Title

Abundance and ecological implications of microplastic debris in the North Pacific Subtropical Gyre

Author

Goldstein, Miriam Chanita

Publication Date

2012

UNIVERSITY OF CALIFORNIA, SAN DIEGO

Abundance and ecological implications of microplastic debris in the North Pacific Subtropical Gyre

A dissertation submitted in partial satisfaction of the requirements for the degree
Doctor of Philosophy

in

Oceanography

by

Miriam Chanita Goldstein

Committee in charge:

Professor Mark D. Ohman, Chair
Professor Lihini I. Aluwihare
Professor Brian Goldfarb
Professor Michael R. Landry
Professor James J. Leichter

2012

The Dissertation of Miriam Chanita Goldstein is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Chair

University of California, San Diego

2012

DEDICATION

For my mother, who took me to the tidepools and didn't mind my pet earthworms.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I feel extraordinarily fortunate to have spent the last 6 years following my scientific muse over a somewhat twisty path. It’s quite a privilege to have the resources and support to be able to ask big questions about how the world works, and I am grateful to the many people and institutions that have made it possible. Foremost among them is my advisor Mark Ohman. It’s impossible to overstate the profound benefits of Mark’s expertise, enthusiasm for the scientific endeavor, and dedication to student training. Mark has taught me how to think like a scientist (something that comes less naturally to me than he might hope), introduced to me to the glories of zooplankton, and tolerated the particular idiosyncrasies of the pelagic plastic problem. The habits of thought I’ve formed under Mark’s tutelage will serve me well throughout life.

I’m also thankful for the help and guidance from my committee. Jim Leichter’s encouragement was fundamental in getting SEAPLEX off the ground, and his fieldwork expertise helped the entire operation run smoothly. Mike Landry supported my attempts to become a zooplankton experimentalist and provided valuable perspective on North Pacific Subtropical Gyre biogeography. Lihini Aluwihare provided critical chemistry guidance despite my somewhat lackluster track record in organic chemistry. Brian Goldfarb made sure that I was considering the larger societal implications of my research.

I very much value the excellent education in science and natural history I received during my classwork, not least because I never quite meant to become an oceanographer. I particularly appreciate the dedication to teaching shown by Lisa Levin, Paul Dayton, Dick Norris, Peter Franks, and Mark Ohman. I am unusually fortunate to have had access to the expertise and samples of North Pacific oceanography pioneers John McGowan, Pooh Venrick, and Lanna Cheng. I'd also like to thank Charles Moore and the Algalita Marine Research Foundation staff for their tireless efforts to raise awareness regarding plastic pollution, which were the original inspiration for this dissertation. My co-authors Lanna Cheng, Marci Rosenberg, Andrew Titmus, Michael Ford, Hank Carson, and Marcus Eriksen were also substantial contributors to this dissertation. I am grateful for their scientific thoughts, hard work, and valuable input.

My research direction and social media activities were inspired by the Center for Marine Biodiversity and Conservation and the Marine Biodiversity IGERT program, founded by Jeremy Jackson and Nancy Knowlton and later led by Dick Norris and Lisa Levin. My early IGERT training and interaction with faculty and fellow trainees, particularly my IGERT cohort Melissa Garren, Damien Cie, and Ben Gilbert, inspired me to think critically about conservation issues. Also, I can't thank Penny Dockry enough for her friendship and support.

I've been fortunate to work closely with several wonderful Scripps offices. The Scripps Communications Office has always been a delight to work with. In particular, Mario "Team Manta" Aguilera went above and beyond his PIO duties. The efforts of the Development Office and the generosity of many private funders (listed at the end of each dissertation chapter) gave the luxury of focusing solely on my research. Rudy Murillo in Government Relations was also extraordinarily helpful in locating funding. The SIO Graduate Office provided both administrative and occasional emotional support – special thanks to Denise Darling, Josh Reeves, Satomi Saito, and Cerise Maue. Ship Operations and Marine Technical Support were very kind to a graduate student with no idea what she was doing, particularly Bruce Appelgate and Rose Dufour. I am most grateful for Phil Zerofski's help with experimental setup, net testing, and for letting me feed the dwarf cuttlefish whenever I felt the need. I spent my first few years at SIO doing a lot of SCUBA diving, and I appreciate Christian McDonald and Rich Walsh's guidance and training.

A great many people were generous with their time and expertise to help me in the field and lab. At sea, all 27 members of the SEAPLEX ship's crew and science party were an amazing team. I can't thank them highly enough for helping to collect the samples that form the backbone of my dissertation. Special thanks to Capt. Wes Hill, resident technician Matt Durham, Pete Davison, and Jesse Powell for their on-the-job training in Big Ship Science. SEAPLEX was also greatly enhanced by the efforts of Jim Dufour, who facilitated the Ocean Voyages Institute/Project Kaisei funding that allowed us an extra week of ship time. Michael Ford, Stephanie Oakes, and the crew of the *Okeanos Explorer* made additional North Pacific Subtropical Gyre data collection possible. Paul Joyce, Erik Zettler, and the chief scientists of Sea Education Association generously allowed me to hitchhike on two cruises, making all my sea-chanty-singing dreams come true. Many thanks to cruise leaders Capt. Pamela Coughlin, Chris Perle, and Deb Goodwin, and to the superb students and professional crews of S230 and S236 for generously sharing their ship time, watches, and Mama Seamans love with me.

Back at Scripps, Annie Townsend shared her immense expertise and love of zooplankton with me, training me up from a humble starting point of “What’s a plankton sock?” and “Why is there a piece of paper inside this jar?” Shonna Dovel showed me how cruise preparation and organization should be done, and was generous with her equipment and filtration know-how. Amy Hays and Southwest Fisheries Science Center generously lent manta tow equipment and showed me how to use and maintain it. Linsey Sala provided logistical support, fun plankton facts, and most importantly, taxonomic companionship. Our identification of the non-calcified bryozoan *Bowerbankia* spp. is a highlight of my time at Scripps. (Yes, I know how nerdy that sounds.) My amazing team of volunteers made processing over 200 samples possible and fun: Kamil Armaiz, Olivia Benge, Carri-Lyn Cameron, Patrick Chung, Dominic Dufour, Andy Pin-Hsien Fan, Chris Gawad, Adam Greco, Rose Hill, Catherine Nickels, Erik Raudzens, Erin Reed, Marci Rosenberg, Marie Ryder, Ashley Salas, Summer Strutt, Thanh Trinh, and Alexandria Warneke. The FTIR analysis was made possible by the Sailor lab, particularly Andrea Potocny and Jess Lee, facilitated by Gustaf Arrhenius.

I began my time at Scripps amidst the aroma of fresh bread on the third floor of Ritter Hall. Thanks to Paul Dayton, Ed Parnell, Jim Leichter, Kristin Riser, Maiko Kasuya, Ryan Darrow, Cynthia Catton Button, Christian Anderson, Damien Cie, Talina Konotchick, and Marco Hatch for forming a wonderful community. Kristin and

Cynthia also taught me a great deal about kelp forest ecology, diving, and why people who get as seasick as I do should probably avoid Point Loma.

I couldn't have asked for better comrades-in-science-arms than my fellow Scripps students. The 2006 Biological Oceanography cohort – Alison Cawood, Meg Rippy, Jesse Powell, and Darcy Taniguchi – not only provided study companions and mutual support, but actually thought the idea of going to the North Pacific Subtropical Gyre to hunt a plastic island was a good idea. I've also had the pleasure of working and playing with Kate Hanson, Celli Hull, Emily Kelly, Cynthia Catton Button, Tonya Huff, Christian Briseño, Matt Forrest, Geoff Cook, Andrew Thurber, Pete Davison, Rebecca Asch, Tali Vardi, Ayana Johnson, Danny Richter, Taylor Stratton Richter, Talina Konotchick, and Marco Hatch, as well as Scripps associates Renee Hatch, James Fischer, and Chelsea Rochman. I've also been fortunate to have the support of long-time friends, particularly Jarrett Byrnes, Carolyn Fredericks, Scott Richmond, GRP, and π, as well as my Deep Sea News/Science Online quasi-virtual compadres. And there is no way I could have gotten through dissertation writing without Brian Switek's seemingly endless supply of great music.

This entire endeavor would not have been remotely possible without the love and support of my husband, Eric Wolff. Back in our Brooklyn kitchen when he asked me what I would do if I could do anything, and I said "marine biologist," I don't think he quite appreciated what he'd be signing up for. Don't worry, Eric – your long sunny nightmare ("always Christmas and never winter") is now over. Finally, I'd like to thank my family, who encouraged me to go to graduate school through very difficult times.

Chapter 2 has been submitted to *PLoS ONE* and is presented as part of this dissertation with the acknowledgement of the study co- authors Andrew J. Titmus and Michael Ford. The dissertation author was the primary investigator and is the primary author of this material.

Chapter 5, in full, is a reprint of the material as it appears in *Biology Letters* 8(5): 817-820, Goldstein, M.C.; Rosenberg M.; Cheng, L., 2012. The dissertation author was the primary investigator and author of this paper.

Chapter 6 is being prepared for submission to *Marine Ecology Progress Series* and is presented as part of this dissertation with the acknowledgement of the study co-authors Henry S. Carson and Marcus Eriksen. The dissertation author was the primary investigator and is the primary author of this material.

VITA

2003	Bachelor of Science, Brown University
2008	Master of Science, Scripps Institution of Oceanography, University of California, San Diego
2012	Doctor of Philosophy, Scripps Institution of Oceanography, University of California, San Diego

PUBLICATIONS

Goldstein, M.C., M. Rosenberg, and L. Cheng. 2012. Increased oceanic microplastic debris enhances oviposition in an endemic pelagic insect. Biology Letters 8:817-820. doi: 10.1098/rsbl.2012.0298/.

