PLASTIC DEBRIS IN DEEP-SEA CANYON, ESTUARINE, AND SHORELINE SEDIMENTS

by

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Approved: ____
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Recent calculations estimate there are currently 5.25 trillion plastic particles afloat in the ocean. Many of these are characterized as microplastics < 5 mm in diameter. Studies from the past decade have shown that no ecosystem is exempt from plastic contamination. This study examined box core sediment samples from Norfolk Canyon, box core and PONER grab samples from the Coos Bay Estuary, and belt transects along the Oregon shoreline to investigate plastic in marine sediments. The average microplastic density in Norfolk Canyon was 12.95 particles per liter of sediment within the canyon, and 2.04 particles per liter of sediment on the adjacent continental slope. I hypothesize that canyons concentrate microplastics due to down-canyon turbidity currents. In the Coos Bay Estuary, the highest density of microplastics was found in the mouth of the estuary. I hypothesize that plastics can sink due to the front created at the intersection between oceanic and estuarine waters, and can become concentrated around geologically structured areas in the estuary mouth. Using belt transects, I surveyed plastic densities on the northern and southern sides of Yaquina Head, Cape Perpetua, and Cape Blanco.

Higher plastic densities were found on the southern beaches in each case. I hypothesize that microplastics may be carried onshore by winds, which blow onto southern-facing beaches on Oregon’s coast during the winter. It is important to understand where plastics are concentrated in marine sediments in order to form hypotheses about both horizontal and vertical transport of plastic in the ocean.

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Introduction

Plastic pollution is a threat to the health of the ocean (Loder and Gerdts, 2015; Rahmstorf and Richardson, 2009). Recent calculations of the amount of marine plastic estimate that there are currently 5.25 trillion plastic particles afloat in the world's oceans (Eriksen et al., 2014; Loder and Gerdts, 2015). Pollution by plastic materials is a danger to marine organisms due to ingestion, entanglement, and habitat destruction (Allsopp et al., 2009; Rahmstorf and Richardson, 2009). These plastic materials are not only bottles and bags; many are characterized as microplastics.

Microplastics in the Marine Environment

Microplastics are defined as plastic particles 0.33-5.0 mm in diameter (Eriksen et al., 2014). These particles are ubiquitous in the marine environment (Courtene-Jones et al., 2017). Research literature on microplastics is limited due to the difficulty of collecting and studying polymers of such small size (Allsopp et al., 2009; Loder and Gerdts, 2015). Even with these difficulties, literature on microplastics has increased dramatically in the last ten years (GESAMP, 2015). Many recent studies are investigating the effects of plastics on marine organisms. Studies suggest that ingesting microplastics is harmful to marine organisms not only because plastic blocks their digestive system, but because it can have toxicological effects as well (Auta et al., 2017; Thompson, 2015). The extent of these effects are still, for the most part, unknown (Thompson, 2015). Nonetheless, the global presence of microplastics is leading to an acknowledgement in the scientific community that precautionary solutions for mitigation ought to be investigated (Thompson, 2015).

Plastic Movement in the Ocean

Studies within the past few decades show that no ecosystem is exempt from plastic contamination, which has been identified on beaches, in reefs, floating through the open ocean, and even in the deep sea (Courtene-Jones et al., 2017; Eriksen et al., 2014). It is important to study the baseline abundance and effects of plastic pollution. If plastic proves to have adverse effects on marine ecosystems, research that focuses developing techniques for mitigation will be required. In studies such as this one, finding zones of plastic accumulation in the ocean allows us to understand where plastics end up in the marine environment (Woodall et al., 2015).

However, tracking plastics in the ocean is difficult. Differences in plastic size, shape, buoyancy, and composition leads to differing movement and settlement patterns (Critchell and Lambrechts, 2016). The varying densities of plastics lead to varying buoyancies; high- and low-density polyethylene, polypropylene, and polystyrene foam tend to float, while polyethylene terephthalate, polyvinyl chloride, and solid polystyrene tend to sink (Ebbesmeyer and Scigliano, 2009). This makes it difficult to track plastic movement, since not all polymers have similar movement in the ocean. Furthermore, environmental factors such as degradation, wind, coastal topography, ocean circulation, tides, weather, temperature, and much more contribute to the transport of marine debris (Critchell and Lambrechts, 2016; Zhang, 2017). Plastic movement in the ocean is influenced by polymer composition, physical factors, and environmental processes, making it complex to model.

Importance of Studying Plastic Concentration

Even with all of these factors and uncertainties, research has shown time and time again that floating objects in the ocean tend to wash into catch basins (Barnes et al., 2009; Critchell and Lambrechts, 2016; Ebbesmeyer and Ingraham, 1994; Ebbesmeyer et al., 2007; Galgani, 1996; Law et al., 2010; Thompson, 2004). These catch basins are areas of the ocean environment with high concentrations of plastics due to local hydrography, bathymetry, and geography (Barnes et al., 2009). Uncovering where these catch basins exist in our marine environments can lead to more effective management and cleanup efforts in the future (Critchell and Lambrechts, 2016; Nixon and Barnea, 2010).

In this study, I set out to analyze marine sediments from three distinct environments along the east and west coasts of the United States in order to discover areas in the ocean with high densities of microplastics. My study will contribute an understanding of where microplastics become concentrated in marine sediments to the field of marine plastics research. From my findings I will propose possible mechanisms for microplastic accumulation in three study environments: deep-sea canyons, estuaries, and shorelines. This study will allow me to form hypotheses about both horizontal and vertical transport of plastic in the ocean.

CHAPTER I

PLASTIC DEBRIS IN NORFOLK CANYON

Introduction

It is currently estimated that there are 5.25 trillion plastic particles afloat in the ocean (Eriksen et al., 2014). However, this figure is lower than expected, since it is estimated that 4.8 to 12.7 million metric tons of plastic enter the ocean from land annually (Jambeck et al., 2015). This difference between calculations of plastics entering the ocean and plastics floating in the ocean has lead researchers to search for sinks (Long et al., 2015). Recently, scientists have been investigating the deep sea as a possible sink for plastics (Courtene-Jones et al., 2017; Van den Beld et al., 2017; Williams et al., 2005).

Plastic polymers, which are normally positively buoyant and float on the surface of the ocean, can become weighed down by biofouling (Barnes et al., 2009; Mordecai et al., 2011). This causes the plastics to sink (Ye and Andrady, 1991). In fact, it is estimated that 70% of plastic in the ocean eventually sink to the seafloor (Pham et al., 2014). Microplastics ingested by marine organisms can be incorporated into their feces and subsequently transported to the sea floor (Courtene-Jones et al., 2017). Microplastics can also sink with settling detritus from the surface, since phytoplankton aggregates incorporate and concentrate small debris (Long et al., 2015).

Litter that sinks is known to accumulate on geologically structured areas such as reefs, seamounts, and canyons (Van den Beld et al., 2017). Areas of high biodiversity, such as cold-water coral reefs, are especially vulnerable to damage by litter (Van den Beld et al., 2017). Plastic may smother or damage biota, and in some situations can become so dense that it leads to anoxic sediment conditions (Mordecai et al., 2011; Ramirez-Llodra et al., 2011). It doesn't easily disappear, either; plastic litter may persist for over 500 years on the sea floor due to the absence of thermal oxidation and solar radiation present on dry land and in the upper ocean (Barnes et al., 2009; Derraik, 2002; Mordecai et al., 2011; Schlining et al., 2013).

Submarine canyons are important environments in the deep sea. These fissure-like channels on the continental margins are hotspots of deep-sea biodiversity (CSA et al., 2017; Leo et al., 2010). Canyons create connections between continental shelves and the deep sea, and are known to be active conduits of sediment and larvae (Bennet, 1984; Mordecai et al., 2011). However, along with essential organic materials, canyons can transport marine litter by funneling currents (Galgani et al., 2000; Schlining et al., 2013; Van den Beld et al., 2017). Litter is known to accumulate in areas of high sedimentation such as canyons (Mordecai et al., 2011). Additionally, canyon currents funneling sediments from the shelf to the abyss are thought to transport lighter plastics (Pham et al., 2014; Ramirez-Llodra et al., 2011; Van den Beld et al., 2017). One hypothesis suggests that litter might accumulate towards the lower parts of canyons, due to down-canyon turbidity currents, but so far, this is inconclusive (Van den Beld et al., 2017).

Current literature on plastics in deep-sea environments is limited. It is difficult to quantify anthropogenic influence on the deep sea due to the expense and effort associated with the exploration of these environments (Naranjo-Elizondo and Cortés, 2018). Most deep-sea studies use ROV video, bottom trawl net, sonar, or submersible techniques to survey plastic pollution (Spengler and Costa, 2008). All of these methods miss smaller microplastic particles. This study is the first to quantify microplastic pollution in submarine canyons. In this research, I use sediment analysis to quantify the microplastics found within canyons and propose potential processes for accumulation of small plastic particles within these deep-sea environments.

I analyzed sediment samples from Norfolk Canyon off the east coast of Virginia, USA to study the scope of microplastic pollution in deep-sea canyons. Norfolk Canyon is one of 13 canyons along the United States middle Atlantic continental margin (Ross et al., 2015). These canyons contain unique habitats with high productivity and diversity, as well as active fisheries (Figure 1). With close proximity to the shoreline, they are also vulnerable to anthropogenic disturbances. Norfolk Canyon is located about 45 km south of Chesapeake Bay and is cut 25 km perpendicular to the shelf of the Mid-Atlantic Bight (Forde, 1981). The canyon walls are relatively smooth in the upward reaches and more rugose in the lower reaches of the canyon.

Water movement of the surface near Norfolk Canyon is dominated by the Slope Sea Gyre. Within the canyon, flow is primarily driven by tides and internal waves. However, turbidity due to currents is much higher within the canyon than on the adjacent continental slope (Ross et al., 2015). Norfolk Canyon currents move downslope in the upper reaches of the canyon. This current movement suggests a mechanism for sediment transport through the deepest parts of the canyon to the abyssal plain (CSA et al., 2017). Along with analyzing sediments, I analyzed ROV video footage from within Norfolk Canyon to quantify and characterize larger debris items found within the canyon.

Are microplastics concentrated within deep-sea canyons? I hypothesize that due to strong down-canyon currents, there will be a higher concentration of microplastics within the canyon than in adjacent areas. To test this hypothesis, I sampled sediment from inside Norfolk Canyon and the adjacent continental slope to compare the two and determine whether microplastics settle within canyon sediments.

Methods

In this study, I analyzed sediment for microplastics collected on the 2012 and 2013 Atlantic Deepwater Canyons cruises. The Atlantic Deepwater Canyons study was a multidisciplinary effort to research the ecosystems of the Mid-Atlantic Bight (MAB) canyons on the northeast coast of the continental United States. This study was funded and executed by the Bureau for Ocean Energy Management, The National Oceanographic and Atmospheric Administration Office of Ocean Exploration and Research, the United States Geological Society, Continental Shelf Associates Ocean Sciences Incorporated, and 11 academic institutions including the University of Oregon.

Sampling occurred on the Atlantic Deepwater Canyons cruises in 2012 and 2013. The 2012 cruise ran from August 15 to October 3, aboard the NOAA ship RV Nancy Foster. The 2013 cruise ran from April 30 to May 27, aboard the NOAA ship RV Ronald H. Brown. Sediment samples were taken with a NIOZ design box corer (30 cm in diameter, 55 cm in height.) The stainless steel box corer had a trip valve to seal the top. To collect sediment, the box corer was lowered vertically from the ship into the canyon. Once it entered the sediment, the top of the box core was sealed by a lid and the bottom of the box core was sealed by the box core knife. Samples were taken along a transect from the adjacent slope to the canyon axis to explore processes governing particle transport within the canyon itself (CSA et al., 2017). For this study, I received nine samples taken at four different depths within Norfolk canyon, at depths ranging from 196 m to 1135 m and seven samples taken at four different depths on the adjacent continental slope, at depths ranging from 188 m to 1118 m (Figure 2). These samples, which ranged in sediment volume from 3-240 mL, were stored in Nalgene jars. Before storage, scientists from the Atlantic Deepwater Canyons cruise removed organisms from the sediment and fixed the samples in formalin.

Before opening the samples, I cleaned all laboratory spaces carefully, including all laboratory benches, equipment, and fume hoods by washing, drying, wiping with 70% ethanol, and drying again. I only used 100% cotton washcloths in cleaning to eliminate the possibility of contaminating samples with synthetic fibers. Once complete, I tested cleanliness by sticking tape to all available surfaces and examining for microfibers and microplastics (Courtene-Jones et al., 2017). I performed all separation methods inside of a fume hood to reduce airborne contamination and avoid inhaling chemicals (Van Cauwenberghe et al., 2013). Throughout analysis, I stored my samples in this fume hood to keep them away from potential synthetic contaminants.

To remove possible plastic from the samples, I used a density differentiation method of filtration and flotation. I used a 43 μm mesh filter for all rinses and filters (Loder and Gerdts, 2015). To minimize loss of sediment particles during rinses and treatments, I secured the mesh filter over the top of all sediment jars, drained out the previous solution, and injected the next solution back through the mesh with a turkey baster. First, I rinsed samples with filtered reverse osmosis (RO) water to remove the formalin fixative. Then I drained the RO water from the samples and submerged the samples in saturated sodium iodide for floatation of any plastic particles.

I submerged samples in 10mL of sodium iodide (NaI,) swirled and shook the bottle to allow for a complete rinse with the salt solution, and allowed the sample to settle for floatation of lower density plastic particles (Claessens et al., 2013; Rocha-Santos and Duarte, 2015; Van Cauwenberghe et al., 2013). NaI, which has a lower density (1.8 gcm^{-3}) than sediment (~ 2.65 gcm^{-3}) but a higher density than plastic polymers (~ 0.05-1.4 gcm^{-3}), allows the plastics to float out of the sediment in the saturated salt solution (Rocha-Santos and Duarte, 2015). I repeated floatation with NaI three times for maximum extraction of plastic pollutants (Claessens et al., 2013). I collected floating microplastics by removing the supernatant, placing the supernatant solution under a dissecting microscope, and picking out the plastic particles (Law et al., 2010). To dry the collected plastic, I placed particles in individual glass dishes and left them in a desiccant chamber for 48 hours. During analysis, I left a dish of water next to the samples as a blank to test for airborne particle contamination. After retrieving the samples from the desiccant chamber I counted the number of individual plastic particles found in each sample and used a VWR analytical balance to measure the mass in milligrams. I then measured the diameter of each particle and photographed it using a dissecting microscope.

I analyzed my data for microplastic density in R using a two-way analysis of variance (ANOVA) to determine whether the factor of location (in the canyon or on the slope) or depth contributed more to the variation seen in the microplastic density per sample. I also ran two regression analyses in R for the samples within the canyon and on the continental slope to test for the relationship between microplastic density and sample depth.

