyrene

* Corresponding author.

E-mail address: dhorn@pdx.edu (D. Horn).

beads. The consequences of microplastic consumption are not well established, but of particular concern is that microplastics can absorb persistent bio-accumulative toxin compounds (PBT) from seawater (Gouin et al., 2011). These include persistent organic pollutants and heavy metals (Mato et al., 2001). Once ingested, they can be transferred to an organism's tissue (Teuten et al., 2009). Ingestion of environmental plastics has been shown to alter endocrine system function in adult fish (Rochman et al., 2014), but only a handful of studies have found evidence of physiological or other negative effects of microplastic ingestion (Katsnelson, 2015). The growing evidence that marine organisms ingest and are negative impacted by microplastics, has generated concern that these pollutants are entering human food systems (Van Cauwenberghe and Janssen, 2014; Rochman et al., 2015).

Sandy beaches are one of the most widespread coastal ecosystems on the planet, yet the impacts of pollution in these important ecosystems has received relatively little attention (Wenner, 1988). We explored the prevalence and consequences of microplastics on sandy beaches along > 900 km of the California coastline, of which 80% (King et al., 2011) is sandy beach habitat. In this habitat, Pacific mole crabs are one of the most common macroinvertebrates in sandy beach ecosystems, making up 84% of the biomass in the California sandy beach habitat (Nielsen et al., 2013). Overall, they are five times more abundant than any other sandy beach invertebrate in this region (Nielsen et al., 2013), which makes them an excellent food source for shore birds (Dugan et al., 2003; MacGinitie, 1938) and nearshore fishes (Carlisle et al., 1960). For example, the barred surfperch feeds almost exclusively on sand crabs, making up to 90% of its diet (Carlisle et al., 1960). As such, they may be a useful indicator species, with their populations reflecting the dynamic physical environment of sandy beaches (Dugan et al., 1994; Veas et al., 2013) and ecotoxicology, taking up persistent organic pollutants (POPs) directly, and via their filter-feeding consumption of POPs adsorbed onto small particulates < 2000 μm (Burnett, 1971; Odum, 1966). Pacific mole crabs have been used to detect domoic acid (Powell et al., 2002), harmful algal bloom increases (Kvitek and Bretz, 2005), and as a biomonitor for heavy metal pollution (Valdovinos and Zuniga, 2002) and DDT (Burnett, 1971) along the coastline. Because they are preyed on by a wide variety of vertebrates, they may be a key link in trophic transfer of harmful substances in the coastal food web (Kvitek et al., 2008).

On the sandy beaches of California, we (1) documented the distribution of microplastics in sediment samples from 51 beaches; and (2) evaluated the prevalence of microplastics in the guts of a filter feeding crustacean, the Pacific mole crab (*Emerita analoga*), sampled from 38 of those beaches.

2. Methods

Along approximately 900 km of the California coast, from Marin county to San Diego county, and on two of the Channel Islands (Santa Cruz and Santa Rosa), we collected samples of sediment from 51 beaches. On each beach, two 100 mL samples of sand were collected by scraping the surface to approximately 10 cm depth: one from the swash zone and one from the high tide line. To assess the density of microplastics in beach sediments, 400 mL of hyper-saline solution was added to each 100 mL sand sample to suspend the microplastics, following the methods of Thompson et al. (2004). The supernatant was filtered and the microplastics captured on each filter were enumerated and categorized by shape, color, and form. To ascertain if there was any difference between samples obtained from the swash zone or high-tide line areas of beaches, a paired *t*-test was used to compare number of microplastic particles separated from 100 mL of sediment. Because that test revealed no difference between swash zone and high-tide line samples, the average of those two samples was used for each beach in subsequent tests.

We used a general linear model to test whether the mean number of microplastic items in sediments from 51 beaches depended land use

(urban, agriculture or rural), or absence or presence of a creek on the beach or littoral cell (Habel and Armstrong, 1978; Patsch and Griggs, 2007). Land use type proximal to beaches and the presence of a stream was determined from satellite imagery, mainly defined by rivers/creeks (inputs), shoreline deposition, and longshore transport. The mean number of microplastic items per 100 mL of sediment was square-root transformed to satisfy assumptions of normality and homogeneity of variance. All statistical tests were completed using Systat 12 Version 12.02.00.

We collected Pacific mole crabs on 38 of the 51 beaches to determine whether they had ingested microplastics (Fig. S1.). Due to logistical constraints we could not collect crabs from every one of the 51 sites. We haphazardly collected 5–15 Pacific mole crabs from aggregations in the swash zone (Efford, 1965), using a shovel or a sand-coring tool, and frozen immediately or placed into a solution of 95% ethanol for preservation until they could be dissected in the laboratory (Fig. 1). We minimized contamination of samples and equipment from environmental microplastics and fibers shed from clothing by the use of nitrile gloves and white cotton lab coats for every dissection. Single crabs were placed individual glass petri dishes and all tools used were washed with deionized water and a 95% ethanol solution between each dissection to minimize the possibility of sample contamination. Carapace length and width were measured to the nearest 0.1 mm. The digestive tracts of dissected crabs were examined for plastic particles or fibers visually, using stereomicroscopy. We characterized microplastics with (Micro ATR FT-IR) Spectroscopy from a small, randomized subsample of particles from sand samples ($n = 10$ particles) and crabs ($n = 10$ fibers).

At 38 beaches where we obtained Pacific mole crab samples, we used a mixed-model ANOVA to test for effects of location (northern California, central California, southern California, or Island beaches), land use, creek presence, and for differences among beaches in the number of microplastic items ingested per crab, where location, land use and creek presence were fixed factors and beach was a random factor.