Wilson, N.G., D. Huang, M.C. Goldstein, H. Cha, G. Giribet G.W. Rouse. 2009. Field collection of *Laevipilina hyalina* McLean, 1979 from southern California, the most accessible living monoplacophoran. Journal of Molluscan Studies 75: 195-197. doi:10.1093/mollus/eyp013.

C. Benham, A.M. Cawood, G.S. Cook, A. Darnell, P.C. Davison, M.C. Goldstein, A.E. Johnson, T. Konotchick, E.M. Maldonado, A.L. Pasulka, J.C. Prairie, S.M. Moseman, V. Tai, C.A. Tanner, T. Vardi, T.S. Whitty & L.A. Levin. 2008. Marine Metapopulations (Book Review). Marine Ecology 29:319-320.

ABSTRACT OF THE DISSERTATION

Abundance and ecological implications of microplastic debris in the North Pacific Subtropical Gyre

by

Miriam Chanita Goldstein

Doctor of Philosophy in Oceanography

University of California, San Diego, 2012

Professor Mark D. Ohman, Chair

Plastic pollution in the North Pacific Subtropical Gyre (NPSG), dubbed the "Great Pacific Garbage Patch," has been the subject of substantial public concern. However, there is relatively limited scientific understanding of how microplastic affects pelagic ecosystems. The motivation for this dissertation is to provide scientific information on the extent and impact of microplastic in the NPSG. The dissertation is organized around two central questions: 1) What are the abundance, distribution, and characteristics of plastic microdebris in the NPSG? 2) What is the impact of this microplastic on the neustonic zooplankton and plastic-associated rafting communities?

I documented widespread, though spatially and temporally variable, plastic pollution in the NPSG and adjacent water masses. The numerical majority of objects are small particles, but the majority of debris surface area is found in large objects. While plastic was highly variable on the submesoscale, an analysis of all available data showed that overall NPSG microplastic concentrations increased by two orders of magnitude between 1972-1988 and 1999-2010. I performed a laboratory weathering experiment on plastic pre-production pellets that suggested that changes in microplastic composition over the eastern North Pacific may be explained by differential rates of weathering between plastic types, and that carbonyl formation may be a proxy for the length of time a plastic object has weathered in the ocean.

Microplastic interacted with marine life through its direct ingestion and by providing a hard substrate for oviposition and settlement. Thirty-three percent of lepadid barnacles collected in 2009 contained microplastic in their gastrointestinal tract. In contrast, neustonic zooplankton did not show significant ingestion of plastic microspheres during a series of at-sea incubation experiments. Oviposition in the oceanic insect *Halobates sericeus* was positively correlated with microplastic abundance. Most plastic-associated macroinvertebrates were known members of the rafting assemblage, but several potentially invasive taxa were also associated with debris. The diversity of taxa in the rafting assemblage increased with debris surface area, as predicted by the concept of island biogeography.

This dissertation demonstrated that microplastic pollution is pervasive at the surface of the NPSG, and that ecological impacts include direct ingestion, release from substrate limitation, and enhanced dispersal. The introduction of microplastic to the NPSG may therefore represent a widespread alteration of the pelagic ecosystem.

CHAPTER 1: Introduction

Roll on, thou deep and dark blue ocean - roll!
Ten thousand fleets sweep over thee in vain;
Man marks the earth with ruin - his control
Stops with the shore.
- Childe Harold's Pilgrimage, Lord Byron (1818)

Mr. McGuire: I just want to say one word to you. Just one word.
Benjamin: Yes, sir.
Mr. McGuire: Are you listening?
Benjamin: Yes, I am.
Mr. McGuire: Plastics.
Benjamin: Exactly how do you mean?
- The Graduate (1967)

Once thought to be infinite and unchanging, the ocean is being altered by anthropogenic activities on a global scale (Pew Oceans Commission 2003). Along with impacts such as climate change, overfishing, and habitat destruction, pollution can cause undesirable changes in marine ecosystems. Historically, studies of oceanic pollution have primarily focused on toxins (e.g., oil and persistent organic pollutants) and eutrophication (e.g., the Gulf of Mexico "Dead Zone," Pew Oceans Commission 2003). However, oceanic litter, termed "marine debris" or "plastic pollution," has been a matter of increasing scientific and public concern (Derraik 2002).

A Brief History of Plastic

Marine debris is comprised primarily of non-biodegradable plastic polymers (Derraik 2002, Barnes et al. 2009). A polymer is a chemical compound made of many repeating units. The individual units, called monomers, link together to form larger molecules. Polymers can be linear, branched, or form two- or three-dimensional structures (University of Southern Mississippi 2005). Natural polymers include DNA, cellulose, hair, and spider silk (American Chemistry Council 2010a).

The first manufactured polymers were created by altering natural polymers. For example, vulcanized rubber was first made by heating natural tree rubber with sulfur, and the first man-made plastic, celluloid, was derived from plant cellulose in 1862 (American Chemistry Council 2010b). The first truly synthetic polymer, Bakelite, was synthesized from coal tar by chemist Leo Hendrik Baekland in 1907 (American Chemistry Council 2010b). After World War I, plastic was made of petroleum, which was more easily processed into raw materials. With the discovery of over 15 new classes of synthetic polymer in the 1940s and 1950s, plastic consumer goods soon became ubiquitous (Andrady and Neal 2009).

Manufactured polymers occur as two basic types. Thermoset polymers have a three-dimensional molecular structure that cannot be melted and re-formed. These include vulcanized rubber and two-part epoxy glues (American Chemistry Council 2010a). Thermoplastic polymers have a linear molecular structure and can be melted and re-hardened (American Chemistry Council 2010a). While hundreds of plastic material types are available, only a few polymer types are both inexpensive and adaptable enough to be widely used. Known as “commodity thermoplastics,” these account for over 90% of the total world demand (Figure 1.1; PlasticsEurope 2008 as cited in Andrady and Neal 2009).

Most thermoplastics are carbon-based (Table 1.1). The simplest, polyethylene, is a repeating chain of carbon and hydrogen atoms. Other thermoplastics have additional atoms, such as chlorine in PVC (American Chemistry Council 2010c). To make consumer goods, plastic resins are nearly always mixed with additional substances known as “additives.” Additives may be inorganic fillers (e.g., carbon or silica), thermal stabilizers, fire retardants, UV stabilizers, or plasticizers.

There are more than 300 types of plasticizer, though only 50 to 100 are in commercial use (European Council for Plasticisers and Intermediates 2010). The most commonly used plasticizers are the phthalates, which are added to PVC to make it soft and flexible (European Council for Plasticisers and Intermediates 2010). Another widely used plasticizer, bisphenol-A (BPA), is added to polycarbonate and epoxy resins used in food containers and food can liners. Of the additives, phthalates and BPA have received the most scientific and public attention due to their potential effects on human and environmental health (Koch and Calafat 2009).

Plastic types

A summary of different plastic resin types may be found in Table 1.1. Worldwide, the most commonly used resin type is polypropylene (PP, resin ID #5; Andrady and Neal 2009; data for Figure 1.1 are based off 2008 sales in North America only.) Polypropylene is primarily used for packaging films (e.g., snack bags), caps and closures for containers, thin-walled flexible containers (e.g., yogurt and margarine tubs), and a wide range of personal goods such as combs and hair dryers (Andrady and Neal 2009).

Polyethylene is the second most commonly used resin type. It is divided into subtypes based on its density - low-density polyethylene (LDPE, resin ID #4) and high-density polyethylene (HDPE, resin ID #2). Half of all polyethylene is used for making plastic films such as shopping bags, cling wraps, and sandwich bags (Andrady and Neal 2009). Polyethylene is also used to make injection-blown food containers such as milk jugs and detergent bottles.

The following three types are each approximately 10% of the global market (Andrady and Neal 2009). Polyvinyl chloride (PVC, resin ID #3) contains chlorine, which renders it non-combustible and thus suitable for building applications, furniture, and piping. PVC most often contains the plasticizer group known as phthalates. Polystyrene (PS, resin ID #6) is primarily used for insulation and packaging. When expanded with air, it is used for consumer goods such as "Styrofoam" coffee cups. Polyethylene terephthalate (PET, resin ID #1) is lightweight, transparent, and resistant to carbon dioxide permeation. It is primarily used in drink bottles and food packaging.

Plastic Appears in the Ocean

Plastics have only been produced in quantity since World War II, but detectable amounts of plastic debris were documented in the open ocean as early as 1972. In the Sargasso Sea, Carpenter and Smith (1972) used a neuston net to sample surface plastic and, extrapolating to a larger area, reported an average of 3,500 pieces of plastic km^{-2}. The debris consisted largely of the preproduction pellets known as "nurdles." Similarly, Colton et al. (1974) found widespread neustonic plastic debris in the western Atlantic. Of stations where plastic was detected, densities ranged from

1,292 to 166,991 pieces km^{-2}. In the central North Pacific, Venrick et al. (1973) noted the occurrence of visible floating debris, including plastic bottles and fragments. On an east to west transect of 35º N, Wong et al. (1974) found plastic debris in 21 of 33 neuston tows, with the highest densities (62 pieces found in a tow, or 34,000 particles km^{-2}) found along approximately 145º W in the northeastern Pacific.