Macroplastic debris was quantified from notes taken by Steve W. Ross (University of North Carolina Wilmington) and ROV video footage taken on the 2012 and 2013 Atlantic Deepwater Canyons cruises. Thirty-four ROV dives over the two cruises recorded 295 h of bottom video observations at depths from 234-1612 m (Ross et al., 2015). These dives used the *Kraken II* ROV (Univ. of Connecticut) for the 2012 cruise, and the *Jason II* ROV (Woods Hole Oceanographic Inst.) for the 2013 cruise. The dives began at the lowest targeted depth and moved upslope (Figure 5). The videos were taken at slow speeds (0.93 km/h) with a 10 cm scaling laser set on wide angle. The ROVs moved as close to the bottom as possible, conducting transects of varying lengths for observation and sampling.

Results

I identified a total of nineteen pieces of plastic from nine sediment samples taken within Norfolk Canyon (Plate 1). Samples in Norfolk Canyon had an average of 12.95 particles per liter of sediment and a standard deviation of 18.61 particles per liter of sediment. These plastics ranged from 0.54–13.53 mm in diameter, including one piece of blue monofilament fishing line with a length of 156.0 mm, and one blue microfiber. Sixteen of the identified plastic pieces are characterized as microplastics, or plastics 0.33–5.0 mm in diameter (Eriksen et al., 2014). Three of the identified plastic pieces are macroplastics larger than 5.0 mm in diameter. The plastics ranged in mass from 0.04–12.59 mg. The range of the mass of plastic per liter of sediment was 0.74–154.14 mg/L. The range of the density of microplastics per sample was 1.41–58.94 pieces/L (Figure 3). The predominant colors of plastic were white (26%), black (16%), and orange (16%).

The largest concentrations of microplastics per liter of sediment were found in two of the deepest samples, at 1133 km and 810 km.

I identified a total of eight pieces of plastic from seven sediment samples taken on the continental slope adjacent to Norfolk Canyon (Plate 2). Samples from the adjacent slope had an average of 2.04 particles per liter of sediment and a standard deviation of 3.26 particles per liter of sediment. These plastics ranged from 0.43–2.46 mm in diameter. All eight are characterized as microplastics. The plastics ranged in mass from 0.01–0.35 mg. The range of the mass of plastic per liter of sediment was 0.40–9.75 mg/L. The range of the density of microplastics per sample was 0.40–9.76 pieces/L (Figure 3). The predominant colors of plastic were blue (50%) and white (37%). The highest concentration of microplastic per liter of sediment was found in the deepest sample, at 1118 km.

ROV video footage revealed that most of the macroplastic debris within Norfolk Canyon was located within the middle reaches of the canyon, at a depth range of 300-400 m. This was consistent for the ROV dives in both 2012 and 2013. Debris items were observed a total of 131 individual times within the 295 h of video footage (Plate 3). The most common items noted were trash, or unidentifiable plastic debris (27%,) trap line (23%,) and fishing line (17%.) Other items noted, in order of abundance, were: trap, plastic, net, bottle, trash bag, can, metal debris, wire, buoy, tire, and crab pot (Figure 6).

Discussion

In the deep-sea environment, submarine canyons are known to be hotspots for plastic accumulation (Mordecai et al., 2011; Ramirez-Llodra et al., 2011). The presence of plastics in submarine canyons is clearly demonstrated in my research, providing further evidence for the eventual settling of plastic to the seafloor. One hypothesis suggests that litter might accumulate towards the lower parts of canyons, due to down-canyon turbidity currents (Van den Beld et al., 2017). A turbidity current is a downslope density current of sediment and water like an underwater avalanche. These currents are known to originate in or near the heads of submarine canyons (Boggs, 2006). Turbidity currents can be generated by inflow of new water, sediment failure, or storms, and flow until the suspended load settles (Boggs, 2006). Sediments settle within canyons in a “fining up” sequence. This sequence means that coarse grain sediments are first to be deposited because they take more energy to keep entrained in the current flow. Following coarse grain sediments, finer and finer grain sizes are deposited, creating a sedimentation pattern of coarse to fine grain sizes (Mulder et al., 2001). This means that lighter microplastics would be entrained in the turbidity current and deposited in the layers of fine grain sediment.

To investigate this hypothesis, I analyzed sediment samples taken within Norfolk Canyon and along the adjacent continental slope. I compared the two sample sets to determine if there is a difference between microplastic density inside and outside of the submarine canyon, and found a higher density of microplastics inside the canyon. I analyzed my data for microplastic density in R. I used a two-way analysis of variance (ANOVA) to determine whether the factor of location (in the canyon or on the slope) or depth contributed more to the variation seen in the microplastic density per sample. The ANOVA also tested whether the two factors have any influence on each other. The ANOVA showed that neither location nor depth had a significant effect on the variation between microplastic density (location $p = 0.17$, depth $p = 0.40$, location and depth $p = 0.75$). Even though I found more microplastics inside the canyon, the density was not significantly higher than on the continental shelf.

To test for the relationship between microplastic density and sample depth, I ran two regression analyses in R for the samples within the canyon and on the continental slope (Figure 4). The analysis for the Norfolk Canyon samples showed that there was not a strong linear relationship between microplastic density and depth within the canyon ($r^2 = 0.43$). The analysis for the Norfolk Slope samples showed that there was not a strong linear relationship between microplastic density and depth outside of the canyon ($r^2 = 0.56$).

Neither the ANOVA nor the regression statistics showed a significant difference in the density of microplastics within the canyon and on the adjacent continental slope. This might be due to the very small sample size associated with the difficulty of sampling the deep sea. Acknowledging the statistics, the location of the samples seems to be the only factor remotely influencing microplastic density (ANOVA location $p = 0.17$), and there seemed to be a potential pattern of higher densities of microplastic within the canyon. I call for further research on microplastic debris in canyon ecosystems to investigate this pattern. Future studies might be able to provide more evidence to the previously mentioned hypothesis that litter accumulates in the lower parts of submarine canyons. Further research might also be able to describe if accumulation is due to the movement of sediment and debris by turbidity currents.

To compare microplastic debris to macroplastic debris within the canyon, I analyzed ROV video footage taken within Norfolk Canyon. I identified debris a total of

131 times over 295 h of footage. The majority of this debris was found within the middle reaches of the canyon, from 300-400 m (Figure 7). This finding suggests that if larger macroplastics and debris are caught within turbidity currents, they are deposited earlier with the heavier coarse grain sediments, while smaller microplastics are deposited later with the lighter fine grain sediments (Mulder et al., 2001). Together, the ROV videos and sediment analysis pose a potential pattern of macroplastic accumulation in the upper reaches of the canyon, and microplastic accumulation in the lower reaches of the canyon.

It is important to identify potential areas of microplastic accumulation in the deep sea to inform further protection efforts. Submarine canyons, along with being important conduits of sediment and larvae to the abyssal plain, are hotspots of deep-sea biodiversity (Bennett, 1984; Leo et al., 2010). Submarine canyons are home to unique cold-water coral communities, which are at risk from plastic pollution (CSA et al., 2017). These unique communities are at risk because litter that sinks is known to accumulate on geologically structured areas such as reefs (Williams et al., 2005). Understanding where plastic accumulates within canyons can inform our efforts to protect these unique and rare environments (Courtene-Jones et al., 2017).

This study is unique because it is the first of its kind to analyze sediment for microplastics within submarine canyons. I did not find a significant difference between the density of microplastics inside and outside of the canyon, but I did find an interesting pattern of macro- and microplastic debris settling that suggests plastics may be concentrated within canyons due to turbidity currents. The implication of this pattern is that submarine canyons may be conduits for microplastic debris from the continental slope to the abyssal plain. More research is necessary to confirm this pattern and hypothesis. However, this study provides another step towards the goal of finding areas of microplastic concentration to further understand how plastics behave in the marine environment.

PART II

PLASTIC DEBRIS IN THE COOS BAY ESTUARY

Introduction

Estuaries create important connections between the land and the sea (McDowell and O'Connor, 1977). Defined as a partially enclosed coastal body of water, estuaries are fed at their head by rivers and empty at their mouths into the ocean (Potter et al., 2010). Estuaries are subject to regular tidal cycles that flush seawater into and out of the estuarine system. These tidal cycles contribute to the movement of materials such as nutrients and larvae from the estuary to the adjacent continental shelf (Miller and Shanks, 2004).

As well as transporting essential organic matter from rivers, estuaries are known to accumulate and transport debris from rivers to the seabed (Spengler and Costa, 2008). Land-based debris enters estuaries mainly through rivers, but can also be blown or washed in directly from land (Carlson et al., 2018; Jambeck et al., 2015; USDA, 1975). Anthropogenic litter in riverine waters is often deposited in estuaries before reaching the ocean (Barnes et al., 2009; Galgani et al., 2000; Woodroffe, 2002). Along with river input, waste can be transported to the sea from estuaries by local hydrography. It has been shown that estuarine embayments can be sinks for materials carried by alongshore currents (Woodroffe, 2002). Movement of estuarine waters can then accumulate the waste in zones of high sedimentation (Galgani et al., 2000). One form of local water movement is the estuarine plume, which washes nutrients, larvae, and debris from the estuary into the sea during low tides (Barnes et al., 2009). Therefore, it is possible that plastics could be fed into estuaries from both rivers at their head, and alongshore currents at their mouth.

For this study, I sampled sediment within the Coos Bay Estuary on the southern coast of Oregon in the United States. Coos Bay has a high tidal exchange ratio (0.77), indicating that most of the water from the estuary travels into the sea during ebb tide (Cziesla, 1999). The Coos Bay Estuary is the second largest estuary in Oregon, however, it is still relatively small (Hickey and Banas, 2003). The estuary is fed by the South Fork Coos and Millicoma Rivers. In smaller rivers such as these, there is not a large displacement of debris, and waste is often found inside of the estuary or in areas with fronts (Acha et al., 2003; Barnes et al., 2009).

Do microplastics concentrate within estuaries? I hypothesize that due to river inputs of debris, there will be a higher concentration of plastics in sediment at the head of the estuary, near the river inputs. To test this hypothesis, I sampled sediment from the upper, middle, and lower zones of the Coos Bay Estuary, as well as from the estuarine plume and the continental shelf.

Methods

In this study, I analyzed sediment for microplastics collected within and near the Coos Bay Estuary (Figure 8). Sediment from the continental shelf was collected in July of 2018 by students from the Oregon Institute of Marine Biology Deep-Sea Biology class. The students used a box corer to take sediment samples from the RV Pacific Storm. The box corer is similar in design to the NIOZ box corer used on the Atlantic Deepwater Canyons cruises (see Part I Methods). I collected sediment from the Coos Bay Estuary in November of 2018 using a PONAR grab deployed from the RV Pugettia. The stainless steel PONAR grab has two opposing jaws that are held open by a latch. This latch is triggered to close the jaws when the grab makes contact with sediment, trapping a sediment sample inside. I took samples from four main locations within the Coos Bay Estuary: (1) the head of the estuary, by river input from the South Fork Coos and Millicoma Rivers; (2) the middle of the estuary by Pony Slough; (3) the mouth of the estuary in between the North Spit and Bastendorff Beach jetties; and (4) the estuarine plume, where water from the estuary empties into the ocean. The Deep-Sea Biology class took samples on the continental shelf from 50-200 m depth, progressing further offshore each sample. These samples were stored in white sample jars.

I cleaned the lab space as previously described to eliminate the possibility of airborne or material contamination of the samples with microplastics or microfibers (see Part I Methods). I used the same methods of filtration and floatation to remove plastic particles from the samples, collecting the floating plastics from the supernatant and drying in a desiccant chamber. After collection, I counted the number of plastics and measured their mass. Using a dissecting microscope, I photographed each particle and used Image J to measure either their diameter (for microplastics) or length (for microfibers).

I analyzed my data for microplastic density in R. I used a two-way analysis of covariance (ANCOVA) to determine whether the factor of location (in the estuary, the plume, or the shelf) or depth contributed most to the variation seen in the microplastic density per sample.

Results

I identified a total of eleven pieces of plastic from eight sediment samples taken within the Coos Bay Estuary (Figure 9). Fifty-five percent of these were microfibers ranging in length from 1.18 – 4.81 mm. Forty-five percent of these were microplastics ranging in diameter from 0.47 – 0.95 mm. The average microplastic density was 5.50 particles per liter of sediment with a standard deviation of 4.87. The predominant colors of plastic and fibers were white (45%) and blue (36%). The largest concentrations of microplastic per liter of sediment were found in the samples taken in the middle of the estuary near Pony Slough, and in the upper estuary near Tremont Avenue in Coos Bay (Figure 10).

I identified a total of 38 pieces of plastic from six sediment samples taken within the estuarine plume, at the mouth of the Coos Bay Estuary (Plate 4). Eighty-two percent of these were microfibers ranging in length from 1.18 – 9.648 mm. Eighteen percent of these were microplastics ranging in diameter from 0.55 – 2.57 mm. The average microplastic density was 17.96 particles per liter of sediment with a standard deviation of 7.81. The predominant colors of plastic and fibers were white (55%), blue (21%), and black (16%). The largest concentrations of microplastic per liter of sediment were found in the samples taken moving northwest out of the mouth of the estuary.

I identified a total of three pieces of plastic from seven sediment samples taken on the continental shelf adjacent to the Coos Bay Estuary. All of these were microplastics, ranging in diameter from 1.43 – 2.92 mm. The average microplastic density was 0.93 particles per liter of sediment with a standard deviation of 1.54. All three pieces were white.

Discussion

Estuaries are known to accumulate and transport debris from rivers to the seabed (Spengler and Costa, 2008). This is largely due to the heavy input of land-based debris from rivers to estuarine environments (Carlson et al., 2018). However, much of this debris is deposited in estuaries before reaching the ocean (Barnes et al., 2009). The presence of microplastics within estuarine sediments is clearly demonstrated in my research, providing evidence that estuaries can be sinks for microplastic pollution from rivers or from the ocean.

To examine microplastic concentration in estuarine environments, I analyzed sediment samples taken within the Coos Bay Estuary, in the estuarine plume at the mouth of the Coos Bay Estuary, and the adjacent continental shelf. I identified a total of eleven plastic pieces within the estuary, 38 plastic pieces within the mouth of the bay and the estuarine plume, and three plastic pieces from the continental shelf. This suggests that microplastics are concentrated within the mouth of the estuary. To statistically test the variation in microplastic density between the estuary, the plume, and the continental shelf, I ran an analysis of covariance (ANCOVA) in R (Figure 11). The ANCOVA showed that location, rather than depth, is the most influential factor in determining the microplastic density in each sample (location $p = 8.46\mathrm{x}10^{-5}$, depth $p = 0.30$, location and depth $p = 0.09$). This shows that the concentration of microplastics found within the plume is statistically higher compared to the amount of microplastics found in the estuary or the shelf ($p = 8.46\mathrm{x}10^{-5}$, $\alpha = 0.05$). This provides evidence for my hypothesis that estuaries can concentrate microplastics. However, microplastics are concentrated within the estuarine plume, rather than near rivers at the head of the estuary like I previously thought.