The natural geographical breaks of Monterey Bay and Point Conception divided the north, central and southern California coast. Land use type proximal to beaches and the presence of a stream was determined from satellite imagery.

An ordinary least squares regression was used to test if the proportion of crabs at a beach with microplastics present in the gut was influenced by the density of microplastics (number of microplastic items per 100 mL of sediment) at that beach. The proportion of crabs per beach that had ingested microplastics was arcsine square-root transformed and the number of microplastic items per 100 mL of sediment was square-root transformed to satisfy assumptions of normality and homogeneity of variances.

To evaluate whether there was a difference in the size of crabs that had ingested microplastics versus those that had not, a *t*-test was used. To explore whether the number of microplastic items present in the gut was a function of crab size, a linear regression was used. The size of each crab was determined by measuring the carapace length from the point on the rostrum to the crease separating the carapace and the abdomen (Efford, 1966; Dugan et al., 1994).

3. Results

Microplastics were found to be present at every one of the 51 beaches sampled (Fig. 2.) The number of microplastic items per 100 mL of sediment ranged from 0 to 60 (11.75 ± 10.64 , mean $\pm$ SD). The vast majority of microplastic items were fibers (95%) and the remainder were particles (Fig. 2). Representative items characterized by micro ATR FT-IR spectroscopy included polypropylene, isotactic polypropylene, atactic polypropylene, polyacrylate, polyethylene, and polyester. All 10 plastic particles examined from sand samples were plastic polymer blends. However, of the 10 fibers extracted from sand

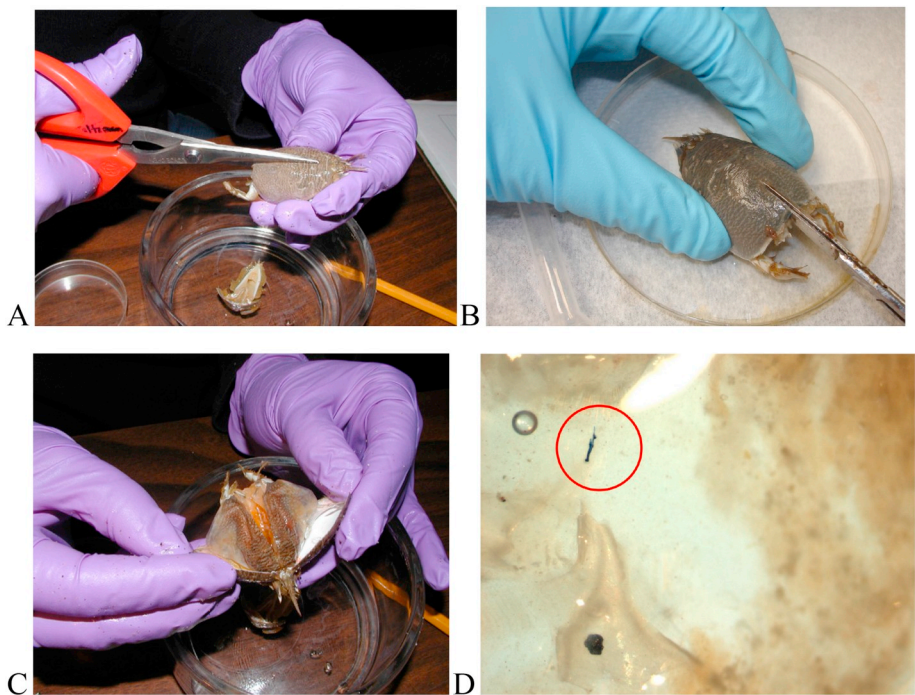


Fig. 1. Dissection of Pacific mole crab. A. Posterior end of crab removed. B. Carapace cut up the middle of the dorsal side. C. Dorsal surface opened to examine interior. D. Plastic fiber found inside a mole crab.

crabs, 5 were a plastic polymer blend and 5 were cellulose based. (See Fig. 1.) (See Tables 1 and 2.)

There was no significant difference between the number of microplastic items per 100 mL sediment sample from the swash zone and high tide line areas of beaches ($t = 1.18, p = 0.24, df = 50$). The abundance of microplastics in sediment, and the relative proportion of fibers versus particles differed among beaches (Fig. 2). The number of microplastic items per 100 mL of sand differed significantly among littoral cells ($F_{6,28} = 2.95, p = 0.02$) (Fig. 4), but did not differ significantly with land use type proximal to the beach ($F_{2,28} = 0.23, p = 0.80$) or creek presence ($F_{1,28} = 1.33, p = 0.26$).

Microplastics were found in the digestive tracts of Pacific mole crabs from every one of the 38 beaches where they were collected. Averaged over all beaches, 35% of crabs had microplastics in their digestive tracts. On individual beaches, the proportion of crabs with

Table 1
Results of ANOVA testing for effects of littoral cell, land use, and creek presence on the number of microplastic items per 100 mL sand.

	df	Mean Squares	F-ratio	p-Value
Littoral cell	6	3.88	3.20	0.01
Land use	2	0.57	0.47	0.63
Creek	1	0.25	0.21	0.65
Error	41	1.21		

microplastics in their digestive tracts ranged from 10 to 80% (Fig. 3). Individual crabs had an average of 0.65 ± 1.64 (mean $\pm$ SD) microplastic items present in the gut, with a maximum of 16 microplastic items per crab. Crabs with microplastics present in the gut did not differ