Though all studies note that the distribution of plastic is extremely variable, the frequency of occurrence of plastic debris appeared to increase from the 1960s and 1970s to the 1980s and 1990s. This increase was detected both by direct measurement of neustonic debris, and by using seabird ingestion as a proxy. In the North Atlantic, Thompson et al. (2004) used continuous plankton recorder measurements to document debris increase between the 1960/70s and the 1980s/90s. In seabirds, the frequency of plastic ingestion in Arctic and subarctic seabirds significantly increased between 1969-1977 and the late 1980s (Robards et al. 1997). In the northwest Atlantic, ingestion by seabirds significantly increased from 1975 to 1989 (Moser and Lee 1992). A similar increase in the 1990s was detected by measuring coastal deposition and seabird ingestion (Barnes et al. 2009).

After the 1980s, there is some question whether plastic density remained constant. Using CalCOFI archived samples, (Gilfillan et al. 2009) detected widespread plastic micro-debris in the southern California Current during the winter cruise in 1984, 1994, and 2007, but did not find a significant increase over time. Visual observations (Barnes and Milner 2005) and neuston tows (Law et al. 2010) in the Atlantic likewise showed no increase in oceanic plastic debris between the 1980s and 2000s. Densities of debris on the coastline appear to have remained constant since the

1990s (Barnes et al. 2009, Ribic et al. 2010), with the exception of some types of Pacific debris, which decreased (Ribic et al. 2012). In addition, the incidence of plastic ingestion in North Pacific procellariiform seabirds rose between 1984 and 1990 but declined afterwards (Spear et al. 1995).

In the past decade, marine debris has remained ubiquitous. In the central Pacific, Moore et al. (2001) found between 31,982 and 969,777 pieces of plastic debris km^{-2}, though this result was based on 11 manta tows of arbitrary duration. Similarly, in the Kuroshio area of the western Pacific, Yamashita and Tanimura (2007) found between 0 and 3.5 million pieces of plastic km^{-2}. On isolated Pacific islands such as Midway Atoll and the northwest Hawaiian islands, 72% of all debris found on beaches consisted of plastic particles, the vast majority of which were less than 5 mm (McDermid and McMullen 2004). In the South Pacific, 87% of floating debris consisted of plastic material (Thiel et al. 2003). Plastic has also been detected on the benthos, both coastally (Ng and Obbard 2006, Browne et al. 2011) and on continental slopes and offshore canyons (Galgani et al. 1996, Watters et al. 2010, Wei et al. 2012).

Plastic types found in the ocean are generally distributed according to density. In a study of plastic collected from coastlines worldwide, most plastics detected were clothing-associated fibers denser than seawater, including polyester (56%), acrylic (23%), polypropylene (7%), polyethylene (6%), and polyamide (Nylon) fibers (3%; Browne et al. 2011). Similar plastic types were identified in other studies of sediment samples off Britain (Thompson et al. 2004) and Singapore (Ng and Obbard 2006). In contrast, the vast majority of debris collected from the central North Pacific was polypropylene and polyethylene, both of which are less dense than seawater (Rios et al. 2007).

The spatial distribution of plastic marine debris is influenced by multiple interacting factors. Both continental and oceanic sources of marine debris vary regionally (Ribic et al. 2010, 2012). Over ocean basins, spatial patterns of debris are influenced by interacting large-scale atmospheric and oceanic circulation patterns, leading to particularly high accumulations of floating debris in the subtropical gyres (Martinez et al. 2009, Goldstein et al. 2012, Maximenko et al. 2012, Lebreton et al. 2012). Over regional scales, convergences such as the North Pacific Subtropical Convergence Zone and the Kuroshio Extension Recirculation Gyre collect debris (Pichel et al. 2007, Howell et al. 2012). Higher densities of debris in coastal waters may also be associated with human population centers (Matsumura and Nasu 1997, Thiel et al. 2003, Browne et al. 2011). Locally, wind patterns affect the distribution of debris by differentially moving or mixing particles of different densities (Browne et al. 2010, Kukulka et al. 2012).

While large-scale ocean circulation leads to the expectation that debris should collect northeast of Hawaii (Kubota 1994, Howell et al. 2012), nearly all the studies cited above (e.g., Colton et al. 1974, Moore et al. 2001, Yamashita and Tanimura 2007) found that neustonic plastic debris had very high spatial variance on scales of 500-2500 km. Day et al. (1990) observed that higher densities of neustonic plastic debris were associated with dense human populations and microscale convergence zones. Similarly, Pichel et al. (2007) found that discarded fishing debris was associated with the North Pacific Subtropical Convergence Zone. However, it can be difficult to link spatial variability in plastic density to specific oceanographic or anthropogenic features. Wong et al. (1974) found that two types of anthropogenic passive particles, tar balls and plastic particles, had markedly different distributions across an east-west transect of the North Pacific, perhaps due to differing source locations.

Determining the residence time of plastic in the ocean is a significant challenge. Plastic in the ocean undergoes both chemical and photochemical weathering, as plasticizers and other chemicals leach out of the polymer matrix and photodegrade, and mechanical weathering, as wind and wave action break the plastic into pieces. The most important process controlling the rate of degradation is heat (Andrady 2011). While plastics may degrade in less than 50 years in certain terrestrial environments (Kyrikou and Briassoulis 2007), this relatively rapid rate of degradation is unlikely to occur in the ocean, where plastic weathers more slowly due to a lack of heat buildup and the blocking of UV light by biofouling organisms (Andrady 1989, 2011). For example, dry polyethylene exposed to sunlight for a year became brittle after only 6 months, while polyethylene in seawater did not become brittle after 12 months (Andrady 2003). Because plastic in seawater is so resistant to degradation, Andrady (2011) has proposed that oceanic microplastics must be generated through initial weathering of plastic objects on shorelines which are subsequently washed out to sea.

Ecological consequences of large plastic debris

The effects of larger pieces of plastic debris on higher trophic levels are relatively well documented, such as entanglement (Laist 1997) and ingestion by megafauna (Robards et al. 1997). Entanglement is estimated to affect over 267 species worldwide, though data exist primarily for charismatic megafauna such as sea turtles, seabirds, and marine mammals that strand on land (reviewed by Laist 1997, Derraik 2002, Allsopp et al. 2006). Entanglement primarily is caused by discarded fishing gear, though consumer products such as six-pack rings have gained a certain notoriety (Allsopp et al. 2006). In vertebrates, entanglement can cause injury and death through increased drag, strangulation, infection, and drowning. Some bird species incorporate plastic debris into their nests, which may increase risk of entanglement (Montevecchi 1991, Hartwig et al. 2007, Sergio et al. 2011). Invertebrates may also be entangled, particularly in lost or discarded fishing equipment such as lobster pots (Antonelis et al. 2011). While individuals are certainly harmed by entanglement, it is more difficult to prove population-level harm, since a large proportion of entangled fauna die at sea without being observed. According to Laist (1997), "indirect analyses for some species offer convincing evidence that effects of entanglement are great enough to limit population growth or accelerate population decline."

Studies of plastic ingestion have primarily focused on vertebrates. In seabirds and mammals, most data have been collected by necropsies performed on beached animals (Allsopp et al. 2006). Of 24 species of seabirds examined in the central Pacific, 17 were found to have ingested plastic (Robards et al. 1997). In nine of those species, more than 80% of collected individuals contained plastic. Similarly, 21 of 38 seabirds species in the North Atlantic contained plastic (Moser and Lee 1992). Plastic ingestion has not been linked directly to seabird death, though ingestion of plastic in some seabirds correlates with body pollutant load (Teuten et al. 2009, Yamashita et al. 2011). In two studies of plastic ingestion by Laysan and black-footed albatross chicks, no link was found between cause of death and plastic ingestion (Sileo et al. 1990, Sievert and Sileo 1993). However, another study found a negative correlation between number of particles ingested and adult body weight, implying that there may be a negative physiological effect of plastic ingestion (Spear et al. 1995). In sea turtles, ingestion of plastic bags and other plastic debris was linked to mortality through the obstruction of the digestive tract (Bjorndal et al. 1994, Bugoni et al. 2001). Cetaceans also ingest plastic. For example, ingested fishing gear was linked to the deaths of two sperm whales (Jacobsen et al. 2010).

Plastic ingestion in fishes has been documented in both freshwater and oceanic environments. Most studies performed in high-plastic areas have found that approximately 10% of fishes sampled in high-plastic areas contain plastic in their stomach contents (Carpenter and Smith 1972, Colton et al. 1974, Kartar et al. 1976, Davison and Asch 2011). None of these studies observed obvious intestinal blockage, and the implications and health effects of plastic ingestion in fishes remain uncertain.

Large pieces of debris may also cause damage to coral reefs and alteration of the benthos. In the northwest Hawaiian islands, 3.2 to 62.2 pieces km^{-2} of large debris, primarily derelict fishing gear, were found on the coral reef (Donohue et al. 2001). This study also cited unpublished data that found that 20% of the weight of some derelict nets consisted of broken coral fragments. In the shallow benthos, the composition and abundance of sediment infauna were altered by the presence of high densities of debris (Uneputty and Evans 1997), and the foraging efficiency of a benthic gastropods reduced (Aloy et al. 2011). In the deep sea, debris was heavily colonized by macroinvertebrates, but other negative effects were not observed (Watters et al. 2010).

Microplastic marine debris: knowns and unknowns

Small plastic particles were observed in the first studies of marine debris (Carpenter and Smith 1972, Wong et al. 1974). These particles are either preproduction pellets or formed from the breakdown of larger particles. Preproduction pellets, known as “nurdles,” are small granules, shaped like a sphere or a cylinder, made of a single type of plastic resin and typically less than 5 mm in diameter (Ogata et al. 2009). These pellets are the industrial feed stock from which plastic items are manufactured, and can be unintentionally discarded during shipping and transport. Particles are formed from the breakdown of larger particles due to ultraviolet light and mechanical stress, as discussed above (Andrady 2011).