I hypothesize that this concentration in the plume could be caused by the converging front at the mouth of the estuary as cooler, denser ocean water is swept downward on contact with warmer, less dense estuarine waters. Concentrating fronts are often formed at the intersection of estuarine and oceanic waters (Pritchard and Huntley, 2002). Buoyant plastics can be pulled downward in the water column by converging fronts (Acha et al., 2003). However, it is unlikely that the plume front is the only mode of transport for plastics to sediments in the mouth of the estuary. This is because the plume is an extension of estuarine water into the ocean, and is not located directly in the mouth of the estuary. Another hypothesis is that plastics sink to the seafloor due to the plume front and are then transported by internal waves into the mouth of the estuary (Acha et al., 2003). There is also a large underwater formation called Guano Rock located in between the North Spit and Bastendorff Beach jetties, which could contribute to the concentrations of microplastic as they are flushed through the mouth of the estuary. This is because plastics that sink are known to accumulate around geologically structured areas (Thompson et al. 2004). The lack of plastics found within the middle of the estuary can be explained by the presence of Fossil Point in that area. Fossil Point is a rocky area, and microplastics cannot settle on hard substrate.

The largest concentration of plastics within the estuary were found near Pony Slough (near the northernmost bend of the estuary) and the head of the estuary near Tremont Avenue in Coos Bay. These data are interesting, since those samples were taken near two known sewage outfalls for the cities of Coos Bay and North Bend. This suggests that plastics in these two sample sites near the sewage outfalls may be from land-based sources, rather than ocean-based sources (Carlson et al., 2018). This information is important to know, since it can inform management of land-based sewage treatment plants. My findings also stress the importance of local land-based mitigation practices such as a reduction in plastic use and organized beach and waterway cleanups, in order to reduce point-source debris inputs to estuaries.

To better understand patterns of plastic debris within estuaries, further research in different seasons is needed. Due to the time constraints of this research, I only took sediment samples in the estuary during the fall, in October and November of 2018. In order to truly understand how microplastics are transported within the estuary, a multi-year study over all four seasons is necessary. Research conducted over multiple years would be able to show the rates of microplastic accumulation, as well as seasonal patterns. Nonetheless, this study provides an important starting point from which to understand how plastics are concentrated within the Coos Bay Estuary.

PART III

PLASTIC DEBRIS SURROUNDING OREGON HEADLANDS

Introduction

Shorelines are the margin between land and sea (Woodroffe, 2002). As such, they allow us to study how land-based litter enters the ocean, and how the ocean returns our litter back to us. Almost half of the world's population lives within 60 km of the shoreline, making this environment especially susceptible to pollution by anthropogenic debris (USDA, 1975; Woodroffe, 2002). Most marine plastics originate near the coast (Zhang, 2017). However, land-based inputs are not the only plastic stressors to our coasts. Past studies have followed the large-scale transport of plastic pollution from its source at a spill in the middle of the Pacific Ocean all the way to the shores of Alaska, the Pacific Northwest of the United States, the arctic, and the European coast (Ebbesmeyer et al., 2007). However, there is currently very little literature that addresses the small-scale transport of plastics in coastal areas (Zhang, 2017).

Wind and wave conditions are the most dominant factors influencing the movement of positively buoyant plastics onto the shoreline (Zhang, 2017). However, coastal accumulation of plastic is highly variable due to beach orientation, river input, coastline topography, local hydrography, and weather patterns (Critchell et al. 2015). The amount of litter accumulated on beaches also varies by season. Furthermore, plastics that accumulate on shorelines are susceptible to resuspension by tides, waves, and storms (Critchell and Lambrechts, 2016).

To further the study of small-scale transport of marine debris, I conducted surveys of Oregon Coast beaches. Specifically, I surveyed beaches around coastal headlands to investigate how the presence of headlands influences plastic abundance on the shoreline. Headlands are land formations on the shoreline that protrude into the ocean (USDA, 1975). This interruption creates eddies on the leeward side of the headlands (Dibble et al., 2018). Past research has shown that larvae tend to accumulate within these leeward headland eddies (Mace and Morgan, 2006). Along Oregon shorelines, currents are predominantly northward in the winter months because of the Davidson Current.

Do microplastics concentrate around headlands? I hypothesize that due to the Davidson Current moving northward, eddies would form on the leeward (Northern) sides of Oregon Coast headlands and would consequently concentrate plastics on the north-facing sides. To test this hypothesis, I surveyed sandy beaches to the north and south of three headlands on the Oregon Coast: Yaquina Head, Cape Perpetua, and Cape Blanco (Figure 12).

Methods

In this study, I conducted shoreline surveys of the northern and southern sandy beaches bordering three headlands on the Oregon Coast. I completed the surveys at low tides during January and February of 2019 (Thiel et al., 2013). The surveys were completed in sets of belt transects marked with tape measures (Figure 13). The transects ranged from 10x2 m to 30x2 m depending on the width of the shoreline. Transect belts were arrayed perpendicular to the ocean, starting at the edge of the rocky coast and running along the sandy beach towards the water.

On the northern beach of Yaquina Head, transects were placed in sets of three, 5 m apart each, with a 30 m gap between adjacent transects. Twenty-four total transects were taken from this beach. In later headland sampling trips, I reduced the amount of transects in order to sample within the time constrains of a single tidal cycle. For the southern beach of Yaquina Head, nine transects were set 30 m apart. Cape Perpetua is a rocky headland, so the surveys were conducted on the two closest beaches: Yachats Ocean Road State Natural Site to the north, and Neptune Beach to the south. Nine transects were set 30 m apart at each of these two sites. At Cape Blanco, nine transects were set 30 m apart on both the northern and southern beaches surrounding the headland. This survey procedure was used in order to quantify the amount of plastics within a set area on the beach, while surveying as much of the beach as possible during each low tide cycle.

Only plastics from the microplastic range (0.33-5 mm in diameter) to macroplastics were quantified in this survey; any smaller plastics were not counted for the study. Only plastics on the surface of the sediment were collected. To quantify the number of plastic fragments within each transect, two people walked the transects up and down on the right and left sides of the rectangle, switching sides in the middle to reduce individual error. This procedure was repeated twice for each transect to ensure all visible debris items were collected. All plastics were collected in paper bags to eliminate possible contamination from storage in plastic containers.

After the surveys, plastics were characterized by size and type. Microplastics are defined as plastic pieces with a diameter of 0.33-5 mm (Ebbesmeyer et al., 2007). Nurdles, which are easily identifiable by their clear to white color and rounded 5 mm shape, were also characterized. Nurdles are plastic preproduction pellets that are a ubiquitous form of litter on beaches around the world (Hammer et al., 2012). Larger identifiable macroplastics were also characterized by type.

I analyzed my data for microplastic density in R. I used a one-way analysis of variance (ANOVA) to determine whether the factor of location (north or south of the headland) had a significant influence on the variation seen in the microplastic density per sample. I ran two regression analyses for the northern and southern sides of the headlands to test for the relationship between microplastic density and distance from the headlands. I repeated this analysis for each headland.

Results

I identified a total of 1,449 pieces of plastic from 33 belt transects on the shorelines surrounding Yaquina Head in Newport, Oregon (Figure 14). 1,443 of these pieces came from the nine transects surveyed on the south side of Yaquina Head. Six of these pieces came from the 24 transects surveyed on the north side of Yaquina Head. Thirty-seven percent of these were microplastics (0.33 – 5.0 mm in diameter), 28% were 5.0 – 10.0 mm in diameter, 14% were greater than 10.0 mm in diameter, and 21% were nurdles. Large identifiable macroplastics included two plastic straws (Figure 17).

I identified a total of 178 pieces of plastic from 18 belt transects on the shorelines surrounding Cape Perpetua in Yachats, Oregon. One hundred and seventy-seven of these pieces came from the nine transects surveyed on the south side of Cape Perpetua. One of these pieces came from the nine transects surveyed on the north side of Cape Perpetua. Fifty-eight percent of these were microplastics (0.33 – 5.0 mm in diameter), 25% of these were plastics 5.0 – 10.0 mm in diameter, 7% of these were plastics greater than 10.0 mm in diameter, and 10% of these were nurdles.

I identified a total of 415 pieces of plastic from 18 belt transects on the shorelines surrounding Cape Blanco in Bandon, Oregon. Two hundred and sixty-two of these pieces came from the nine transects surveyed on the south side of Cape Blanco. One-hundred and fifty-three of these pieces came from the nine transects surveyed on the north side of Cape Blanco. Thirty-two percent of these were microplastics (0.33 – 5.0 mm in diameter), 27% of these were plastics 5.0 – 10.0 mm in diameter, 29% of these were plastics greater than 10.0 mm in diameter, and 12% of these were nurdles. Some large identifiable macroplastics included three bottlecaps, a dive light, a pen cap, and two pieces of cellophane.

Discussion

Most marine plastics originate near the coastline (Zhang, 2017). In addition, marine debris that originates in the ocean often finds its way to shorelines due to transport by the ocean currents, gyres, smaller-scale currents, and wind and weather patterns (Critchell and Lambrechts, 2016; Thiel et al., 2013). The concept of debris transport and accumulation has been extensively studied for large-scale ocean circulation systems, such as ocean gyres that catch and transport large volumes of plastic (Ebbesmeyer and Ingraham, 1994; Ebbesmeyer et al., 2007; Hammer et al., 2012). However, there is very little primary literature surrounding the small-scale, local transport of plastic in coastal circulation systems (Zhang, 2017).

It has been shown that the presence of headlands concentrates larvae in coastal systems (Ebert and Russell, 1988; Mace and Morgan, 2006). To investigate whether this phenomenon occurs in regards to positively buoyant plastic, I examined microplastic concentration near headlands on the Oregon coast. I compared plastic surveys from beaches on the north and south sides of Yaquina Head, Cape Perpetua, and Cape Blanco. Near all three headlands, there was a higher density of microplastics per transect area on the southern beaches.

I analyzed my data for microplastic density in R. To test for the relationship between microplastic density and distance from the headlands, I ran two regression analyses for the northern and southern sides of the headlands (Figure 15). I repeated this analysis for each headland. The analysis for the northern beach samples showed that there was not a strong linear relationship between microplastic density and distance from the headlands (Yaquina $r^2 = 0.11$, Perpetua $r^2 = 0.02$, Blanco $r^2 = 0.58$). The analysis for the southern beach samples showed that there was not a strong linear relationship between microplastic density and distance from the headlands (Yaquina $r^2 = 0.07$, Perpetua $r^2 = 0.06$, Blanco $r^2 = 0.002$). This shows that for all three sample sites, the amount of microplastics found per transect area does not depend on how near or far the transect is set from the headland.

To determine which factor determines the density of microplastics on Oregon shorelines, I used an analysis of variance (ANOVA). This ANOVA tested whether the location of the transect (north or south of the headland) had an influence on the density of debris found (Figure 16). The ANOVA showed that location has a significant effect on the variation between microplastic density ($p = 5.21 \times 10^{-7}$, $\alpha = 0.05$). This means that there was a significant difference between debris concentration on the northern and southern sides of headlands on the Oregon Coast. This provides evidence to my hypothesis that headlands influence the concentration of marine debris.

However, my original thought was that plastics would be more concentrated on the northern side of headlands due to eddies created by northern-flowing offshore currents. Upon further research, I believe that this is due to smaller-scale wave patterns than I was previously considering. Under my previous hypothesis, I assumed that the north-flowing Davidson Current would create concentrating eddies on the northern sides of headlands. The Davidson Current is the primary alongshore current off of the Oregon coast in the winter months (Mazzini et al., 2014). However, the Davidson Current does not create a lot of eddies in its travel; instead, it mostly moves northward (Austin and Barth, 2002). Furthermore, the Davidson Current is far enough offshore that it will likely not affect the small-scale movement of debris from the ocean onto beaches. It is possible that debris carried in the Davidson Current from California could fall off and be swept shoreward by smaller nearshore currents, but it is unlikely that the Davidson Current itself is the primary mode of transportation of plastics onto Oregon beaches.

Rather than focusing on large-scale currents, my research has revealed the importance of small, localized wind and water motion in the transport of microplastics. Wind and wave conditions are known to dominate the surface drifting of microplastics near the shoreline (Zhang, 2017). Furthermore, it has been shown that beaches facing the dominant wind direction are more likely to accumulate debris (Critchell et al., 2015). In the winter months, when I conducted my surveys, Oregon has winter wind and waves from the south moving northeast. This is a strong explanation for the accumulation of microplastics on the south-facing sides of headlands.

Coastline topography is also an important consideration in determining where plastics accumulate on Oregon beaches (Critchell et al., 2015). The beaches to the north and south of Yaquina Head are both dissipative beaches, with wide surf zones. Beaches such as these are more open to receiving debris from the open ocean (Shih and Komar, 1994). The beaches to the north and south of Cape Perpetua and the beach to the north of Cape Blanco are also dissipative beaches. However, the beach to the south of Cape Blanco is a reflective beach. Reflective beaches, in contrast to dissipative beaches, have narrow surf zones and waves that tend to reflect off of the beach rather than rolling slowly up the sand. In this kind of a beach environment, most debris does not stick because the surf zone tends to be steep and turbulent (Wright and Short, 1984). This could explain why I found a more equal distribution of debris on the north and south sides of Cape Blanco, in contrast to the other headlands, where there was a clear majority of plastic along the south-facing beach.

Another potential explanation for the accumulation of plastics along the southern sides of headlands is the presence of littoral cells. Littoral cells are sections of the shoreline defined as long sandy beaches bordered by headlands (Shih and Komar, 1994). Littoral cells have specific patterns of sediment circulation. The northern end of a littoral cell (which would be at the southern side of a headland,) is a weak point in the cell where debris can fall out of the system onto the shore. My last potential explanation for the observed plastic concentration is that headlands create interruptions of alongshore flow of materials. This interruption could lead to a localized deposition of debris. Any nearshore northern-flowing current interrupted by a headland could lead to an accumulation of debris on the southern side of the headland.