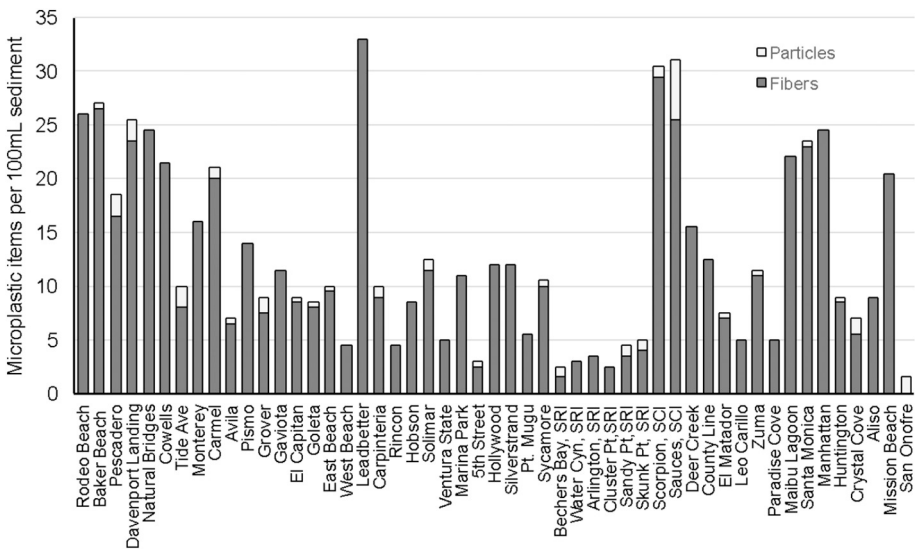


Fig. 2. Average number of microplastic items per 100 mL of sediment from 51 sandy beaches along 900 km of the California coast. Error bars omitted for clarity.

Table 2

Results of mixed-model ANOVA testing for effects of location, land use, creek presence, and for differences among beaches on the number of microplastic items ingested per Pacific mole crab, where location, land use and creek presence were fixed factors and beach was a random factor.

	Numerator df	Denominator df	Mean Squares	F-ratio	p-Value
Location	3	30.6	1.49	0.31	0.82
Land Use	2	31.0	1.23	0.26	0.77
Creek	1	22.3	0.28	0.05	0.83
Location*Land Use	3	25.7	0.27	0.05	0.98
Location*Creek	2	30.1	0.16	0.03	0.97
Land Use*Creek	2	34.5	0.64	0.14	0.87
Beach(Creek*Land Use*Location)	24	282.0	5.42	2.21	0.001
Error		282.0	2.45		

significantly in size (carapace length) from those without ($t = 1.76$, $df = 318$, $p = 0.08$), but of those crabs that had ingested microplastics, larger crabs had significantly more microplastic items in their guts than smaller crabs, though the predictive power of the relationship was weak ($r^2 = 0.09$, $p < 0.01$, $n = 105$; Fig. 5).

The number of microplastic items ingested by crabs was not related to location ($F_{3,24} = 0.31$, $p = 0.82$), land use type proximal to the beach ($F_{2,24} = 0.26$, $p = 0.77$), or the presence of a creek ($F_{1,24} = 0.05$, $p = 0.83$). The proportion of crabs at a beach that had microplastics present in the gut was not related to the density of microplastics in the sediment at that beach ($r^2 = 0.001$, $p = 0.81$, $n = 38$; Fig. 6).

4. Discussion

4.1. Distribution of microplastics

We found microplastics in the sediment at every beach sampled along 900 km of the California coastline, and in Pacific mole crabs at every beach where they were collected. The density of microplastics in our sediment samples from the California coast was comparable with other studies using similar methodologies with beach and subtidal sediments around the coasts of Sweden (Norén, 2007), United Kingdom (Thompson et al., 2004; Browne et al., 2010) and Florida and Maine in