Both types of particles, termed “microplastic,” are defined as having a diameter less than 5 mm (Arthur et al. 2008), though some studies have also used 1 mm as the threshhold (Browne et al. 2011). Microplastics as measured at sea often have a functional lower bound of 333 μm, as that is a standard mesh size for measuring neustonic organisms, although there are plastic particles smaller than 333 μm in the ocean (Arthur et al. 2008). Plastic particles with a diameter as small as 1 μm have been detected in sediments (Frias et al. 2010).

Microplastic comprises the vast numerical majority of debris in the ocean, though the shape of the size-frequency distribution has differed between studies (Hidalgo-Ruz et al. 2012). Plastic particles less than 3 mm accounted for 82% by number of the plastic in the North Pacific Gyre and 62% by number of the plastic in the Kuroshio (Moore et al. 2001, Yamashita and Tanimura 2007). On isolated Pacific islands such as Midway Atoll and the northwest Hawaiian islands, 91% of plastic debris collected on beaches was less than 5 mm. Of that debris, 11% consisted of preproduction pellets (McDermid and McMullen 2004). In the California Current, microplastic debris was detected at 56-68% of winter CalCOFI stations over three decades (Gilfillan et al. 2009). Most microplastic debris sampling has taken place in the neuston, on beaches, and in coastal sediments (Hidalgo-Ruz et al. 2012).

Vertical distribution of microplastic in the water column may be dependent on local wind conditions. Kukulka et al. (2012) found an inverse relationship between wind speed and surface plastic concentration in the North Atlantic Subtropical Gyre. Based on those data and a one-dimensional column model, they estimated that 54% of plastic pieces are mixed below surface tow depths under average wind conditions. Doyle et al. (2011) found a similar pattern of suspended debris off southern California, though Lattin et al. (2004) found more debris closer to the benthos in Santa Monica Bay, California.

Zooplankton interactions with microplastic particles have scarcely been studied. As suggested by Doyle et al. (2011), encounter rates are key in determining if microplastic debris adversely affects plankton. Many marine debris studies have included a “plastic to plankton ratio” (Moore et al. 2001, 2002, Lattin et al. 2004, Collignon et al. 2012). However, this ratio has been calculated using the dry weight of both plastic debris and plankton, and is therefore biased by the inclusion of rare, large pieces of debris. For example, the 6:1 plastic to plankton ratio was calculated using data from 6 daytime manta tows taken over arbitrary distances in the North Pacific Subtropical Gyre, and included rare large debris in the plastic weight (in this case, 1 plastic bottle and 1 m of polypropylene line, Moore et al. 2001). In contrast, Doyle et al. (2011) estimated that the mass of plastic debris in the southern Bering Sea and California Current ecosystems was many orders of magnitude lower than the biomass of zooplankton. This could imply that neustonic zooplankton would rarely encounter or interact with microplastic debris.

Ingestion of microplastic particles has been studied in the laboratory, but rarely in natural ecosystems. The only study to specifically examine zooplankton ingestion of microplastic debris remains unpublished outside of an abstract, which states that krill ingested 20 μm polyethylene fragments in the laboratory (Andrady unpublished data, cited in Arthur et al. 2008). In an earlier generation of laboratory studies focused on particle size selectivity, calanoid copepods and cladocerans readily ingested polystyrene spheres ranging from 5 to 60 μm in diameter (Burns 1968, Wilson 1973, Frost 1977), though at much lower rates than algae at equivalent concentrations (Huntley et al. 1983, Paffenhofer and Van Sant 1985). Copepod ingestion of plastic may be species-specific – the marine copepod *Temora longicornis* was more likely to ingest plastic beads that *Pseudocalanus* spp., and both were more likely to ingest plastic than the freshwater copepod *Eudiaptomus gracilis* (DeMott 1988). Salps also ingested polystyrene beads with diameters from 2-6 μm (Kremer and Madin 1992).

Copepod nauplii appear to avoid ingesting plastic spheres (Donaghay and Small 1979, Fernández 1979), though this result depends to some extent on the sphere size (Zankai 1991).

In these studies, the plastic spheres were released in fecal pellets and appeared to cause no acute harm to the organisms (Frost 1977). However, some studies also investigated the possibility that the presence of non-edible particles such as plastic could reduce the rate of feeding on edible particles. Evidence of this reduction was found in some studies (Huntley et al. 1983, Ayukai 1987), but not others (DeMott 1989), and was dependent on particle size (Huntley et al. 1983).

There are more studies on microplastic ingestion in benthic invertebrates, though only one has taken place in a natural ecosystem. This study found microplastic fibers in the guts of 100 out of 120 Norway lobster (*Nephrops norvegicus*) collected off the west coast of Scotland. In laboratory-based studies, microplastic particles were readily ingested by filter-feeding and deposit-feeding benthic invertebrates. When kept in aquaria with plastic particles, lugworms, amphipods, and barnacles ingested plastic within a few days (Thompson et al. 2004). When fed plastic particles mixed with sediment, holothurians ingested more plastic particles at higher proportions than encounter rate would explain, suggesting that they may selectively ingest plastic (Graham and Thompson 2009). The hemolymph of blue mussels (*Mytilus edulis*) incubated with micrometer-sized plastic spherules was found to contain the spherules up to 48 days after exposure (Browne et al. 2008), and the presence of plastic reduced mussel filtration rate (Wegner et al. 2012). None of these studies showed acute negative effects from plastic ingestion, though they were all relatively short-term.

Microplastics may have ecotoxicological effects. Polypropylene is directly toxic to phytoplankton in culture, most likely due to its pentachlorophenol and tetrachlorophenol preservatives (Andersen 2005). Small particles of plastic and plastic resin pellets accumulate high levels of persistent organic pollutants such as PCBs and DDT (Mato et al. 2001, Frias et al. 2010), hydrocarbons (Hirai et al. 2011, Van et al. 2012), and metals (Ashton et al. 2010, Holmes et al. 2012). Persistent organic pollutants were recently shown to pass from plastic particles to the bodies of birds that ingest them (Teuten et al. 2009).

Ecotoxicological effects may also be caused by the release of plasticizers. Plasticizer molecules are embedded in the plastic polymer matrix, but not directly attached. They may therefore be released into organisms via ingestion or into the environment through the degradation of plastic. Plasticizers have been detected in landfill leachate, sewage outflow, and particles collected from the ocean (Teuten et al. 2009, Hirai et al. 2011). Though there are many types of plasticizers, phthalates and BPA have been most studied due to their association with food products and baby bottles. Phthalates and BPA have been shown to “affect reproduction in all studied animal groups, to impair development in crustaceans and amphibians and to induce genetic aberrations” (Oehlmann et al. 2009). In small mammal studies, high doses of plasticizers have been associated with testicular abnormalities and other reproductive disorders as well as thyroid disease (Talsness et al. 2009). In humans, phthalates and BPA may be associated with altered endocrine function and have negative reproductive or developmental effects, though studies are limited (Meeker et al. 2009).

Plastic-associated fouling communities

Hard substrates in the naturally occurring pelagic environment have long played host to a suite of specialized species. A variety of objects, including algae, pumice, and wood, have provided transport and hard surfaces for benthic organisms (Thiel and Gutow 2005a). Pelagic plastic debris is ideally suited for rafting due to its abundance, buoyancy, and persistence, and has rapidly become a common substrate. Rafting on plastic debris has been observed all over the world (Thiel and Gutow 2005a), and increases with supply of plastic debris. For example, though rafting is usually rare in the Southern Ocean due to low temperatures and large waves, rafting on plastic debris has been observed (Barnes and Fraser 2003). However, most studies have examined beached debris or ghost nets, not microplastics (Winston et al. 1997, Barnes and Fraser 2003).

The composition of the rafting community depends on the type of object and its stability. In general, artificial substrates do not host the same communities as natural substrates. In the coastal northwest Atlantic, Tyrrell and Byers (2007) found that artificial substrates favored nonindigenous species. Similarly, rip-rap communities were found to have a lower diversity of mobile benthic invertebrates than natural rocky intertidal communities (Pister 2009). In the case of rafting objects, biotic rafts (e.g., wood, drifting kelp) do not drift for as long as abiotic rafts (e.g., plastic, tar), but do provide a food source for rafting organisms, and may therefore may be more successful at transporting a variety of species (Donlan and Nelson 2003, Thiel and Gutow 2005b). The stability of the rafting object may also affect the diversity of the attached community – pieces with fewer changes of orientation have greater species richness and cover than less stable pieces (Bravo et al. 2011). In addition, fouling increases the specific gravity of the raft, which may cause sinking in the water column and a subsequent rise to the surface if fouling organisms die or are removed by predators (Ye and Andrady 1991).

Thiel and Haye (2006) classified rafting routes as frequent, intermittent, or episodic. Frequent rafting routes are highly localized and occur often, such as the displacement of seagrass mats. Intermittent rafting routes are regional and occur primarily through the displacement of giant kelps. Episodic routes are over long distances, such as ocean basins, and occur rarely, such as through the introduction of floating pumice from a volcanic eruption. However, they note that plastic debris is fundamentally different than these natural rafting substrates:

> For two main reasons, plastics do not fit the natural rafting routes discussed above: (a) they are delivered to the oceans almost anywhere, in estuaries, bays and in the open ocean, albeit with regional differences in intensity and (b) some of them are extremely long-lived and can therefore be transported over very long distances. They share some features with substrata found on frequent rafting routes (abundant supply), but they differ in other features (plastics offer no food value and are highly persistent). Similarly, some of their characteristics resemble those of substrata on episodic rafting routes (low food value and high longevity), but other characteristics are very different (plastics are supplied relatively consistently; Thiel and Haye 2006).