It is important to know where plastic pollution is concentrated along the Oregon shoreline to inform future cleanup efforts. By targeting cleanups towards areas known to accumulate high concentrations of plastic, we can maximize efforts and plastic removed, rather than wasting valuable time cleaning beaches that are not highly polluted. To better understand patterns of plastic accumulation along the Oregon shoreline, further research should be conducted over multiple seasons. Due to the time constraints of this research, I only surveyed beaches surrounding the three headlands during the winter, in January and February of 2019. A study that spans all four seasons would be able to show whether plastic accumulation around headlands alternates between the north and south depending on the season and the predominant wind and wave direction. Nonetheless, this study shows that plastics are concentrated on beaches to the south of Oregon headlands in the winter. This information can be used to inform future studies and hypotheses about plastic concentration in other seasons.

Figures

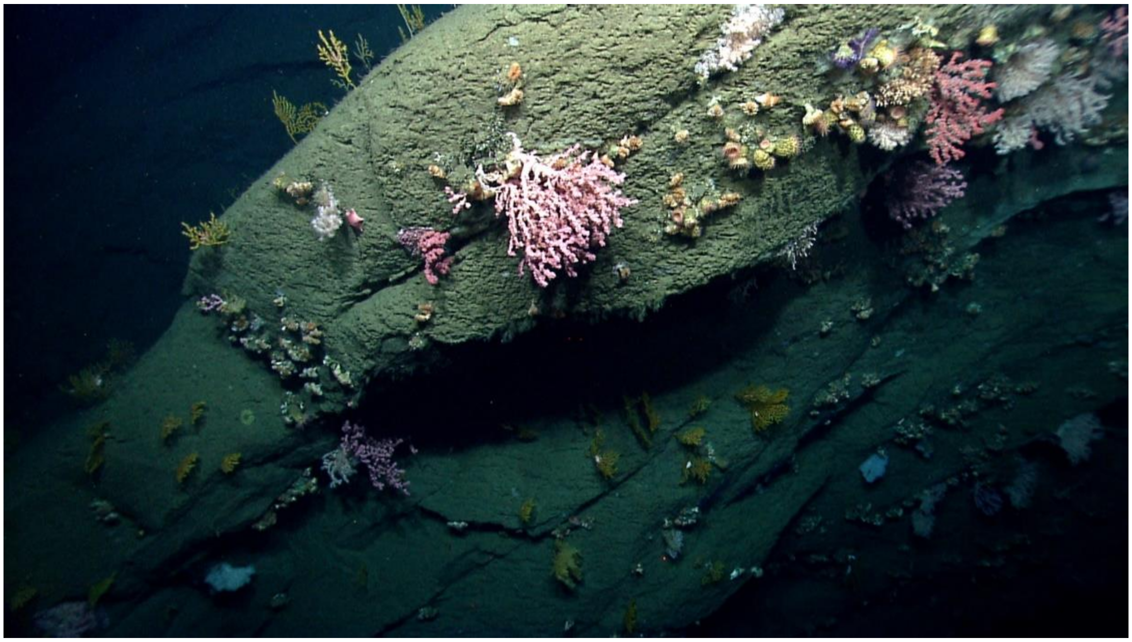

Figure 1. Deep-sea canyon coral community. Photograph of Norfolk Canyon cold-water coral communities taken on the Atlantic Deepwater Canyons cruises. Image courtesy of Deepwater Canyons 2012 Expedition, NOAA-OER/BOEM.

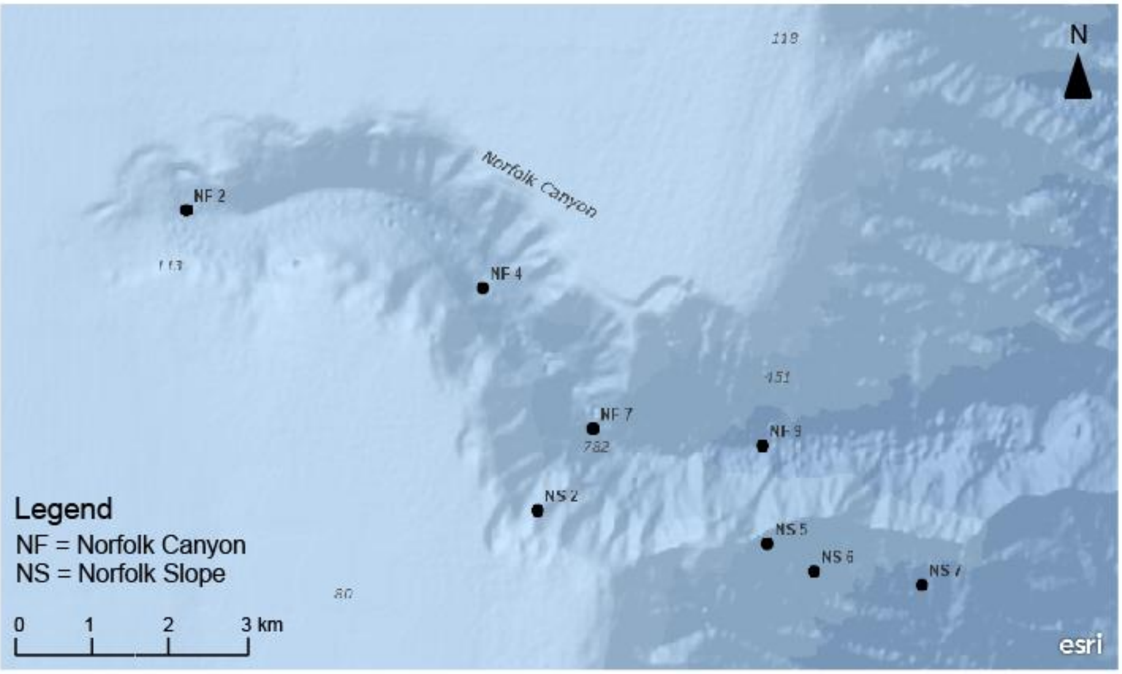

Figure 2. Map of sampling locations within Norfolk Canyon for this study. NF = samples taken within Norfolk Canyon. NS = samples taken on the adjacent continental slope. Samples taken using a NIOZ design box corer on the 2012-2013 Atlantic Deepwater Canyons cruises. Map created with Esri ARCGIS.

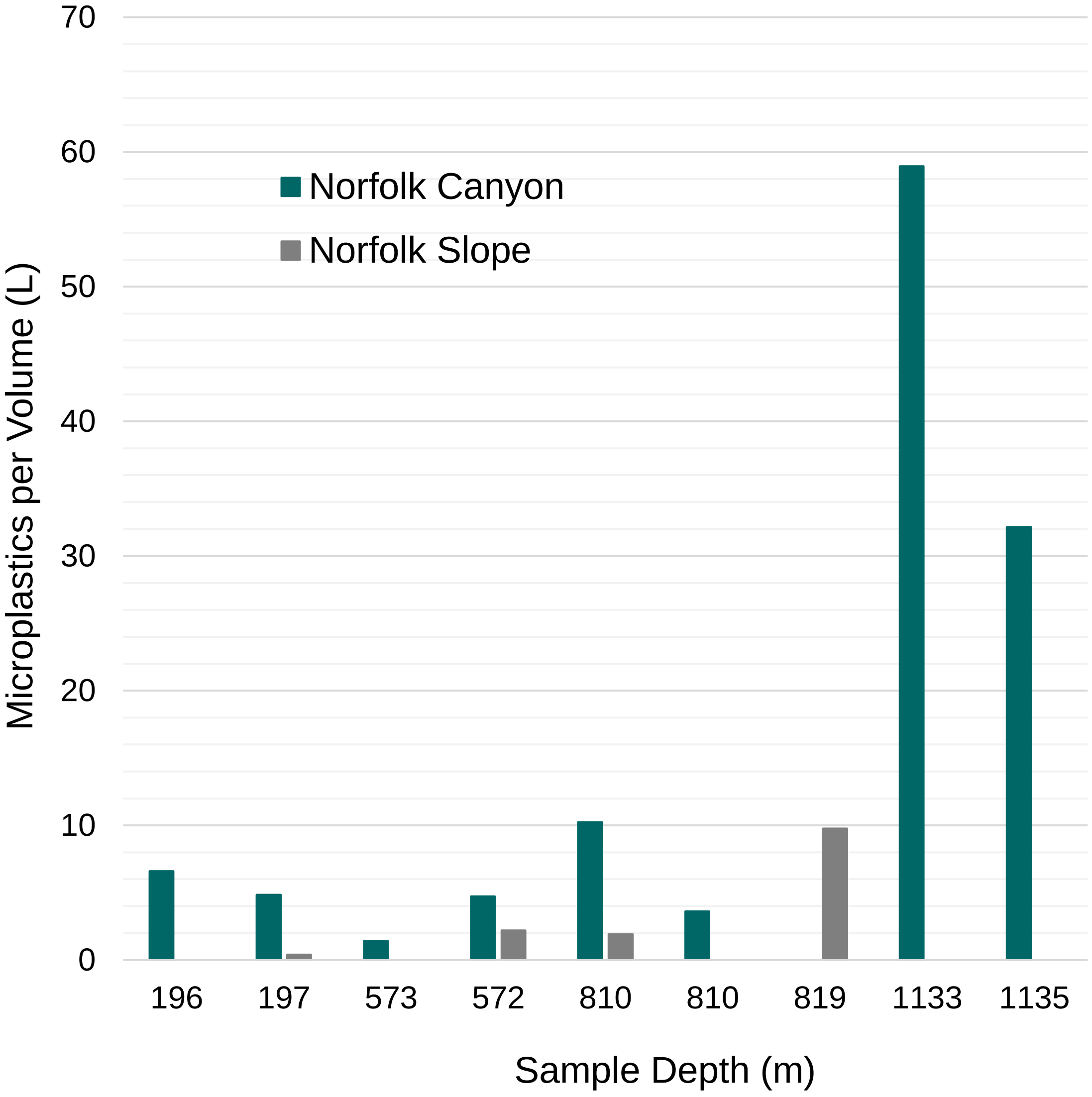

Figure 3. Microplastic density in Norfolk Canyon and the adjacent continental slope. Microplastics were removed from sediment samples by density differentiation techniques, dried in a desiccant chamber, weighed with a VWR scale, and counted under a dissecting microscope.

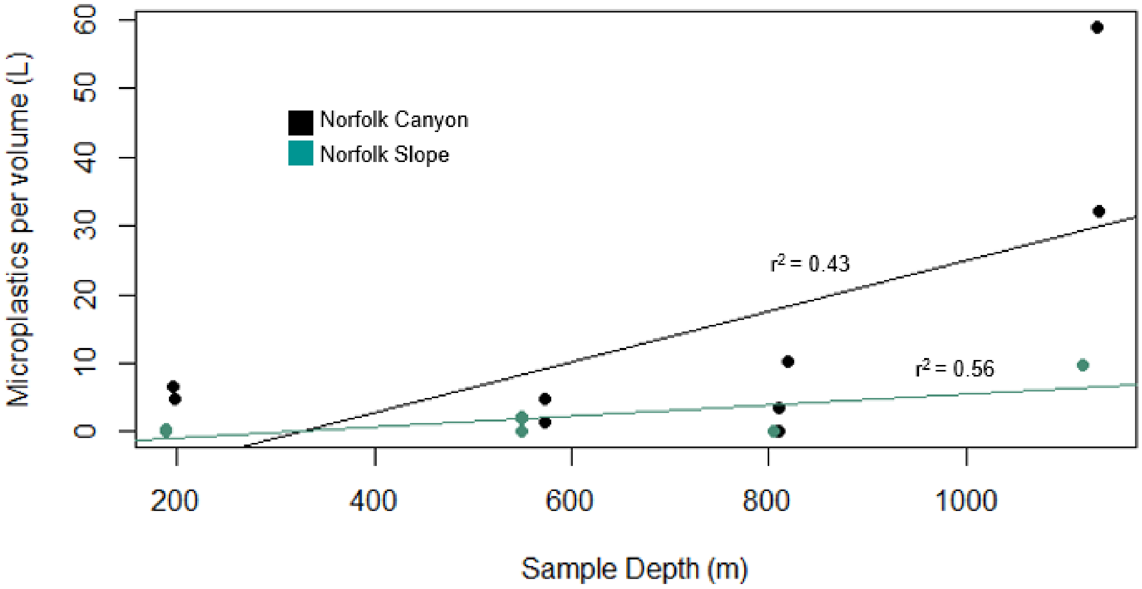

Figure 4. Regression analysis of microplastic density in Norfolk Canyon and the adjacent continental slope. This regression analysis tests for the linear relationship between depth and number of microplastics per volume of sediment. Canyon p = 0.054. Slope p = 0.055.

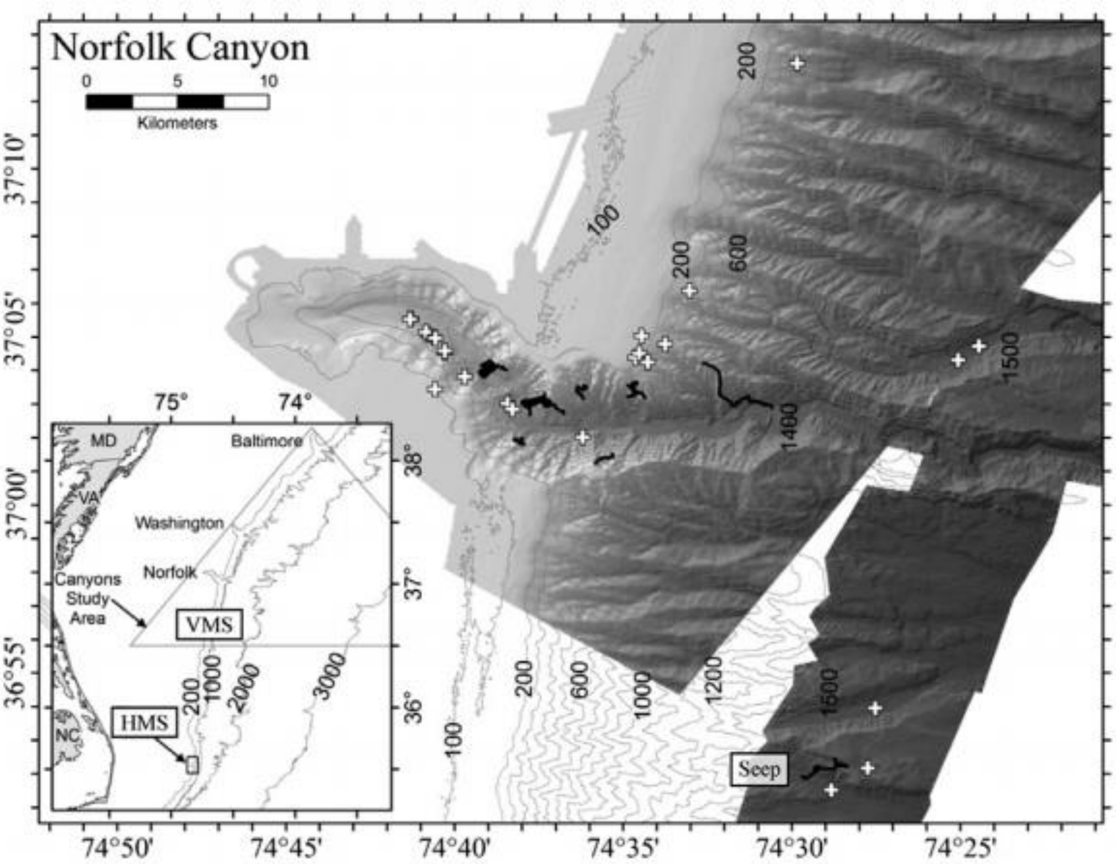

Figure 5. Bathymetric map of Norfolk Canyon derived from multibeam sonar on the Atlantic Deepwater Canyons cruises. Black lines show ROV transects, while crosses show the location of trawls taken for biological analysis on the cruises. Modified from Ross et al. 2015.