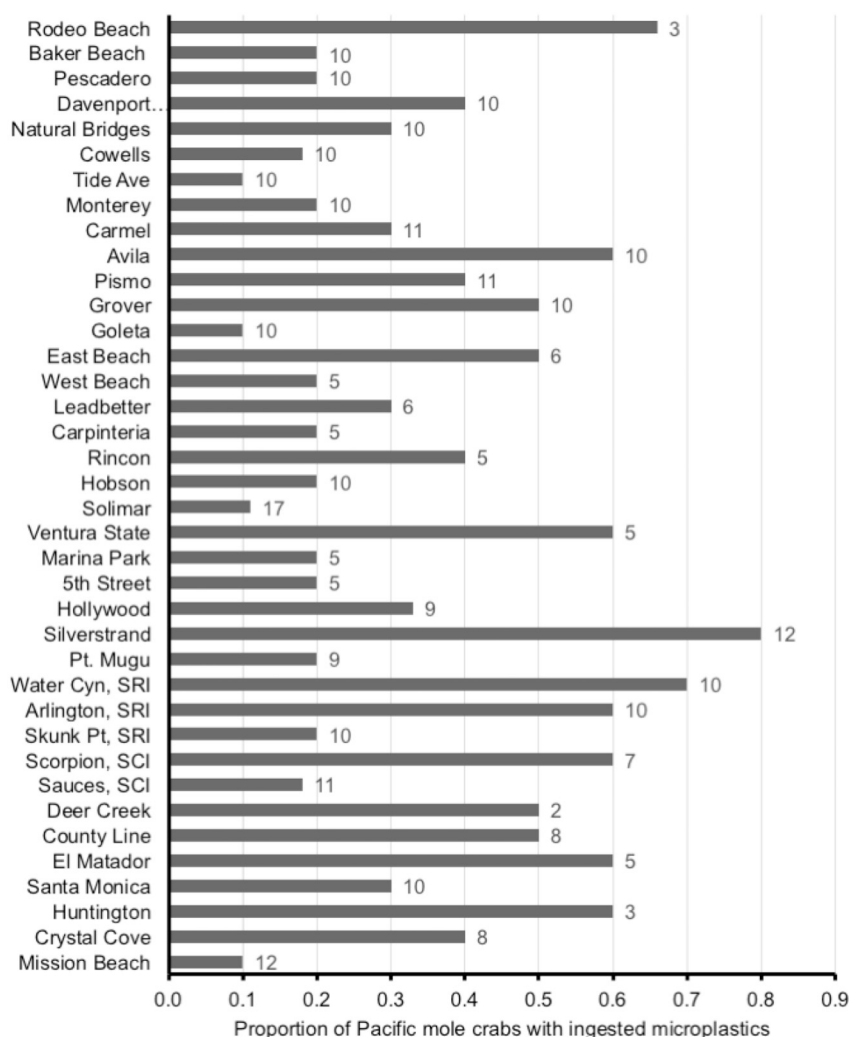


Fig. 3. Proportion of Pacific mole crabs (*Emerita analoga*) that were found to have microplastic items present in their guts at 38 beaches in California ($n = 320$). Bars are labeled with the number of Pacific mole crabs collected at each beach.

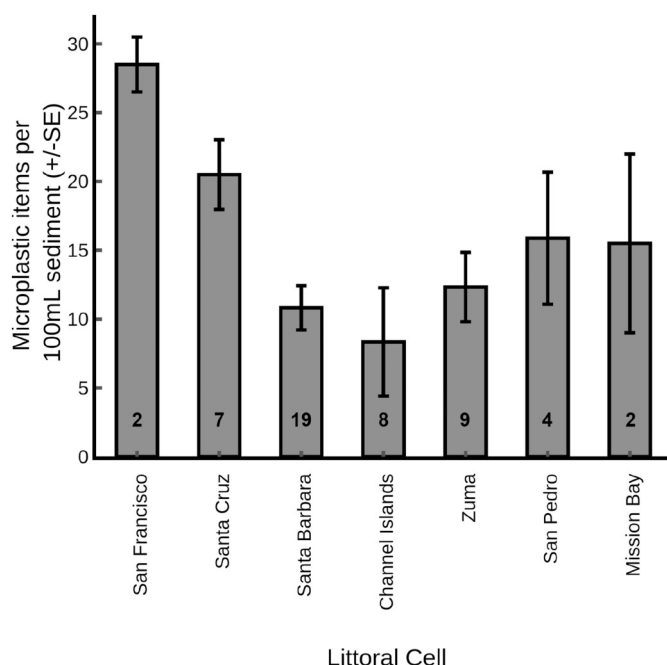


Fig. 4. Mean number of microplastic items per 100 mL of sediment ($\pm$ SE) from 51 beaches within seven littoral cells on the California coast. Littoral cells are labeled with the number of beaches examined for microplastics within each cell.

the United States of America (Graham and Thompson, 2009). The processes that determine the distribution and accumulation of microplastic items in sediments are not well understood (Van Cauwenberghe et al., 2015). The various sources of marine microplastics (Browne, 2015), their physical properties (Murray and Cowie, 2011), formation of biofilms (Ye and Andrad, 1991; Lobelle and Cunliffe, 2011) and nearshore oceanographic processes act to influence the distribution of microplastics in beach sediments. Shores around the world are contaminated with polyester, acrylic, polypropylene, polyethylene, and polyamide fibers, which may be discharged from washing machine effluent, in wastewater, and via sewage treatment plants (Thompson

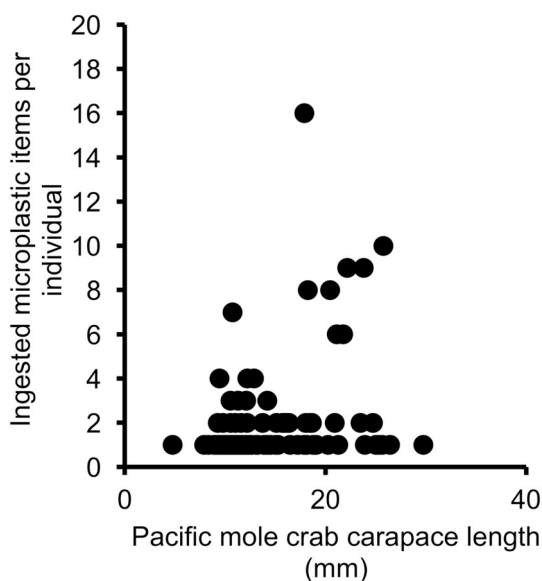


Fig. 5. Of Pacific mole crabs that had ingested microplastics, larger crabs tended to have more microplastic items in their guts than smaller crabs ($r^2 = 0.09$, $p < 0.01$, $n = 105$).