For these reasons, they predict that plastic debris will most alter dispersal along episodic rafting routes as areas with low natural abundances of rafting substrate (e.g., the subtropical gyres) accumulate plastic debris.

The unusual properties of plastic make it a vector for the transport of nonindigenous species. For example, a piece of flotsam with traces of tropical biota, including self-fertilizing corals, was recently discovered in the Netherlands

(Hoeksema et al. 2012). Due to the slow velocity of debris drift, rafted invertebrates are thought to be more viable than those transported by other methods such as ballast water or ship hull fouling (Barnes 2002, Lewis et al. 2005). Benthic organisms such as bryozoans, barnacles, and hydroids are commonly found on plastic debris, and at least one new species introduction has resulted from rafting on plastic debris (Aliani and Molcard 2003, Barnes and Milner 2005). Species that are able to grow on plastic debris have significantly increased in abundance, such as three species of cheilostome bryozoan found primarily on plastic debris around the globe (Winston 1982, Winston et al. 1997). The particular vulnerability of island ecosystems to invasions and the large amount of plastic debris collecting on the mid-Pacific islands (e.g., the Northwest Hawaiian Islands National Monument) makes lateral transport of fouling species a matter of particular concern in the North Pacific (McDermid and McMullen 2004).

Diversity patterns in open-ocean rafting communities, particularly plastic-associated communities, are largely unexplored. In many ecosystems, diversity is predicted by the species-area curve, in which the number of species increases as a function of available surface area, though the shape of this curve has been a matter of some debate (He and Legendre 1996). The concept of island biogeography, which predicts that species diversity is a balance between arrival of species through migration and the loss through extinction, is based on the species-area curve (MacArthur and Wilson 1963). While the species-area curve is one of the most widely observed patterns in ecology, there are exceptions, such as the “small-island effect,” in which the areas of the ecosystems observed are all too small for a diversity pattern to be detected (Lomolino 2000). It is unknown whether plastic-associated rafting communities follow this pattern, particularly since artificial substrates strongly select for particular life history traits (Figure 1.2). For example, boring organisms such as teredinid bivalves and sphaeromatid isopods are frequently found rafting on biotic substrates, but are not found on plastic (Thiel and Gutow 2005a, Thiel and Haye 2006).

The North Pacific Subtropical Gyre

The North Pacific Subtropical Gyre (NPSG) has received significant media attention as the location of the "Great Pacific Garbage Patch," a term attributed to oceanographer Curtis Ebbesmeyer. Driven by the trade winds, the NPSG rotates in an anticyclonic direction (Sverdrup et al. 1946). Thought to be the largest contiguous biome on earth (Karl 1999), this semiclosed system has been in place since the early Pliocene (McGowan and Walker 1979). Though it is an area of extremely low productivity, the Gyre contains a unique and diverse fauna with distinct planktonic assemblages (Fager and McGowan 1963).

The NPSG was originally thought to be a stable climax community with high species diversity, where community dynamics are regulated by biological interactions rather than physical disturbance (McGowan and Walker 1979). However, the incorporation of the microbial loop into scientific understanding of the food web, the discovery of coccoid cyanobacteria, and greater understanding of the importance of mesoscale variation has recast the NPSG as a more dynamic ecosystem (Karl 1999, Landry 2002). The NPSG also appears to be changing on decadal scales, which has been attributed to variation in the El Niño-Southern Oscillation and in the Pacific Decadal Oscillation. For example, over three decades, phytoplankton standing stock as inferred by chlorophyll has increased by a factor of two (Venrick et al. 1987), and mesozooplankton biomass may also have increased two-fold (Landry et al. 2001).

The neuston community is a specialized subset of the overall NPSG community associated with the air-sea interface. Exactly what constitutes "neuston" has been a matter of some debate in the literature, and substantial energy has been spent on defining neustonic terminology (reviewed in Marshall and Burchardt 2005). For example, neustonic biota has been classified as epineuston (organisms that live on the water's surface and are exposed to air) and hyponeuston (organisms that live on the underside of the surface layer). Additional terminology was developed for organisms that occupy space both above and below the water, such as the siphonophore *Physalia physalis* (metaneuston or exopleuston), and to distinguish organisms that are associated with the surface film for their entire lifecycle (euhyponeuston) from those that vertically migrate (planktohyponeuston) and those that inhabit this space for only part of their lives (merohyponeuston or endopleuston; David 1967, Zaitsev 1971, Hempel and Weikert 1972, Banse 1975). This has been made yet more complicated by referring to the entire upper water column as the epineuston, driving some researchers to distinguish the surface-associated community by terming it the pleustal zone and the biota that live there the pleuston (Banse 1975, Cheng 1975). For simplicity, in the following discussion I will refer to both the surface habitat and its associated biota as simply the neuston.

The oceanic neustonic assemblage is distinct from the biota found lower in the water column only in the tropical and subtropical waters between 40° N and 40° S, where sea surface temperature rarely falls below 10° C (Savilov 1968 as cited in Cheng 1975). The most striking feature of this assemblage is the vibrant blue and purple coloration of much of the zooplankton, include cnidarians, pontellid copepods, and gastropods. Sir Alister Hardy wrote of the cnidarian *Velella velella* "They are colored like the sea itself, deep blue…" (Hardy 1965). While this coloration was originally thought to offer protection from harmful ultraviolet light, the absorption maximum for blue carotenoproteins is approximately 630-660 nm, which would protect against relatively harmless red light (Herring 1967). In contrast, the deep red coloration of alpine freshwater copepods does appear to offer protection from harmful wavelengths of visible light (Hairston 1976). Other hypotheses for the blue coloration of the neuston include camouflage against visual predators in the air (e.g., seabirds) or from the neuston (e.g., flying fish), but blue coloration would not protect against either silhouette-based visual predation from below or from non-visual predators (Herring 1967).

The neustonic zooplankton are dominated by a relatively small number of conspicuous drifting organisms. Obligate surface-associated cnidarians include the siphonophore *Physalia physalis* and the chondrophores *Velella velella* and *Porpita porpita. Physalia* is preyed upon by the nudibranchs *Glaucus atlantica* and the much less abundant *Glaucilla* spp., and the chondrophores are consumed by the prosobranch gastropod *Janthina* spp. (Bieri 1966). The gerrid insect *Halobates* spp. and pontellid copepods are also abundant (Herring 1967, Cheng 1975). At night, the diversity of the neuston greatly increases due to diel vertical migration (David 1967).

The NPSG lacks pelagic algae, such as the *Sargassum* found in the North Atlantic Subtropical Gyre, so the rafting community is thought to have originated in association with substrates such as logs, pumice, and megafauna such as turtles (Thiel and Gutow 2005b). For example, the epipelagic crab *Planes* spp. is commonly found on both flotsam and as a epibiont of olive ridley sea turtles (*Lepidochelys olivacea*; Frick et al. 2011), and the lepadomorph barnacles have been found both in association with abiotic and biota flotsam (Cheng and Lewin 1976).

Rafting objects are often dominated by three species of lepadomorph barnacles (*Lepas anatifera, Lepas pacifica,* and *Lepas (Dosima) fascularis*; Newman and Abbott 1980). *Lepas (Dosima) fasicularis* must settle onto a floating object, but is able to form its own float at the end of the juvenile stage and drift independently thereafter (Newman and Abbott 1980). The three species of *Lepas* are omnivorous, feeding opportunistically on the neustonic zooplankton, and are said to "hold a singular position in having more sources of food to draw upon than any other organisms in the neuston (Bieri 1966)." The lepadomorph barnacles are themselves preyed upon by omnivorous epipelagic crabs (*Planes* spp.) and the rafting nudibranch *Fiona pinnata* (Bieri 1966, Davenport 1992). Other conspicuous inhabitants of the rafting community are the cheilostome bryozoans (Winston et al. 1997), the barnacle-associated parasitic polychaete *Hipponoe gaudichaudi* (Cheng 1975), and the isopod *Idothea* spp. (Herring 1969, Gutow et al. 2006).

The “Great Pacific Garbage Patch”

The accumulation of plastic debris in the North Pacific has received significant media attention that has led to the initiation of policy discussion. This rise in public interest can be largely attributed to the environmental non-governmental organization (NGO) Algalita Marine Research Foundation and its founder, Charles Moore (Kaiser 2010). Moore attributes his interest in marine debris to pollution encountered when sailing through the NPSG:

> It seemed unbelievable, but I never found a clear spot. In the week it took to cross the subtropical high, no matter what time of day I looked, plastic debris was floating everywhere: bottles, bottle caps, wrappers, fragments. Months later, after I discussed what I had seen with the oceanographer Curtis Ebbesmeyer, perhaps the world's leading expert on flotsam, he began referring to the area as the "eastern garbage patch." But "patch" doesn't begin to convey the reality. Ebbesmeyer has estimated that the area, nearly covered with floating plastic debris, is roughly the size of Texas (Moore 2003).

Moore’s journey and Ebbesmeyer’s creation of the phrase “garbage patch” and Texas analogy have had a powerful influence on the public imagination. For example, a LexisNexis search yielded 1,553 articles that mentioned “garbage patch” since 2001. These included 893 newspaper articles, 259 newswires and press releases, and 49 industry or trade press reports. The term “Great Pacific Garbage Patch” appeared in 2006 and has also proved popular, with 852 articles.