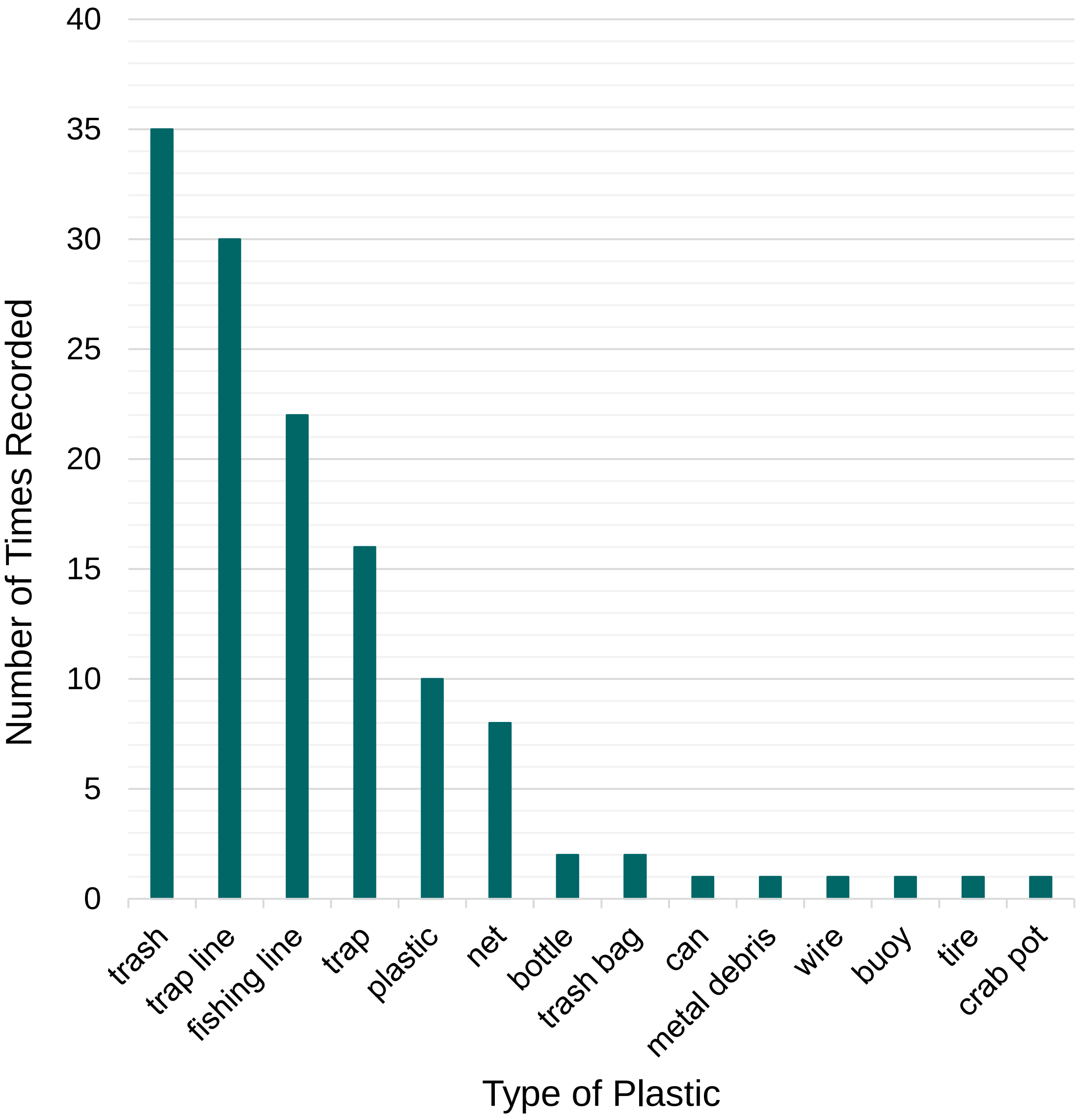

Figure 6. Types of debris recorded in video footage from 34 ROV dives from the Atlantic Deepwater Canyons cruises in 2012-2013. 295 h of bottom video observations were recorded at depths from 234-1612 m. These dives used the Kraken II ROV (Univ. of Connecticut) for the 2012 cruise, and the Jason II ROV (Woods Hole Oceanographic Inst.) for the 2013 cruise. The videos were taken at slow speeds (0.93 km/h) with a 10 cm scaling laser set on wide angle. “Trash” is defined as unidentified plastic debris.

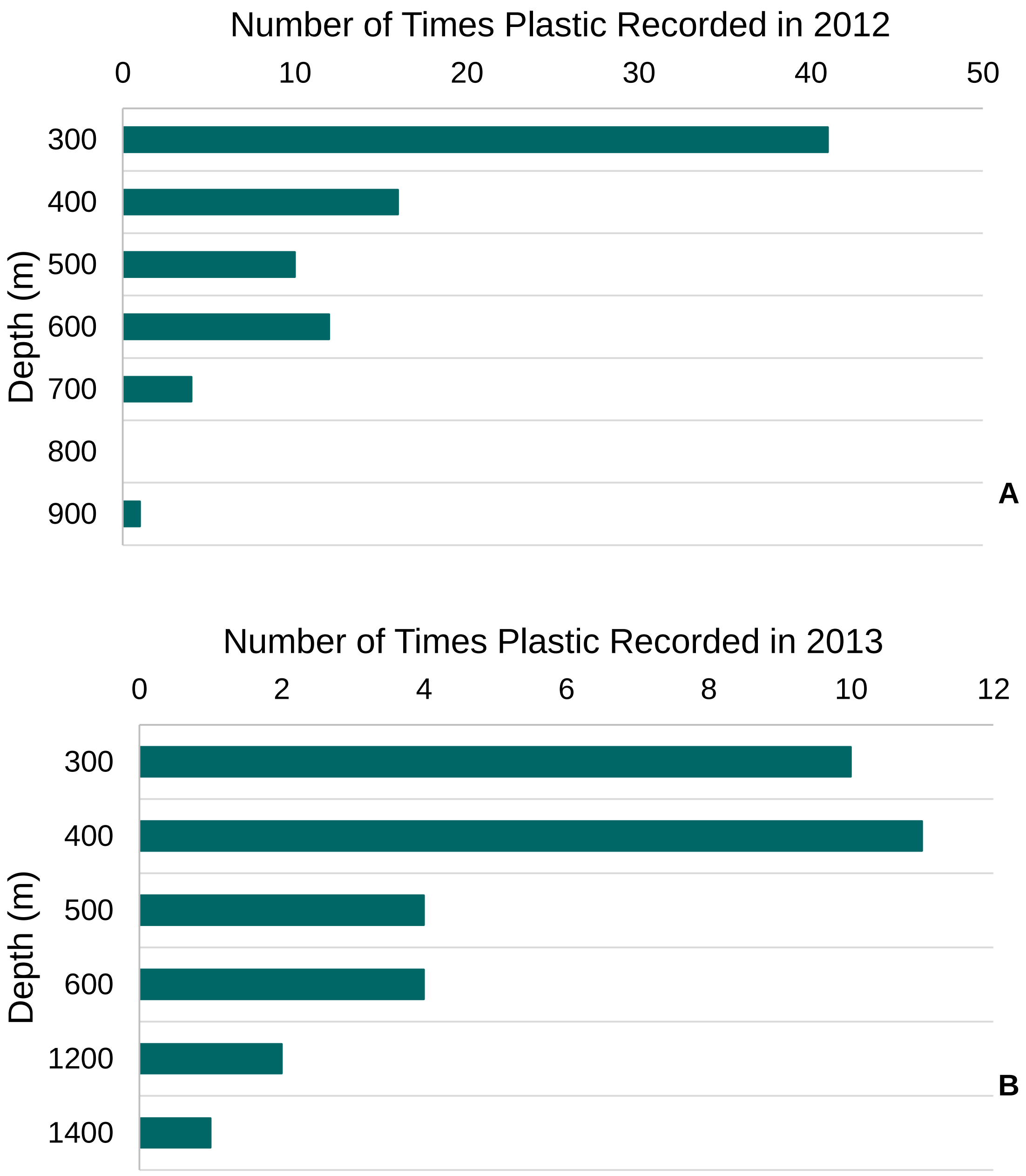

Figure 7. Total number of debris items recorded at each depth range in video footage from the Atlantic Deepwater Canyons cruises. The cruises deployed 34 total ROV dives over 2012 (A) and 2013 (B). The exact depth was recorded for each debris item observed along the ROV video transect. Values are not scaled to length of ROV dive since starting and ending coordinates do not correspond with the distance traveled.

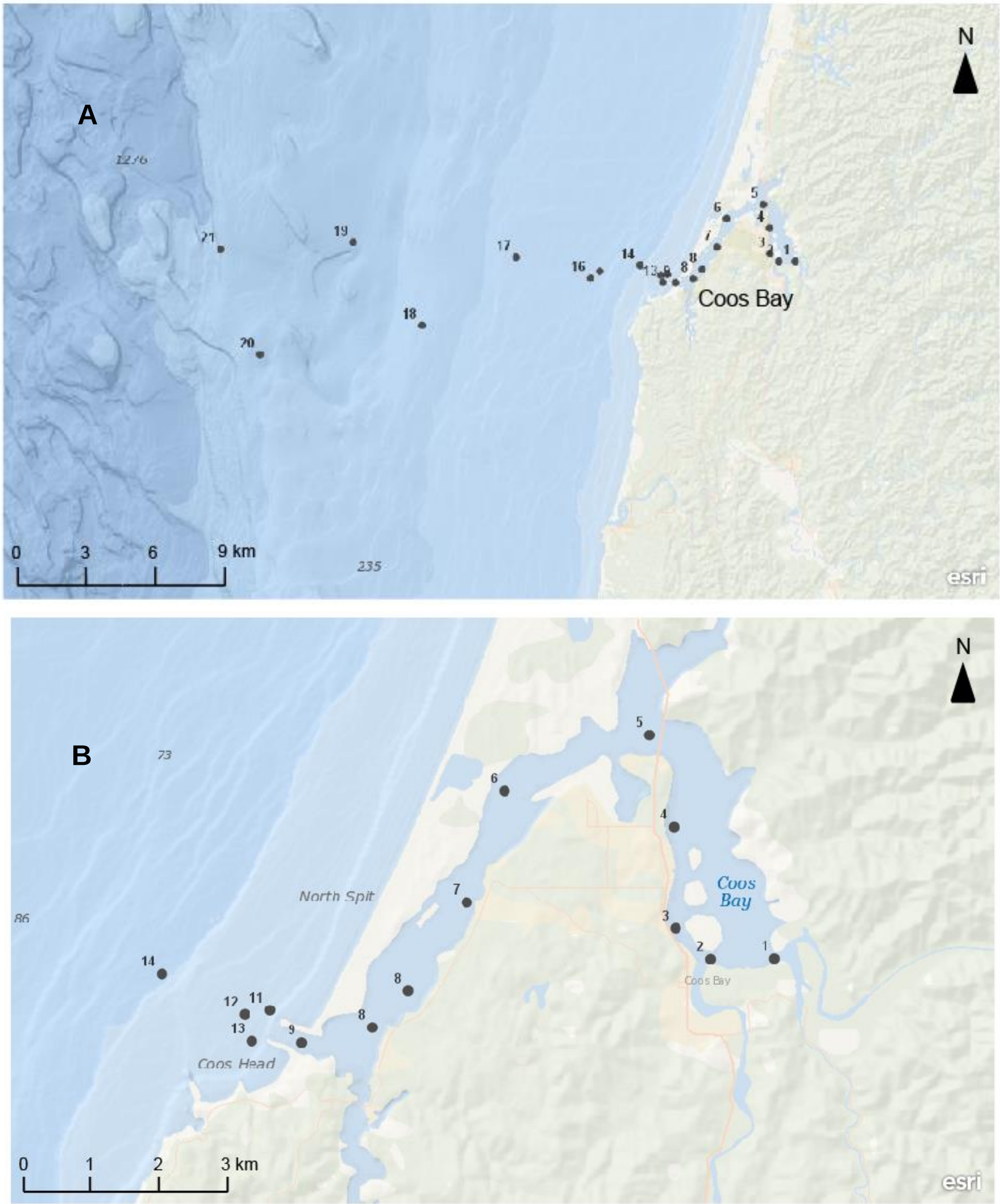

Figure 8. Sampling locations in the Coos Bay Estuary for this study. A. Map of all 21 sampling locations from the Coos Bay Estuary, the estuarine plume, and the continental shelf. B. Map of the first 14 sampling locations from the Coos Bay Estuary and the estuarine plume. Samples 1-8 were taken within the estuary with a PONAR grab deployed from the RV Pugettia. Samples 9-14 were taken within the estuary mouth and out into the estuarine plume with a PONAR grab deployed from the RV Pluteus. Samples 15-21 were taken on the adjacent continental shelf with a box corer deployed from the RV Pacific Storm. Map created with Esri ARCGIS.