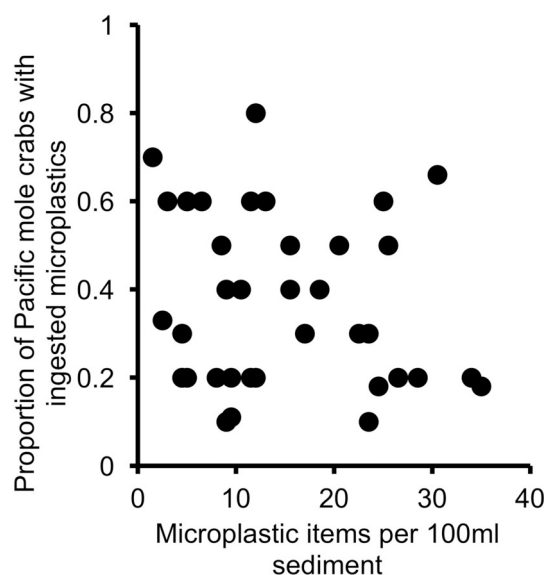


Fig. 6. The proportion of Pacific mole crabs at a beach with microplastics present in the gut was not significantly influenced by the density of microplastics (number of microplastic items per 100 mL of sediment) at that beach ($r^2 = 0.001$, $p = 0.81$, $n = 38$).

et al., 2009). Although microplastics appear to be more abundant in areas that are more densely populated by humans (reviewed in Van Cauwenberghe et al., 2015), microplastics have been found in areas remote from human habitation (Thompson et al., 2009; Lavers and Bond, 2017).

We found that microplastic abundance differed among littoral cells. Beach sediments in California are predominantly derived from rivers (Willis et al., 2002) and littoral cells form the framework for understanding the sources, sinks and transport of sediments in the nearshore environment along the California coast (Patsch and Griggs, 2007). The composition of beaches within a littoral cell, therefore, is reflective of land-based and nearshore processes at that regional scale. Differences we observed in microplastic distribution at the littoral cell scale is likely to be reflective of the influences of human population density and freshwater inputs combined with nearshore oceanographic processes acting within each cell. Although higher concentrations of microplastic in sediments have been found near freshwater inputs (Claessens et al., 2011; Vianello et al., 2013), we found no significant influence of local, land-based inputs at the scale of individual beaches, despite differences among littoral cells. Some of the lowest concentrations of microplastics in our study were at the uninhabited Channel Islands (> 20 miles from the mainland coast). Although the Channel Islands are an uninhabited, protected area, the composition of microplastic items (fibers vs particles) was similar to mainland beaches, which suggests a mainland origin of microplastics, and that microplastics from freshwater sources may be being redistributed on the open coast.

Within beaches, we found no evidence that microplastic density differed among beach zones. There was no significant difference in the abundance of microplastic items between the high tide line and the swash zone. Elsewhere, macroplastics and larger microplastic particles (> 2 mm) have been shown to accumulate at the high tide line (Heo et al., 2013). Our contrasting finding may be a result of the types of microplastics that were most prevalent in our samples, fibers rather than particles accounted for about 95% of all microplastic items in the sediments we collected.

4.2. Ingestion of microplastics

The increase in abundance of microplastics in marine systems (Thompson et al., 2004; Claessens et al., 2011) and their small size

(among other factors governing their bioavailability) gives them the potential to be ingested by wide range of organisms. The susceptibility of species to microplastic ingestion will be dependent upon the concentration of microplastics in an organism's habitat, feeding mode, and selectivity (Wright et al., 2013). Beaches have particularly high densities of plastics (Sherrington, 2016) and microplastics are found at high concentrations in intertidal coastal sediments (Thompson et al., 2004). Biota inhabiting these sedimentary habitats, including deposit and detritus-feeding organisms and planktivores, filter- and suspension-feeders that occupy the adjacent shallow-water intertidal are exposed to the risk of microplastic ingestion. Pacific mole crabs feed on plankton at the interface of these shallow-water intertidal habitats where wave action may mix and resuspend microplastics of various densities. The selectivity of their filter-feeding mode is based upon size (Knox and Boolootian (1963) and particle wettability/adhesion (Conova, 1999; Ward and Shumway, 2004), therefore, depending on the physical and surface properties (including biofilms), they are likely ingesting plankton-sized microplastics (0.004 to 2 mm diameter (Efford, 1966)) present at the water/sediment margin. Sand crabs use a set of antennae with feather-like structures to feed. These antennae are unfolded and held up above the sand to capture food as the rushing water passes thru them (Efford, 1965). While the water is rushing over, the antennae are pulled into the feeding cavity and any food and sand is scraped off for digestion (Efford, 1965). This feeding method allows the sand crab to collect small particles of food but also ends up with sand particles in its digestive tract (Efford, 1965). It is possible that microfibrils are more available than plastic particles to filter feeders, because they are more abundant, more readily suspended by wave action, and more “sticky” (Ward and Shumway, 2004) due to their chemical makeup. Based on a small subsample, we found that about half of fibers ingested by Pacific mole crabs were cellulose based, a trend that follows recent findings that up to or more than half the fibers ingested are cellulose based (Rochman et al., 2015; Davidson and Dudas, 2016; Zhao et al., 2016). Although the presence of microplastics in the gut of Pacific mole crabs was common on beaches in our study, we found no predictive relationship between high microplastic density at a beach and the proportion of crabs that had ingested microplastics.