However, scientific knowledge has not kept pace with public interest (Figure 1.3). While scientific work on oceanic plastic pollution goes back to the early 1970s, oceanic plastic pollution, particularly in the NPSG, has not been a major topic of research. The lack of data has meant that there is little scientific information on which to base public policy, education programs, or industry reform initiatives, and the void has therefore been filled by activists and lobbyists.

Research questions: potential impacts of microplastic on NPSG neuston

The motivation for this dissertation is to provide scientific information on the extent and impact of microplastic in the NPSG. This began as the mission of the graduate student-designed and led Scripps Environmental Accumulation of Plastic Expedition (SEAPLEX), whose goals were to quantitatively examine the distribution, abundance, and ecological effect of plastic debris in the NPSG. SEAPLEX questions and data form the core of this dissertation, though other data sources are included.

The dissertation is organized around two central questions:

1) What is the abundance, distribution, and type of plastic microdebris in the NPSG?
2) What is the impact of this microplastic on the neustonic zooplankton and plastic-associated rafting communities?

Descriptions of chapters

In Chapter 2, my co-authors and I quantify the distribution, abundance and size of microplastic in the NPSG, California Current, and transition region between them, over multiple spatial scales in summer 2009 and fall 2010. By combining plankton net samples of microplastic with quantitative visual observations of macroplastic, we provide the first continuous size spectra of plastic marine debris. We also compare the mass of microplastic debris with concurrently measured biomass of zooplankton, and further illustrate that the concentration of plastic measured at the sea-air interface can be influenced by wind-induced mixing at the sea surface.

In Chapter 3, I estimate plastic weathering rates by comparing microplastics naturally weathered in the ocean with microplastics degraded under known experimental conditions. The primary tool for these analyses is Fourier Transform Infrared Spectroscopy (FTIR), which can both identify plastic type and provide estimates of photodegradation. I present data on the composition of microplastic over the northeast Pacific, and assess four chemical weathering indices for use in qualitatively estimate microplastic oceanic residence

In Chapter 4, ingestion by neustonic invertebrates is examined. This chapter reports on a series of at-sea ingestion experiments in which NPSG neustonic zooplankton were incubated with fluorescent microspheres. I also describe the ingestion of microplastic by the gooseneck barnacle *Lepas pacifica* and *Lepas anatifera.*

Chapter 5, published in *Biology Letters* (2012), describes the decadal-scale rise of microplastic in the NPSG and links this increase to an increase in oviposition in the pelagic insect *Halobates sericeus.* The goal of this study was to investigate the impact of microplastic debris as a novel habitat in the NPSG. To do this, my co-authors and I (i) quantify the increase in North Pacific microplastic over the past four decades; and (ii) correlate the increase in microplastic between 1972–1973 and 2009–2010 to changes *in H. sericeus* abundance and oviposition.

In Chapter 6, my co-authors and I describe the microplastic-associated rafting communities of the NPSG, and determine whether any species can be classified as potentially invasive. We also test whether the microplastic functions as “islands” that are described by a predictable species-area relationship.

I finish in Chapter 7 by placing my results in the context of the public dialogue around oceanic plastic pollution. Using reports, articles, and images, I describe the ways in which oceanic plastic has been understood by various stakeholders, including academics, government agencies, policy makers, NGOs, and members of the public. By exploring how plastic pollution is understood by various segments of society, and placing my findings within this framework, I attempt to provide guidance for future research and potentially, public policy.

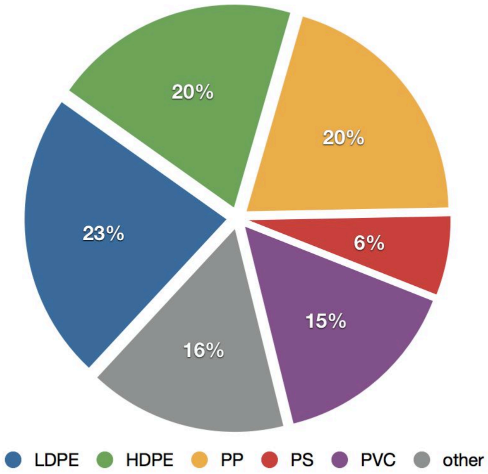


Figure 1.1. Total 2008 commodity thermoplastic sales by resin type in North America
Total quantity is 39 million metric tons dry weight. No data were available for PET or mixed resin materials. These data do not include thermoset resins (American Chemistry Council 2008).

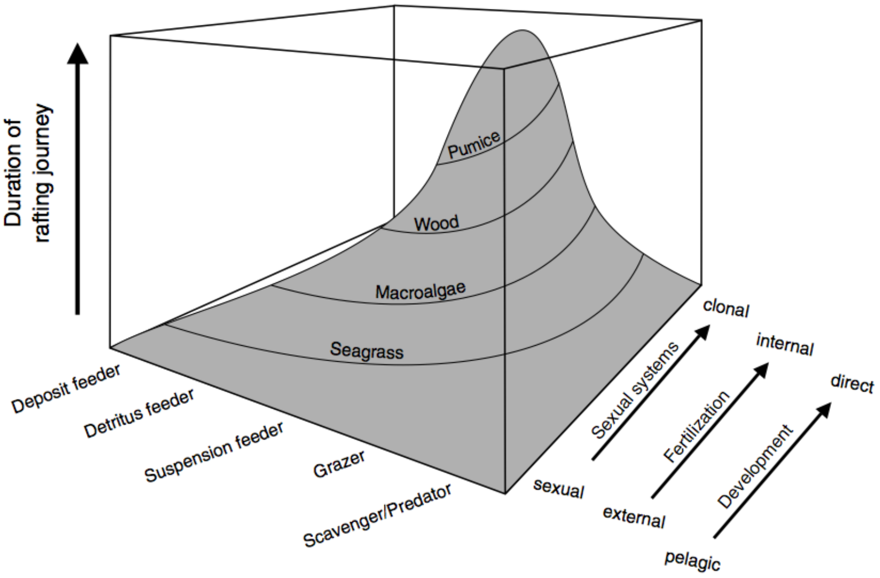


Figure 1.2. Schematic from Thiel & Haye (2006) showing the hypothesized relationship between life history characteristics and rafting success
Organisms with feeding and reproductive traits amenable to rafting are able to persist longer than organisms with unfavorable traits, which limits the diversity of rafting communities. Plastic and other artificial substrates are not shown, but are likely similar to non-biotic natural substrates such as pumice.

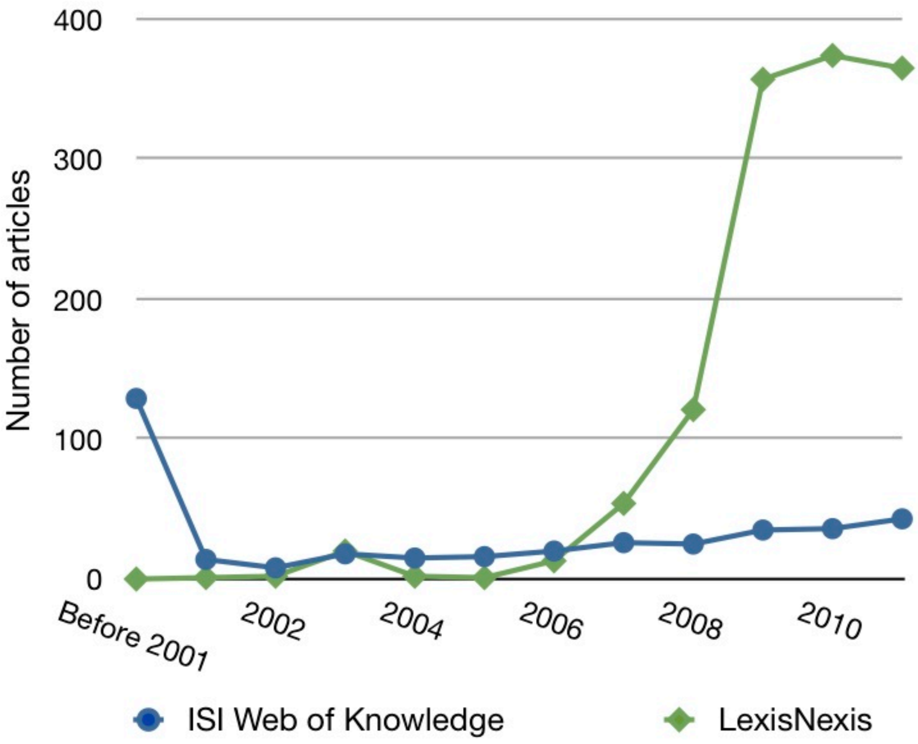
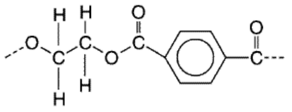
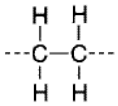
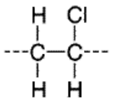
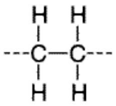
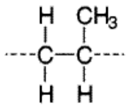
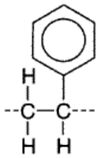


Figure 1.3. Number of academic articles vs. popular articles on oceanic plastic 1984-2011
Academic articles were quantified in ISI Web of Knowledge using the search terms "marine debris" OR "plastic pollution." Popular articles were quantified in LexisNexis using the search terms "garbage patch" OR "Great Pacific Garbage Patch."

Table 1.1. Resin identification coding system

This system was developing by the Society of the Plastic Industries as a voluntary consumer information initiative. Sources: [1](American Chemistry Council 2010d) [2](Freund Container & Supply 2010), [3](American Chemistry Council 2010e), [4](Andrady and Neal 2009).