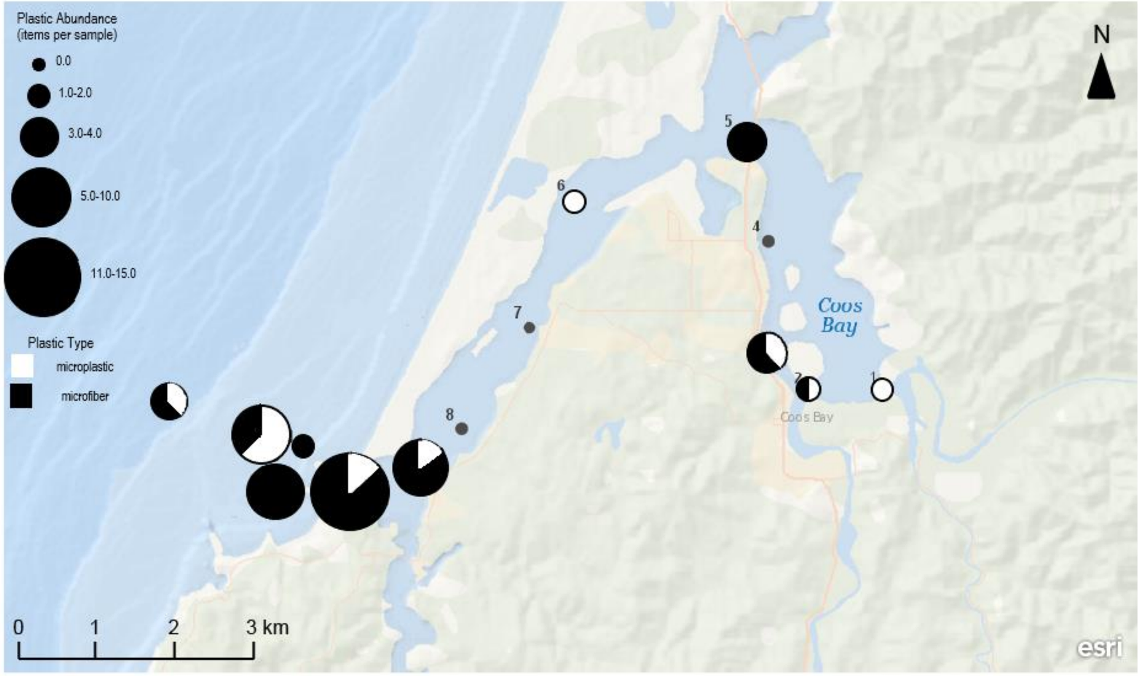

Figure 9. Items of plastic per sample from the Coos Bay Estuary and estuarine plume. Size of the pie chart corresponds with number of plastics per sample. Color corresponds with microplastic (white) or microfiber (black.) Continental shelf samples not depicted.

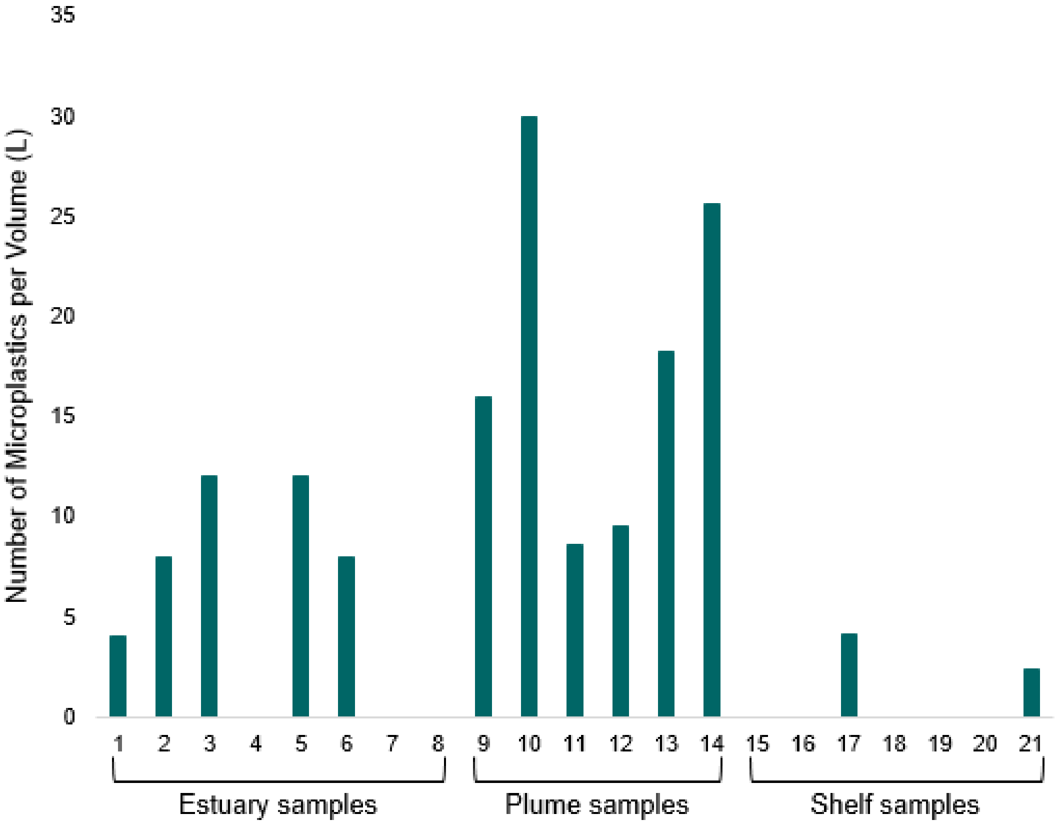

Figure 10. Microplastic density in the Coos Bay Estuary. Density for the estuary, the estuarine plume, and the continental shelf calculated as number of microplastics per liter of sediment. Both microplastics and microfibers are included in the count.

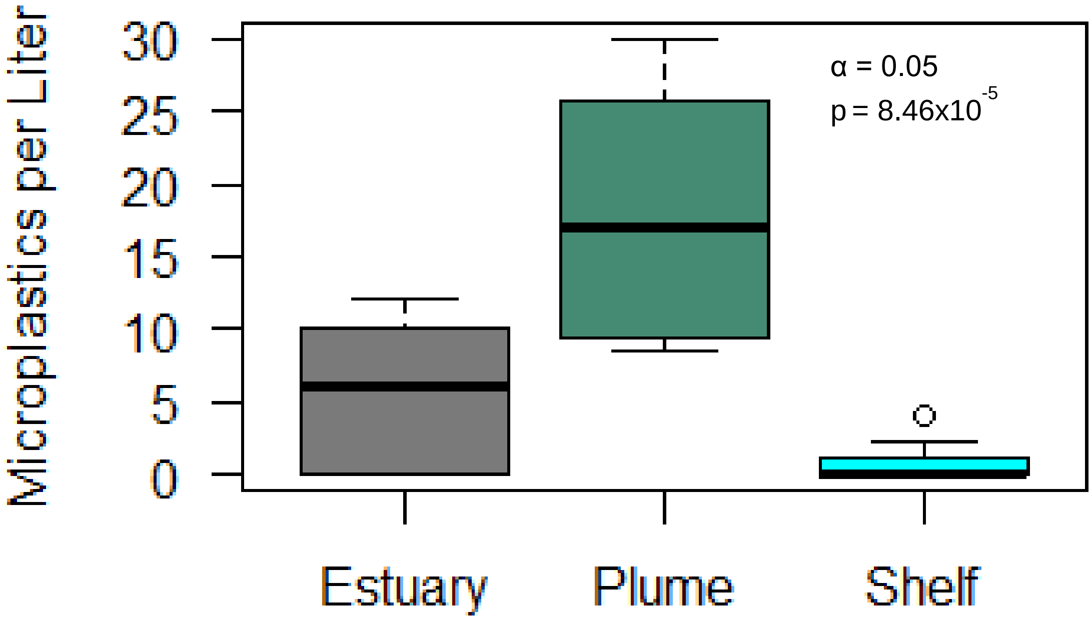

Figure 11. Box plot for an ANCOVA test for analysis of microplastic density in the Coos Bay Estuary, the estuarine plume, and the adjacent continental shelf. This analysis of covariance shows that location is the primary factor in determining the variation seen between sample sets ($p = 8.46x10^{-5}$, $\alpha = 0.05$).

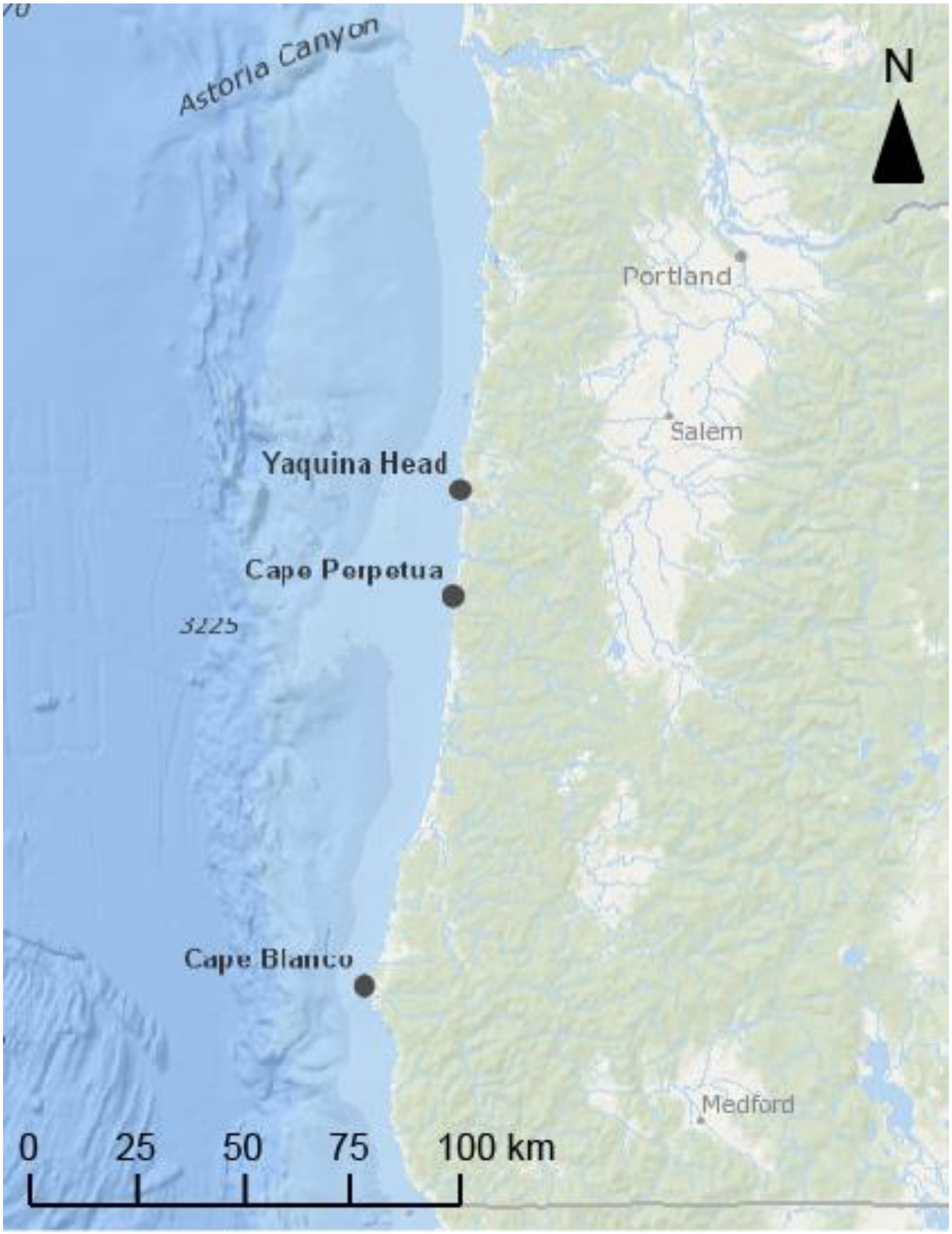

Figure 12. Map of the Oregon shoreline from the northern border at the Columbia River to the southern border with California. Three headlands from this study are labeled: Yaquina Head by Newport, Oregon, Cape Perpetua by Yachats, Oregon, and Cape Blanco by Bandon, Oregon.

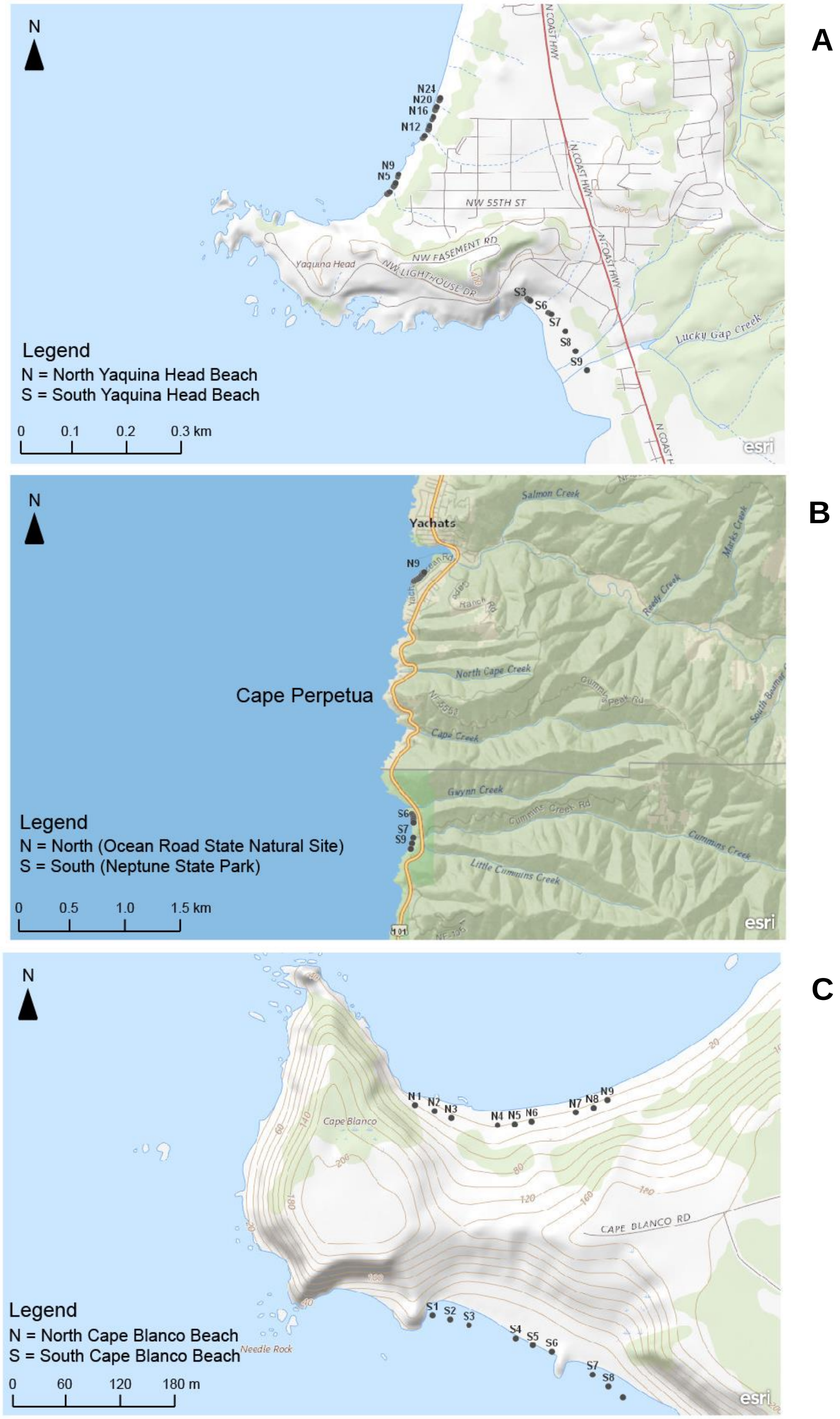

Figure 13. Map of headland sampling locations. N = northern beach samples. S = southern beach samples. Samples were taken as belt transects along the beach perpendicular to the shoreline. A. Yaquina Head headland near Newport, Oregon. B. Cape Perpetua headland near Yachats, Oregon. Northern samples were taken on Yachats Ocean Road State Natural Site. Southern samples were taken on Neptune Beach. C. Cape Blanco headland near Bandon, Oregon.