It is increasingly apparent that microplastics are ubiquitous in marine ecosystems and throughout the food web. Ingestion of microplastics has been reported from a wide variety of organisms from zooplankton (Desforges et al., 2015) to megafauna (Germanov et al., 2018), where organisms at a variety of trophic levels (including polychaetes, crustaceans, echinoderms, bryozoans, bivalves, fish, seabirds and marine mammals) may consume microplastics directly or via lower trophic levels (Von Moos et al., 2012; Lusher, 2015). Pacific mole crabs are one of the dominant macro-invertebrates in sandy beach ecosystems. Their abundance and broad geographical distribution makes them a useful indicator species in the detection of pollutants, such as DDT, domoic acid, and heavy metals in sandy beach habitats (Burnett, 1971; Powell et al., 2002; Valdovinos and Zuniga, 2002; Kvitek and Bretz, 2005). As filter-feeders inhabiting the shallow, nearshore waters, and as prey for a variety of shorebirds (Kvitek and Bretz, 2005) and nearshore fishes, including fishery-target species (Perry, 1980), they may be an important mechanism for the introduction of microplastics into near-shore food-webs. Microplastics may act as a pathway for pollutants to transfer into the tissues of marine organisms (Browne et al., 2013) and ingestion of plastics by a variety of marine organisms has been shown to have deleterious effects (Von Moos et al., 2012). Although evidence for trophic transfer is currently being investigated (Eriksson and Burton, 2003; Murray and Cowie, 2011), with continued inputs of microplastics into marine ecosystems, trophic transfer and bioaccumulation of microplastics and associated toxicants appears inevitable. Effects on human health of exposure to micro- and nano-plastics via a variety of pathways, including consumption of seafood products (Galloway, 2015) is a growing concern.

Acknowledgements

This research was partially supported by USDA NIFA Award No. 2015-38422-24058. Award Title Water Resources Experiential Learning for USDA Careers. We want to thank our colleagues from California State University Channel Islands, including Kiki Patsch who provided insight on littoral cells, Tevin Schmidt and Vanessa Van Heerden for their assistance in the beginning of the project, Ralph Diego and others for their work in the field, and those who helped collect crabs for the project. We thank Mark Steele for providing helpful suggestions on the manuscript. We thank two anonymous reviewers and the special issue managing guest editor Amy Uhrin for comments and suggestions that improved this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.marpolbul.2018.12.039>.

References

- Barnes, D.K., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. *Philos. Trans. R. Soc. B* 364, 1985–1998.
- Browne, M.A., 2015. Sources and pathways of microplastics to habitats. In: *Marine Anthropogenic Litter*. Springer, pp. 229–244.
- Browne, M.A., Galloway, T.S., Thompson, R.C., 2010. Spatial patterns of plastic debris along estuarine shorelines. *Environ. Sci. Technol.* 44, 3404–3409.
- Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., Thompson, R., 2011. Accumulation of microplastic on shorelines worldwide: sources and sinks. *Environ. Sci. Technol.* 45, 9175–9179.
- Browne, M.A., Niven, S.J., Galloway, T.S., Rowland, S.J., Thompson, R.C., 2013. Microplastic moves pollutants and additives to worms, reducing functions linked to health and biodiversity. *Curr. Biol.* 23, 2388–2392.
- Burnett, R., 1971. DDT residues: distribution of concentrations in *Emerita analoga* (Stimpson) along coastal California. *Science* 174, 606–608.
- Carlisle, J.G., Schott, J.W., Abramson, N.J., 1960. The Barred Surfperch (*Amphistichus argenteus* Agassiz) in Southern California. (Department of Fish and Game, Print. Division, Documents Section).
- Choy, C.A., Drazen, J.C., 2013. Plastic for dinner? Observations of frequent debris ingestion by pelagic predatory fishes from the central North Pacific. *Mar. Ecol. Prog. Ser.* 485, 155–163.
- Claessens, M., De Meester, S., Van Landuyt, L., De Clerck, K., Janssen, C.R., 2011. Occurrence and distribution of microplastics in marine sediments along the Belgian coast. *Mar. Pollut. Bull.* 62, 2199–2204.
- Cole, M., Lindeque, P., Halsband, C., Galloway, T.S., 2011. Microplastics as contaminants in the marine environment: a review. *Mar. Pollut. Bull.* 62, 2588–2597.
- Conova, S., 1999. Role of particle wettability in capture by a suspension-feeding crab (*Emerita talpoida*). *Mar. Biol.* 133, 419–428.
- Davidson, K., Dudas, S.E., 2016. Microplastic ingestion by wild and cultured Manila clams (*Venerupis philippinarum*) from Baynes Sound, British Columbia. *Arch. Environ. Contam. Toxicol.* 71, 147–156.
- Davison, P., Asch, R.G., 2011. Plastic ingestion by mesopelagic fishes in the North Pacific Subtropical Gyre. *Mar. Ecol. Prog. Ser.* 432, 173–180.
- Desforges, J.-P.W., Galbraith, M., Ross, P.S., 2015. Ingestion of microplastics by zooplankton in the Northeast Pacific Ocean. *Arch. Environ. Contam. Toxicol.* 69, 320–330.
- Dugan, J.E., Hubbard, D.M., Wenner, A.M., 1994. Geographic variation in life history of the sand crab, *Emerita analoga* (Stimpson) on the California coast: relationships to environmental variables. *J. Exp. Mar. Biol. Ecol.* 181, 255–278.
- Dugan, J.E., Hubbard, D.M., McCrary, M.D., Pierson, M.O., 2003. The response of macrofauna communities and shorebirds to macrophyte wrack subsidies on exposed sandy beaches of southern California. *Estuar. Coast. Shelf Sci.* 58, 25–40.
- Efford, I.E., 1965. Aggregation in the sand crab, *Emerita analoga* (Stimpson). *J. Anim. Ecol.* 63–75.
- Efford, I.E., 1966. Feeding in the sand crab, *Emerita analoga* (Stimpson) (Decapoda, Anomura). *Crustaceana* 10, 167–182.
- Eriksson, C., Burton, H., 2003. Origins and biological accumulation of small plastic particles in fur seals from Macquarie Island. *AMBIO J. Hum. Environ.* 32, 380–384.
- Fendall, L.S., Sewell, M.A., 2009. Contributing to marine pollution by washing your face: microplastics in facial cleansers. *Mar. Pollut. Bull.* 58, 1225–1228.
- Galloway, T.S., 2015. Micro- and nano-plastics and human health. In: *Marine Anthropogenic Litter*. Springer, pp. 343–366.
- Germanov, E.S., Marshall, A.D., Bejder, L., Fossi, M.C., Loneragan, N.R., 2018. Microplastics: no small problem for filter-feeding megafauna. *Trends Ecol. Evol.* 33, 227–232.
- Gouin, T., Roche, N., Lohmann, R., Hodges, G., 2011. A thermodynamic approach for assessing the environmental exposure of chemicals absorbed to microplastic. *Environ. Sci. Technol.* 45, 1466–1472.