Resin ID[1]	**Plastic Type[1]**	**Density[2]** (g/cm^3)	**Molecular Structure[3]**	**Date of first manu-facture [4]**	**Common Applications[1,3]**
1	Polyethyelene Terephthalate (PET)	1.35		Early 1970s	Disposable clear plastic drink bottles, food jars
2	High Density Polyethylene (HDPE)	0.94 - 0.965		1955	Milk containers, detergent bottles, toys
3	Polyvinyl Chloride (PVC)	1.35		Late 1920s	Pipes and fittings, vinyl siding, synthetic-leather products, shampoo bottles
4	Low Density Polyethylene (LDPE)	0.91-0.925		1935	Shrink wrap, dry cleaning bags, freezer bags
5	Polypropylene (PP)	0.89-0.91		1957	Flexible containers, bottle caps, fibers
6	Polystyrene (PS)	1.0-1.1		1937	Disposable cutlery, packing peanuts, CDs
7	Everything else (e.g., nylon, polycarbonate, polyurethanes, polymethyl methacrylate)	Varies	NA	NA	Three- and five-gallon reusable water bottles, nylon stockings, musical instruments, varnish, Plexiglas

References

Aliani, S., and A. Molcard. 2003. Hitch-hiking on floating marine debris: macrobenthic species in the Western Mediterranean Sea. Hydrobiologia 503:59–67. doi: 10.1023/B:HYDR.0000008480.95045.26.

Allsopp, M., A. Walters, D. Santillo, and P. Johnston. 2006. Plastic debris in the world's oceans. Page 44. Greenpeace.

Aloy, A. B., B. M. Vallejo Jr., and M. A. Juinio-Meñez. 2011. Increased plastic litter cover affects the foraging activity of the sandy intertidal gastropod Nassarius pullus. Marine Pollution Bulletin 62:1772–1779. doi: 10.1016/j.marpolbul.2011.05.021.

American Chemistry Council. 2008. ACC Resin Statistics Annual Summary. Retrieved March 24, 2010, from http://www.americanchemistry.com/s_acc/sec_policyissues.asp?CID=996&DID=3948.

American Chemistry Council. 2010a. Polymer Definitions and Properties. Retrieved March 26, 2010, from http://www.americanchemistry.com/s_plastics/doc.asp?CID=1571&DID=5971.

American Chemistry Council. 2010b. Life Cycle of a Plastic Product. Retrieved March 26, 2010, from http://www.americanchemistry.com/s_plastics/doc.asp?CID=1571&DID=5972.

American Chemistry Council. 2010c. How is plastic made? Retrieved March 26, 2010, from http://www.americanchemistry.com/s_plastics/doc.asp?CID=1571&DID=5974.

American Chemistry Council. 2010d. Resin Identification Codes. Retrieved March 26, 2010, from http://www.americanchemistry.com/s_plastics/doc.asp?CID=1102&DID=4644.

American Chemistry Council. 2010e. History of Polymers & Plastics for Teachers. Retrieved March 26, 2010, from http://www.americanchemistry.com/hops/intro_to_plastics/teachers.html.

Andersen, A. 2005. Algal Culturing Techniques. Phycological Society of America, Elsevier Press, Burlington MA.

Andrady, A. 1989. Environmental degradation of plastics under land and marine exposure conditions. Proceedings of the Second International Conference on Marine Debris. United States Dept of Commerce, Honolulu, Hawaii.

Andrady, A. L. 2003. Weathering of polyethylene (LDPE) and enhanced photodegradable polyethylene in the marine environment. Journal of Applied Polymer Science 39:363–370. doi: 10.1002/app.1990.070390213.

Andrady, A. L. 2011. Microplastics in the marine environment. Marine Pollution Bulletin 62:1596–1605. doi: 10.1016/j.marpolbul.2011.05.030.

Andrady, A. L., and M. A. Neal. 2009. Applications and societal benefits of plastics. Philosophical Transactions of the Royal Society B: Biological Sciences 364:1977–1984. doi: 10.1098/rstb.2008.0304.

Antonelis, K., D. Huppert, D. Velasquez, and J. June. 2011. Dungeness crab mortality due to lost traps and a cost–benefit analysis of trap removal in Washington State waters of the Salish Sea. North American Journal of Fisheries Management 31:880–893. doi: 10.1080/02755947.2011.590113.

Arthur, C., J. Baker, and Bamford, H. (Eds.). 2008. Proceedings of the International Research Workshop on the Occurrence, Effects, and Fate of Microplastic Marine Debris. United States Dept of Commerce.

Ashton, K., L. Holmes, and A. Turner. 2010. Association of metals with plastic production pellets in the marine environment. Marine Pollution Bulletin 60:2050–2055. doi: 10.1016/j.marpolbul.2010.07.014.

Ayukai, T. 1987. Discriminate feeding of the calanoid copepod Acartia clausi in mixtures of phytoplankton and inert particles. Marine Biology 94:579–587. doi: 10.1007/BF00431404.

Banse, K. 1975. Pleuston and neuston: On the categories of organisms in the uppermost pelagial. Internationale Revue der gesamten Hydrobiologie und Hydrographie 60:439–447. doi: 10.1002/iroh.19750600401.

Barnes, D. K. A. 2002. Invasions by marine life on plastic debris. Nature 416:808–809. doi: 10.1038/416808a.

Barnes, D. K. A., and K. P. P. Fraser. 2003. Rafting by five phyla on man-made flotsam in the Southern Ocean. Marine Ecology Progress Series 262:289–291. doi: 10.3354/meps262289.

Barnes, D. K. A., F. Galgani, R. C. Thompson, and M. Barlaz. 2009. Accumulation and fragmentation of plastic debris in global environments. Philosophical Transactions of the Royal Society of London B 364:1985–1998. doi: 10.1098/rstb.2008.0205.

Barnes, D. K. A., and P. Milner. 2005. Drifting plastic and its consequences for sessile organism dispersal in the Atlantic Ocean. Marine Biology 146:815–825. doi: 10.1007/s00227-004-1474-8.

Bieri, R. 1966. Feeding preferences and rates of the snail, Ianthina prolongata, the barnacle, Lepas anserifera, the nudibranchs, Glaucus atlanticus and Fiona pinnata, and the food web in the marine neuston. Publications of the Seto Marine Biological Laboratory 14:161–170.

Bjorndal, K. A., A. B. Bolten, and C. J. Lagueux. 1994. Ingestion of marine debris by juvenile sea turtles in coastal Florida habitats. Marine Pollution Bulletin 28:154–158. doi: 10.1016/0025-326X(94)90391-3.

Bravo, M., J. C. Astudillo, D. Lancellotti, G. LunaJorquera, N. Valdivia, and M. Thiel. 2011. Rafting on abiotic substrata: properties of floating items and their influence on community succession. Marine Ecology Progress Series 439:1–17. doi: 10.3354/meps09344.

Browne, M. A., P. Crump, S. J. Niven, E. Teuten, A. Tonkin, T. Galloway, and R. Thompson. 2011. Accumulation of microplastic on shorelines woldwide: sources and sinks. Environmental Science & Technology 45:9175–9179. doi: 10.1021/es201811s.

Browne, M. A., A. Dissanayake, T. S. Galloway, D. M. Lowe, and R. C. Thompson. 2008. Ingested microscopic plastic translocates to the circulatory system of the mussel, Mytilus edulis (L). Environmental Science & Technology 42:5026–31. doi: 10.1021/es800249a.

Browne, M. A., T. S. Galloway, and R. C. Thompson. 2010. Spatial patterns of plastic debris along estuarine shorelines. Environmental Science & Technology 44:3404–3409. doi: 10.1021/es903784e.

Bugoni, L., L. Krause, and M. V. Petry. 2001. Marine debris and human impacts on sea turtles in southern Brazil. Marine Pollution Bulletin 42:1330–1334. doi: 10.1016/S0025-326X(01)00147-3.

Burns, C. W. 1968. The relationship between body size of filter-feeding Cladocera and the maximum size of particle ingested. Limnology and Oceanography 13:675–678.

Carpenter, E. J., and K. L. Smith. 1972. Plastics on the Sargasso Sea surface. Science 175:1240. doi: 10.1126/science.175.4027.1240.

Cheng, L. 1975. Marine pleuston-animals at the sea-air interface. Oceanography and Marine Biology: An Annual Review 13:181–212.

Cheng, L., and R. A. Lewin. 1976. Goose barnacles (Cirripedia: Thoracica) on flotsam beached at La Jolla, California. Fishery Bulletin 74.

Collignon, A., J.-H. Hecq, F. Glagani, P. Voisin, F. Collard, and A. Goffart. 2012. Neustonic microplastic and zooplankton in the North Western Mediterranean Sea. Marine Pollution Bulletin 64:861–864. doi: 10.1016/j.marpolbul.2012.01.011.

Colton, J. B., F. D. Knapp, and B. R. Burns. 1974. Plastic particles in surface waters of the northwestern Atlantic. Science 185:491–497. doi: 10.1126/science.185.4150.491.

Davenport, J. 1992. Observations on the ecology, behaviour, swimming mechanism and energetics of the neustonic grapsid crab, Planes minutus. Journal of the Marine Biological Association of the United Kingdom 72:611–620. doi: 10.1017/S0025315400059385.

David, P. M. 1967. Illustrations of oceanic neuston. Symposia of the Zoological Society of London 19:211–213.

Davison, P., and R. G. Asch. 2011. Plastic ingestion by mesopelagic fishes in the North Pacific Subtropical Gyre. Marine Ecology Progress Series 432:173–180. doi: 10.3354/meps09142.