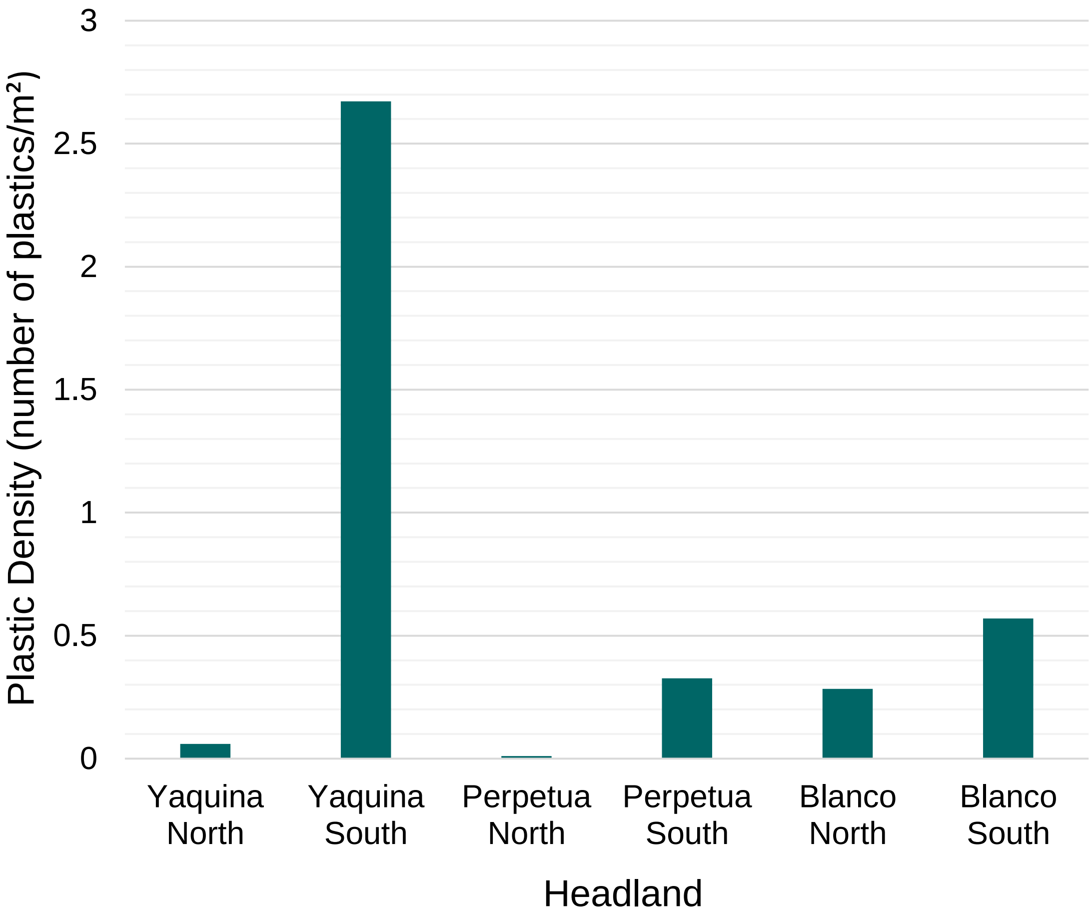

Figure 14. Plastic density on Oregon shorelines. Number of plastics collected from both the northern and southern beaches of the Yaquina Head, Cape Perpetua, and Cape Blanco headlands in Oregon. Data reported as the average number of plastics per transect, calculated using the area of each transect. Yaquina standard deviation = 1.55 particles per meter squared. Perpetua standard deviation = 0.16 particles per meter squared. Blanco standard deviation = 0.42 particles per meter squared.

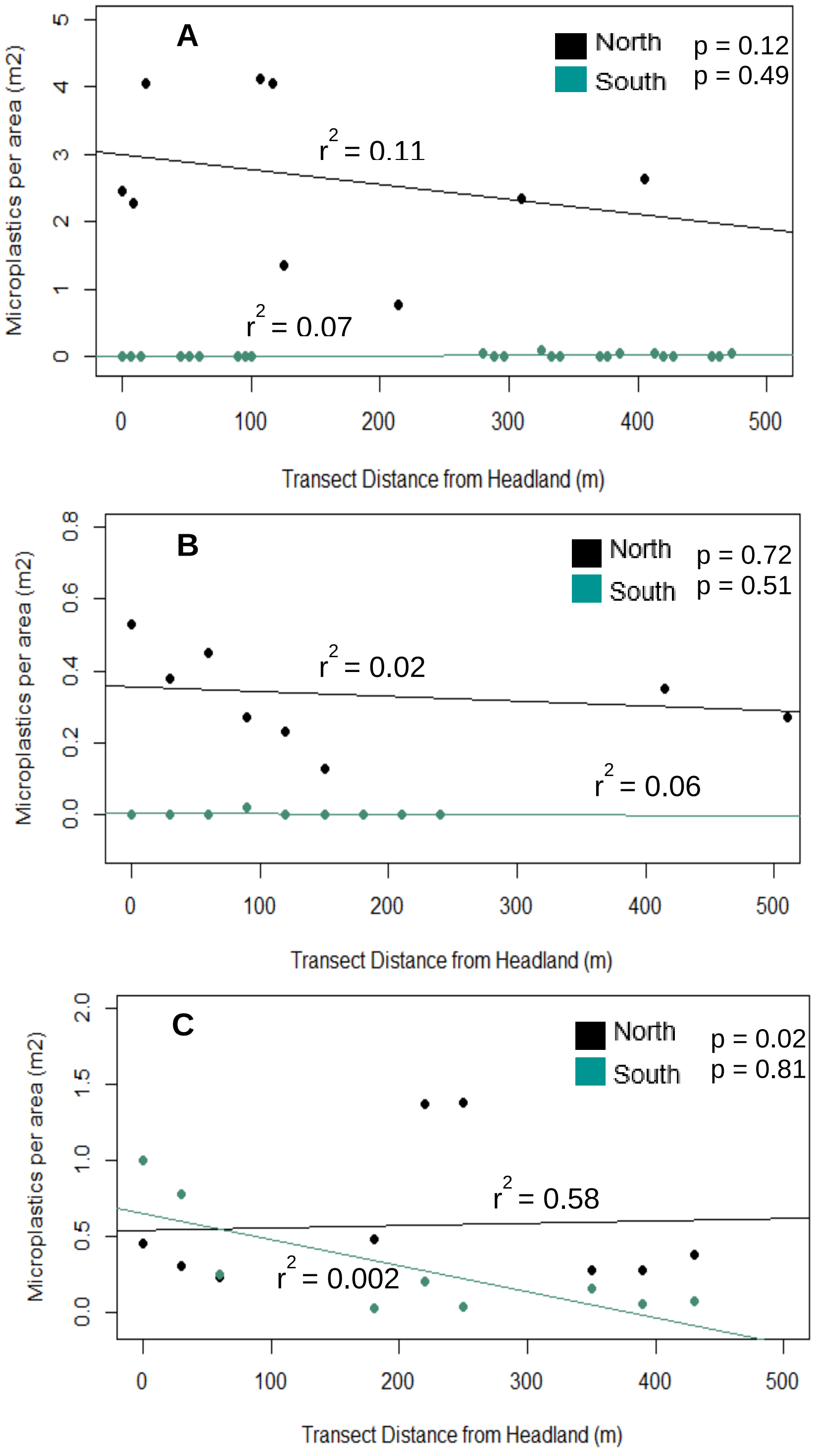

Figure 15. Regression analysis for microplastic density on beaches surrounding Oregon headlands. This regression tests for the linear relationship between distance from headland and number of microplastics per area of sediment. A. Yaquina Head regression. B. Cape Perpetua regression. C. Cape Blanco regression.

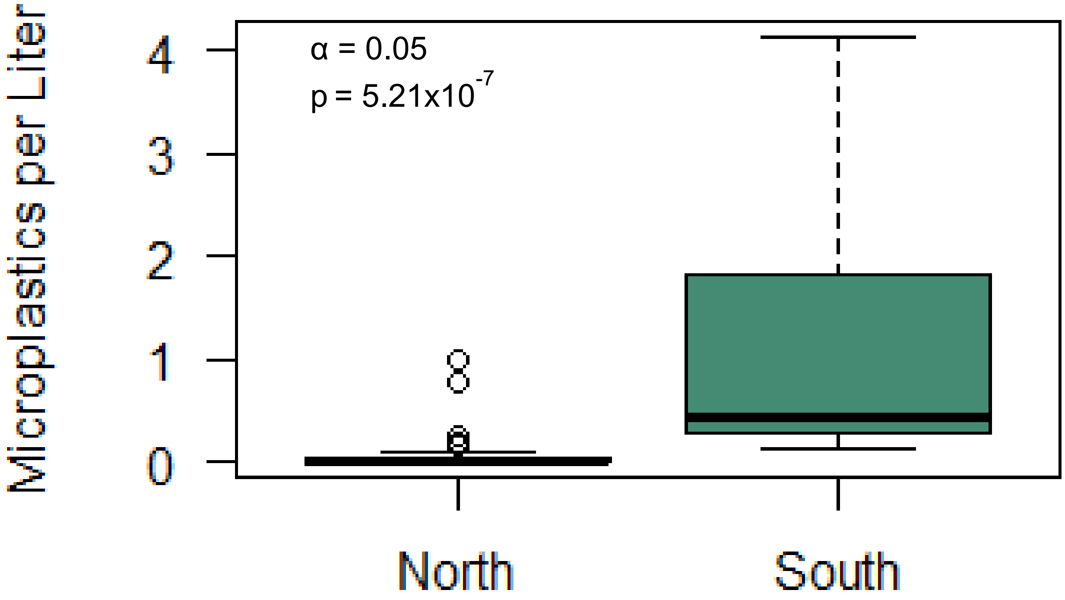

Figure 16. Box plot for an ANOVA test for analysis of microplastic on the northern and southern beaches of Yaquina Bay, Cape Perpetua, and Cape Blanco. This analysis of variance shows that location is a significant factor in determining the variation seen between sample sets ($p = 5.21 \times 10^{-7}$, $\alpha = 0.05$).

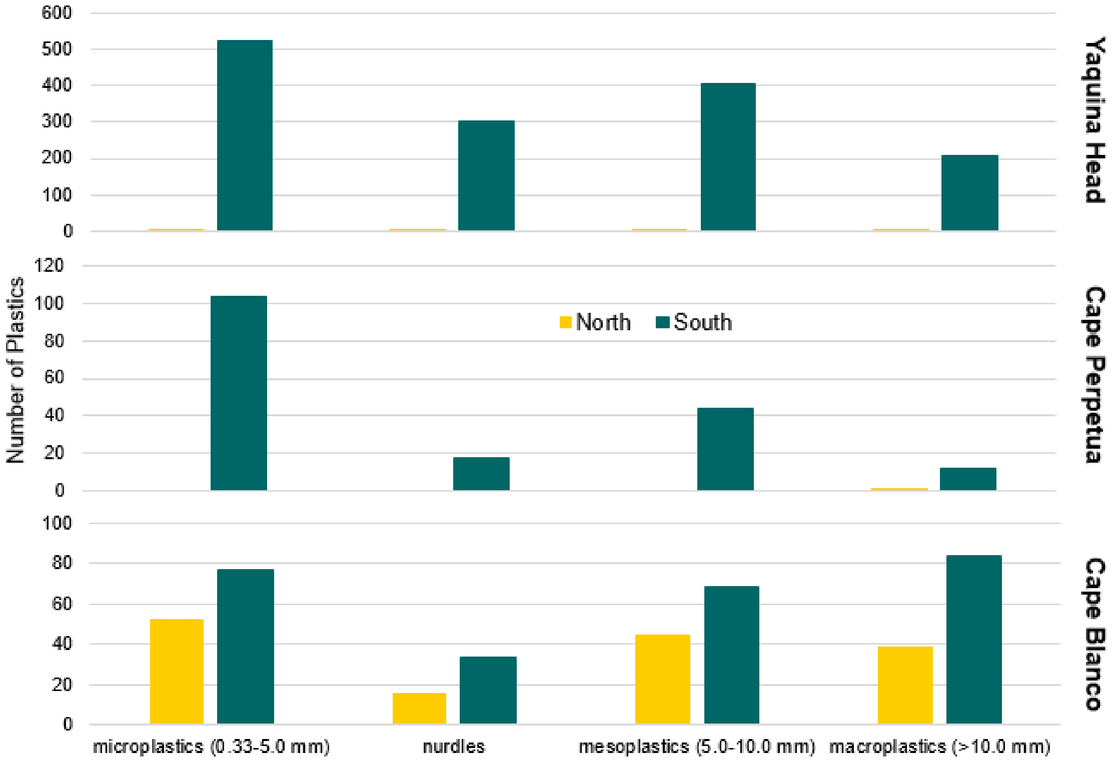

Figure 17. Size characterization of plastics on Oregon shorelines. Plastics collected from shoreline transects on beaches around Oregon headlands. Plastics are characterized by size. Nurdles are easily identifiable pre-production plastic pellets, and are included in the microplastics size category.