- Graham, E.R., Thompson, J.T., 2009. Deposit-and suspension-feeding sea cucumbers (Echinodermata) ingest plastic fragments. *J. Exp. Mar. Biol. Ecol.* 368, 22–29.
- Habel, J., Armstrong, G., 1978. Assessment and Atlas of Shoreline Erosion Along the California Coast. California Department of Navigation and Ocean Development, pp. 277.
- Heo, N.W., Hong, S.H., Han, G.M., Hong, S., Lee, J., Song, Y.K., Jang, M., Shim, W.J., 2013. Distribution of small plastic debris in cross-section and high strandline on Heungnam beach, South Korea. *Ocean Sci. J.* 48, 225–233.
- Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. *Science* 347, 768–771.
- Katsnelson, A., 2015. News feature: microplastics present pollution puzzle. *Proc. Natl. Acad. Sci.* 112, 5547–5549.
- King, P.G., McGregor, A.R., Whittet, J.D., 2011. The Economic Costs of Sea-level Rise to California Beach Communities. Fresno: California Department of Boating and Waterways (Retrieved October 1:2010).
- Knox, C., Boolootian, R.A., 1963. Functional morphology of the external appendages of *Emerita analoga*. *Bull. South. Calif. Acad. Sci.* 62, 45–68.
- Kühn, S., Schaafsma, F.L., van Werven, B., Flores, H., Bergmann, M., Egelkraut-Holtus, M., Tekman, M.B., van Franeker, J.A., 2018. Plastic ingestion by juvenile polar cod (*Boreogadus saida*) in the Arctic Ocean. *Polar Biol.* 1–10.
- Kvitek, R., Bretz, C., 2005. Shorebird foraging behavior, diet, and abundance vary with harmful algal bloom toxin concentrations in invertebrate prey. *Mar. Ecol. Prog. Ser.* 293, 303–309.
- Kvitek, R., Panáček, A., Soukupova, J., Kolář, M., Večeřová, R., Prucek, R., Holecova, M., Zbořil, R., 2008. Effect of surfactants and polymers on stability and antibacterial activity of silver nanoparticles (NPs). *J. Phys. Chem. C* 112, 5825–5834.
- Lavers, J.L., Bond, A.L., 2017. Exceptional and rapid accumulation of anthropogenic debris on one of the world's most remote and pristine islands. *Proc. Natl. Acad. Sci.* 114, 6052–6055.
- Lobelle, D., Cunliffe, M., 2011. Early microbial biofilm formation on marine plastic debris. *Mar. Pollut. Bull.* 62, 197–200.
- Lusher, A., 2015. Microplastics in the marine environment: distribution, interactions and effects. In: *Marine Anthropogenic Litter*. Springer, pp. 245–307.
- MacGinitie, G., 1938. Movements and mating habits of the sand crab, *Emerita analoga*. *Am. Midl. Nat.* 471–481.
- Masura, J., Baker, J.E., Foster, G.D., Arthur, C., Herring, C., 2015. Laboratory methods for the analysis of microplastics in the marine environment: recommendations for quantifying synthetic particles in waters and sediments. In: *NOAA Technical Memorandum NOS-OR&R-48*.
- Mato, Y., Isobe, T., Takada, H., Kanehiro, H., Ohtake, C., Kaminuma, T., 2001. Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. *Environ. Sci. Technol.* 35, 318–324.
- Murray, F., Cowie, P.R., 2011. Plastic contamination in the decapod crustacean *Nephrops norvegicus* (Linnaeus, 1758). *Mar. Pollut. Bull.* 62, 1207–1217.
- Nielsen, K.J., Morgan, S.G., Dugan, J.E., 2013. Baseline Characterization of Sandy Beach Ecosystems in California's North-Central Coast Region.
- Norén, F., 2007. Small Plastic Particles in Coastal Swedish Waters. N-Research Report, Commissioned by KIMO Sweden. (Submitted to BDC).
- Odum, E.P., 1966. The strategy of ecosystem development. *Science* 164.
- Patsch, K., Griggs, G., 2007. Development of Sand Budgets for California's Major Littoral Cells. Institute of Marine Sciences.
- Perry, D.M., 1980. Factors influencing aggregation patterns in the sand crab *Emerita analoga* (Crustacea: Hippidae). *Oecologia* 45, 379–384.
- Pham, C.K., Ramirez-Llodra, E., Alt, C.H., Amaro, T., Bergmann, M., Canals, M., Davies, J., Duineveld, G., Galgani, F., Howell, K.L., 2014. Marine litter distribution and density in European seas, from the shelves to deep basins. *PLoS One* 9, e95839.
- Powell, C.L., Ferdin, M., Busman, M., Kvitek, R.G., Doucette, G.J., 2002. Development of a protocol for determination of domoic acid in the sand crab (*Emerita analoga*): a possible new indicator species. *Toxicon* 40, 485–492.