Appendix A

Representative sample of microplastics collected by this study

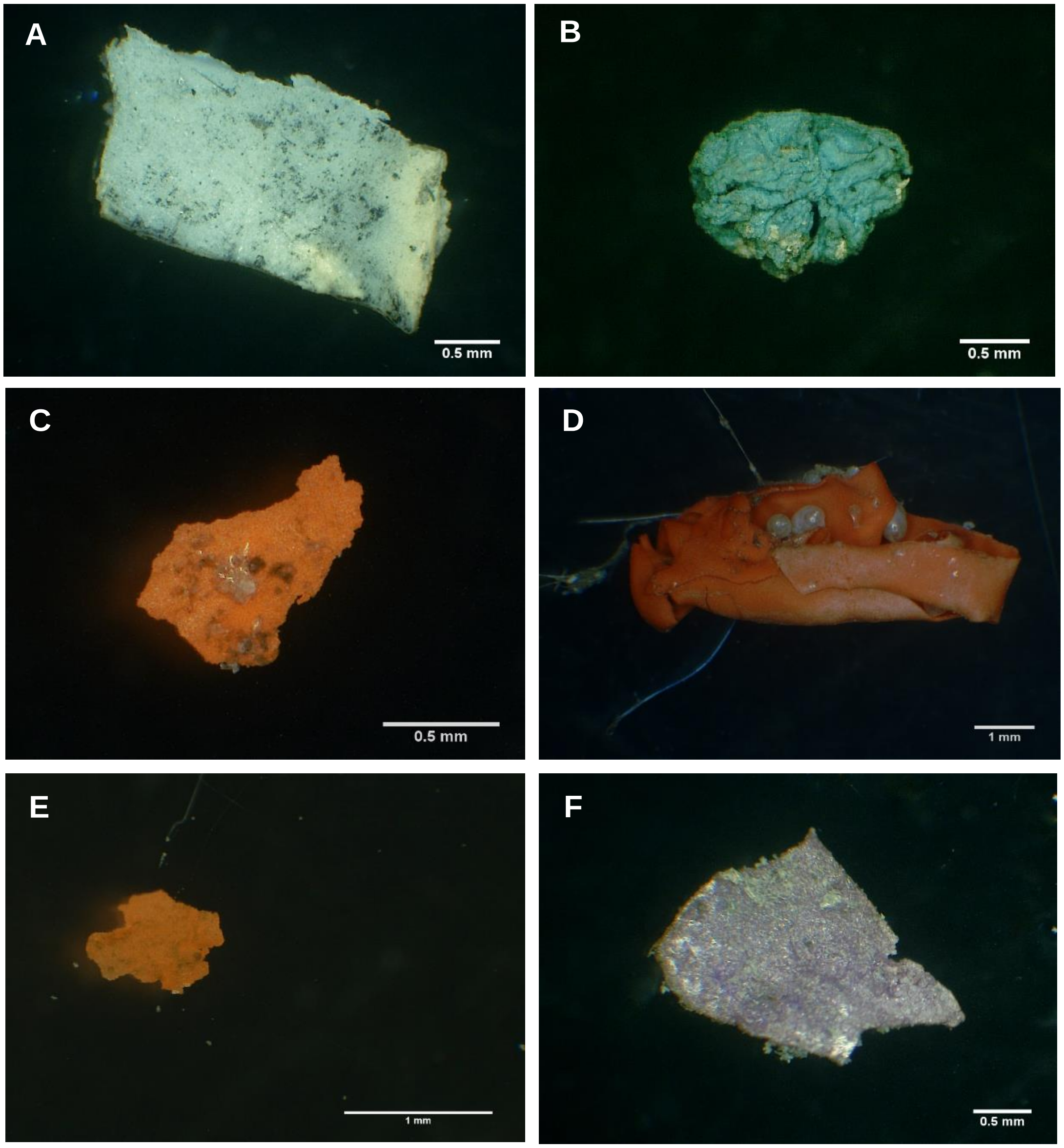

Plate 1. Representative sample of microplastics found in Norfolk Canyon samples. A. NF 1, 196 m. B. NF 2, 197 m. C. NF 5, 819 m. D. NF 5, 819 m. E. NF 5, 819 m. F. NF 8, 1133 m..

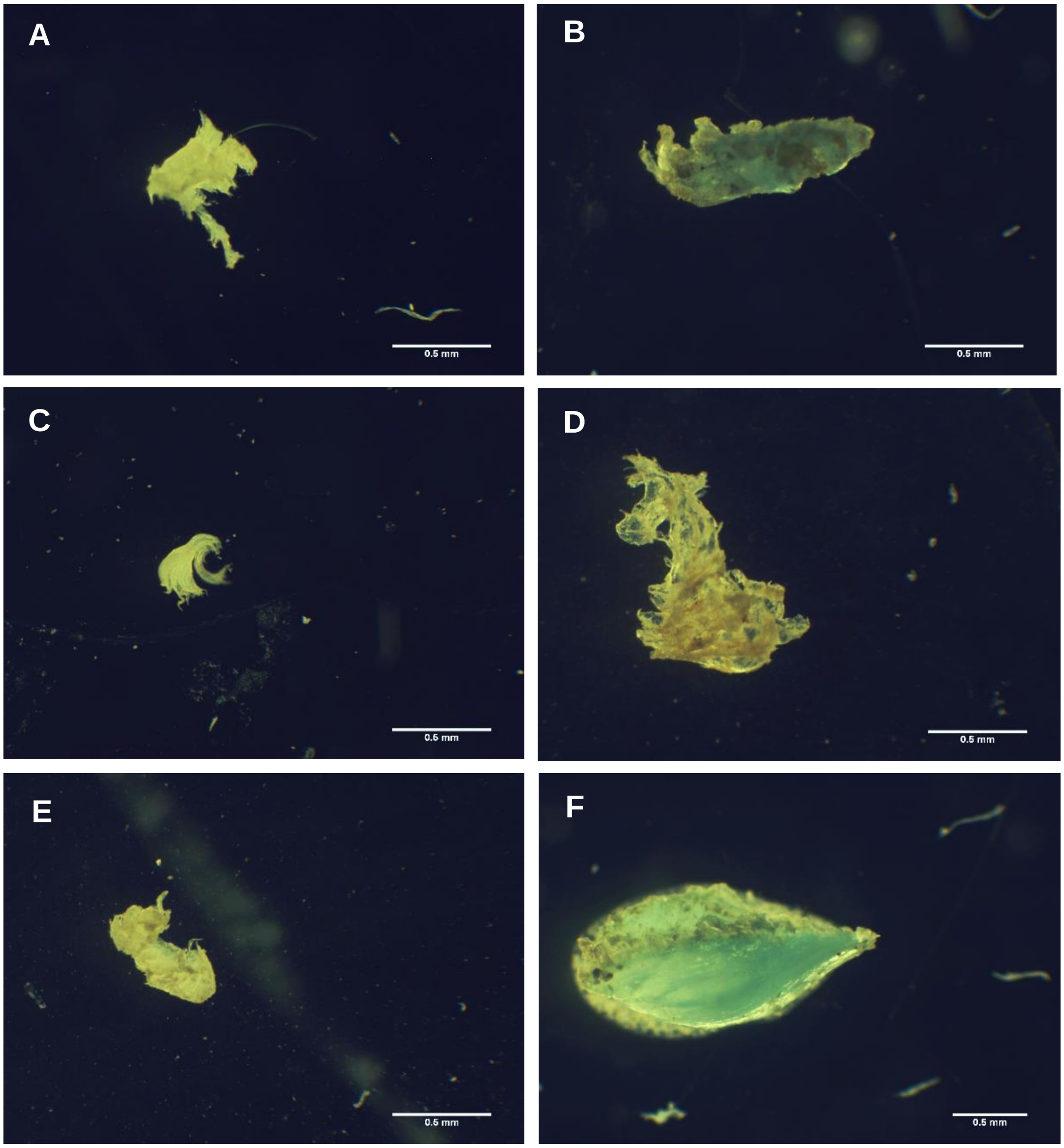

Plate 2. Representative sample of microplastics found in Norfolk Slope samples. A. NS 2, 188 m. B. NS 4, 550 m. C. NS 4, 550 m. D. NS 5, 550 m. E. NS 5, 550 m. F. NS 7, 1118 m.

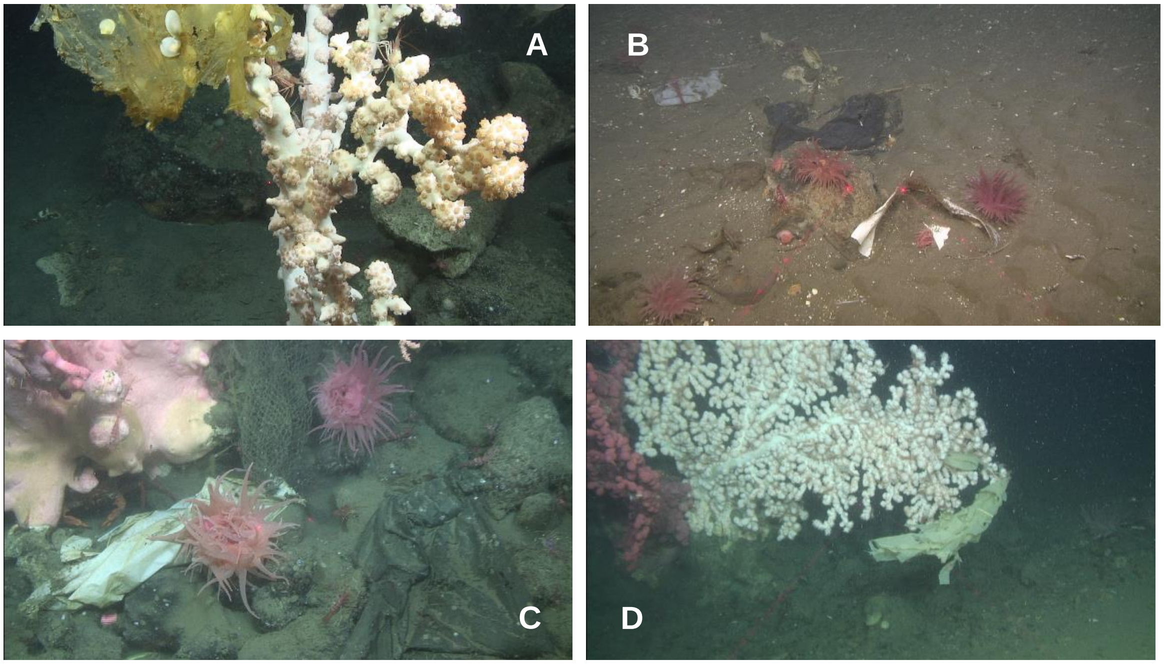

Plate 3. Representative sample of debris observed in ROV dive footage videos from the 2012 Atlantic Deepwater Canyon cruise. For the 2012 cruise, the *Kraken II* ROV (Univ. of Connecticut) was deployed off of the RV Nancy Foster. Videos were taken at slow speeds (0.93 km/h) with a 10 cm scaling laser set on wide angle. Dive frames taken by Steve W. Ross. A. Plastic entangled on a coral from Dive 10. B. Plastic partially buried in the seafloor near anemones from Dive 12. C. Plastic bags and a net near anemones and a crab from Dive 15. D. Plastic entangled on a coral from Dive 15.

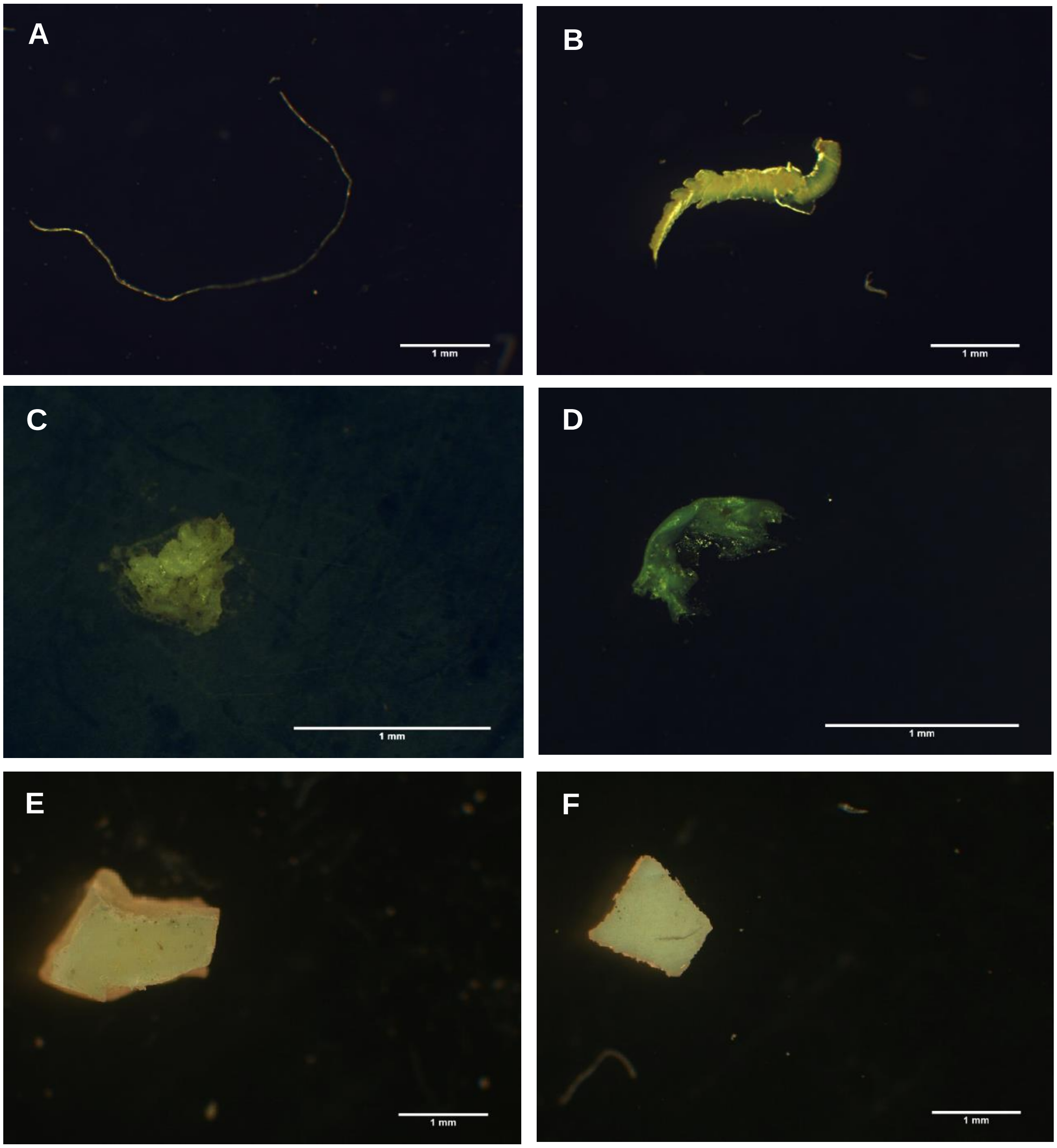

Plate 4. Representative sample of microplastics found in all three Coos Bay location samples. A. Estuary, sample 3. B. Estuary, sample 9. C. Plume, sample 3. D. Plume, sample 6. E. Shelf, sample 3. F. Shelf, sample 9.

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