- Reisser, J.W., Slat, B., Noble, K.D., Plessis, K.D., Epp, M., Proietti, M.C., Sonnevile, J.d., Becker, T., Pattiaratchi, C., 2015. The Vertical Distribution of Buoyant Plastics at Sea: an Observational Study in the North Atlantic Gyre.
- Rochman, C.M., Kurobe, T., Flores, I., Teh, S.J., 2014. Early warning signs of endocrine disruption in adult fish from the ingestion of polyethylene with and without sorbed chemical pollutants from the marine environment. *Sci. Total Environ.* 493, 656–661.
- Rochman, C.M., Tahir, A., Williams, S.L., Baxa, D.V., Lam, R., Miller, J.T., Teh, F.-C., Werorilangi, S., Teh, S.J., 2015. Anthropogenic debris in seafood: plastic debris and fibers from textiles in fish and bivalves sold for human consumption. *Sci. Rep.* 5, 14340.
- Sciences, B. O., U. S. E. P. A. Oceans, and C. P. Division, 1992. Plastic Pellets in the Aquatic Environment: Sources and Recommendations. United States Environmental Protection Agency, Office of Water.
- Setälä, O., Fleming-Lehtinen, V., Lehtiniemi, M., 2014. Ingestion and transfer of microplastics in the planktonic food web. *Environ. Pollut.* 185, 77–83.
- Sherrington, C., 2016. Plastics in the marine environment. In: *EUNOMIA (June 2016)*, . <http://www.eunomia.co.uk/reports-tools/plastics-in-the-marine-environment>.
- Teuten, E.L., Saquing, J.M., Knappe, D.R., Barlaz, M.A., Jonsson, S., Björn, A., Rowland, S.J., Thompson, R.C., Galloway, T.S., Yamashita, R., 2009. Transport and release of chemicals from plastics to the environment and to wildlife. *Philos. Trans. R. Soc. Lond. B* 364, 2027–2045.
- Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? *Science* 304, 838.
- Thompson, R.C., Moore, C.J., Vom Saal, F.S., Swan, S.H., 2009. Plastics, the environment and human health: current consensus and future trends. *Philos. Trans. R. Soc. Lond. B* 364, 2153–2166.
- Valdovinos, C., Zuniga, M., 2002. Copper acute toxicity tests with the sand crab *Emerita analoga* (Decapoda: Hippidae): a biomonitor of heavy metal pollution in Chilean coastal seawater? *Bull. Environ. Contam. Toxicol.* 69, 393–400.
- Van Cauwenberghe, L., Janssen, C.R., 2014. Microplastics in bivalves cultured for human consumption. *Environ. Pollut.* 193, 65–70.
- Van Cauwenberghe, L., Devriese, L., Galgani, F., Robbins, J., Janssen, C.R., 2015. Microplastics in sediments: a review of techniques, occurrence and effects. *Mar. Environ. Res.* 111, 5–17.
- Van Sebille, E., Wilcox, C., Lebreton, L., Maximenko, N., Hardesty, B.D., Van Franeker, J.A., Eriksen, M., Siegel, D., Galgani, F., Law, K.L., 2015. A global inventory of small floating plastic debris. *Environ. Res. Lett.* 10, 124006.
- Veas, R., Hernández-Miranda, E., Quiñones, R., Díaz-Cabrera, E., Rojas, J., Fariña, J., 2013. The influence of environmental factors on the abundance and recruitment of the sand crab *Emerita analoga* (Stimpson 1857): source-sink dynamics? *Mar. Environ. Res.* 89, 9–20.
- Vianello, A., Boldrin, A., Guerriero, P., Moschino, V., Rella, R., Sturaro, A., Da Ros, L., 2013. Microplastic particles in sediments of Lagoon of Venice, Italy: first observations on occurrence, spatial patterns and identification. *Estuar. Coast. Shelf Sci.* 130, 54–61.
- Von Moos, N., Burkhardt-Holm, P., Köhler, A., 2012. Uptake and effects of microplastics on cells and tissue of the blue mussel *Mytilus edulis* L. after an experimental exposure. *Environ. Sci. Technol.* 46, 11327–11335.
- Ward, J.E., Shumway, S.E., 2004. Separating the grain from the chaff: particle selection in suspension-and deposit-feeding bivalves. *J. Exp. Mar. Biol. Ecol.* 300, 83–130.
- Wenner, A.M., 1988. Crustaceans and other invertebrates as indicators of beach pollution. In: *Marine Organisms as Indicators*. Springer, pp. 199–229.
- Willis, C., Sherman, D., Lockwood, B., 2002. Chapter 7: impediments to fluvial delivery of sediment to the shoreline. In: *California Beach Restoration Study*. California Boating and Waterways and State Coastal Conservancy, Sacramento, California (280p).
- Ye, S., Andrady, A.L., 1991. Fouling of floating plastic debris under Biscayne Bay exposure conditions. *Mar. Pollut. Bull.* 22, 608–613.
- Zhao, S., Zhu, L., Li, D., 2016. Microscopic anthropogenic litter in terrestrial birds from Shanghai, China: not only plastics but also natural fibers. *Sci. Total Environ.* 550, 1110–1115.