Day, R. H., D. G. Shaw, and S. E. Ignell. 1990. The quantitative distribution and characteristics of neuston plastic in the North Pacific Ocean, 1984-1988. Pages 247–266 Proceedings of the Second International Conference on Marine Debris, April 2-7, 1989, Honolulu, Hawaii. U. S. Department of Commerce, NOAA Technical Memorandum, NMFS, NOAA-TM-NMFS-SWFC-154.

DeMott, W. R. 1988. Discrimination between algae and artificial particles by freshwater and marine copepods. Limnology and Oceanography 33:397–408.

DeMott, W. R. 1989. Optimal foraging theory as a predictor of chemically mediated food selection by suspension-feeding copepods. Limnology and Oceanography 34:140–154.

Derraik, J. G. B. 2002. The pollution of the marine environment by plastic debris: a review. Marine Pollution Bulletin 44:842–852. doi: 10.1016/S0025-326X(02)00220-5.

Donaghay, P. L., and L. F. Small. 1979. Food selection capabilities of the estuarine copepod Acartia clausi. Marine Biology 52:137–146. doi: 10.1007/BF00390421.

Donlan, C. J., and P. A. Nelson. 2003. Observations of invertebrate colonized flotsam in the eastern tropical Pacific, with a discussion of rafting. Bulletin of Marine Science 72:231–240.

Donohue, M. J., R. C. Boland, C. M. Sramek, and G. A. Antonelis. 2001. Derelict fishing gear in the northwestern Hawaiian Islands: diving surveys and debris removal in 1999 confirm threat to coral reef ecosystems. Marine Pollution Bulletin 42:1301–1312. doi: 10.1016/S0025-326X(01)00139-4.

Doyle, M. J., W. Watson, N. M. Bowlin, and S. B. Sheavly. 2011. Plastic particles in coastal pelagic ecosystems of the Northeast Pacific ocean. Marine Environmental Research 71:41–52. doi: 10.1016/j.marenvres.2010.10.001.

European Council for Plasticisers and Intermediates. 2010. Plasticisers Information Centre. Retrieved March 27, 2010, from http://www.plasticisers.org/.

Fager, E. W., and J. A. McGowan. 1963. Zooplankton species groups in North Pacific. Science 140:453–460.

Fernández, F. 1979. Particle selection in the nauplius of Calanus pacificus. Journal of Plankton Research 1:313 –328. doi: 10.1093/plankt/1.4.313.

Freund Container & Supply. 2010. Plastic Properties. Retrieved March 26, 2010, from http://www.freundcontainer.com/article.asp?ai=72&bhcd2=1269628965.

Frias, J. P. G. L., P. Sobral, and A. M. Ferreira. 2010. Organic pollutants in microplastics from two beaches of the Portuguese coast. Marine Pollution Bulletin 60:1988–1992. doi: 10.1016/j.marpolbul.2010.07.030.

Frick, M. G., K. Kopitsky, A. B. Bolten, K. A. Bjorndal, and H. R. Martins. 2011. Sympatry in grapsoid crabs (genera Planes and Plagusia) from olive ridley sea turtles (Lepidochelys olivacea), with descriptions of crab diets and masticatory structures. Marine Biology 158:1699–1708. doi: 10.1007/s00227-011-1684-9.

Frost, B. W. 1977. Feeding behavior of Calanus pacificus in mixtures of food particles. Limnology and Oceanography 22:472–491.

Galgani, F., A. Souplet, and Y. Cadiou. 1996. Accumulation of debris on the deep sea floor off in French Mediterranean coast. Marine Ecology Progress Series 142:225–234. doi: 10.3354/meps142225.

Gilfillan, L. R., M. D. Ohman, M. J. Doyle, and W. Watson. 2009. Occurrence of plastic micro-debris in the southern California Current system. CalCOFI Report 50:123–133.

Goldstein, M. C., M. Rosenberg, and L. Cheng. 2012. Increased oceanic microplastic debris enhances oviposition in an endemic pelagic insect. Biology Letters 8:817–820. doi: 10.1098/rsbl.2012.0298.

Graham, E. R., and J. T. Thompson. 2009. Deposit- and suspension-feeding sea cucumbers (Echinodermata) ingest plastic fragments. Journal of Experimental Marine Biology and Ecology 368:22–29. doi: 10.1016/j.jembe.2008.09.007.

Gutow, L., J. Strahl, C. Wiencke, H.-D. Franke, and R. Saborowski. 2006. Behavioural and metabolic adaptations of marine isopods to the rafting life style. Marine Biology 149:821–828. doi: 10.1007/s00227-006-0257-9.

Hairston, N. C. 1976. Photoprotection by carotenoid pigments in the copepod Diaptomus nevadensis. Proceedings of the National Academy of Sciences 73:971–974.

Hardy, A. 1965. The Open Sea: Its Natural History. Houghton Milton, Boston.

Hartwig, E., T. Clemens, and M. Heckroth. 2007. Plastic debris as nesting material in a kittiwake (Rissa tridactyla) colony at the Jammerbugt, Northwest Denmark. Marine Pollution Bulletin 54:595–597. doi: 10.1016/j.marpolbul.2007.01.027.

He, F., and P. Legendre. 1996. On species-area relations. The American Naturalist 148:719–737.

Hempel, G., and H. Weikert. 1972. The neuston of the subtropical and boreal northeastern Atlantic Ocean: a review. Marine Biology 13:70–88. doi: 10.1007/BF00351141.

Herring, P. J. 1967. The pigments of plankton at the sea surface. Symposia of the Zoological Society of London 19:215–235.

Herring, P. J. 1969. Pigmentation and carotenoid metabolism of the marine isopod Idotea metallica. Journal of the Marine Biological Association of the United Kingdom 49:767–779. doi: 10.1017/S0025315400037279.

Hidalgo-Ruz, V., L. Gutow, R. C. Thompson, and M. Thiel. 2012. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environmental Science & Technology 46:3060–3075. doi: 10.1021/es2031505.

Hirai, H., H. Takada, Y. Ogata, R. Yamashita, K. Mizukawa, M. Saha, C. Kwan, C. Moore, H. Gray, D. Laursen, E. R. Zettler, J. W. Farrington, C. M. Reddy, E.

E. Peacock, and M. W. Ward. 2011. Organic micropollutants in marine plastics debris from the open ocean and remote and urban beaches. Marine Pollution Bulletin 62:1683–1692. doi: 10.1016/j.marpolbul.2011.06.004.

Hoeksema, B. W., P. J. Roos, and G. C. Cadee. 2012. Trans-Atlantic rafting by the brooding reef coral Favia fragum on man-made flotsam. Marine Ecology Progress Series 445:209–218. doi: 10.3354/meps09460.

Holmes, L. A., A. Turner, and R. C. Thompson. 2012. Adsorption of trace metals to plastic resin pellets in the marine environment. Environmental Pollution 160:42–48. doi: 10.1016/j.envpol.2011.08.052.

Howell, E. A., S. J. Bograd, C. Morishige, M. P. Seki, and J. J. Polovina. 2012. On North Pacific circulation and associated marine debris concentration. Marine Pollution Bulletin 65:16–22. doi: 10.1016/j.marpolbul.2011.04.034.

Huntley, M. E., K.-G. Barthel, and J. L. Star. 1983. Particle rejection by Calanus pacificus: discrimination between similarly sized particles. Marine Biology 74:151–160. doi: 10.1007/BF00413918.

Jacobsen, J. K., L. Massey, and F. Gulland. 2010. Fatal ingestion of floating net debris by two sperm whales (Physeter macrocephalus). Marine Pollution Bulletin 60:765–767. doi: 10.1016/j.marpolbul.2010.03.008.

Kaiser, J. 2010. The Dirt on Ocean Garbage Patches. Science 328:1506. doi: 10.1126/science.328.5985.1506.

Karl, D. M. 1999. A sea of change: Biogeochemical variability in the North Pacific Subtropical Gyre. Ecosystems 2:181–214. doi: 10.1007/s100219900068.

Kartar, S., F. Abou-Seedo, and M. Sainsbury. 1976. Polystyrene spherules in the Severn Estuary: a progress report. Marine Pollution Bulletin 7:52. doi: 10.1016/0025-326X(76)90092-8.

Koch, H. M., and A. M. Calafat. 2009. Human body burdens of chemicals used in plastic manufacture. Philosophical Transactions of the Royal Society B: Biological Sciences 364:2063–2078. doi: 10.1098/rstb.2008.0208.

Kremer, P., and L. P. Madin. 1992. Particle retention efficiency of salps. Journal of Plankton Research 14:1009–1015. doi: 10.1093/plankt/14.7.1009.

Kubota, M. 1994. A mechanism for the accumulation of floating marine debris north of Hawaii. Journal of Physical Oceanography 24:1059–1064.

Kukulka, T., G. Proskurowski, S. Morét-Ferguson, D. W. Meyer, and K. L. Law. 2012. The effect of wind mixing on the vertical distribution of buoyant plastic debris. Geophysical Research Letters 39:6 pp. doi: 201210.1029/2012GL051116.

Kyrikou, I., and D. Briassoulis. 2007. Biodegradation of agricultural plastic films: a critical review. Journal of Polymers and the Environment 15:125–150. doi: 10.1007/s10924-007-0053-8.

Laist, D. 1997. Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. Pages 99–140 *in* J. Coe and D. Rogers, editors. Marine debris: sources, impact and solutions. Springer, New York.

Landry, M. R. 2002. Integrating classical and microbial food web concepts: evolving views from the open-ocean tropical Pacific. Hydrobiologia 480:29–39. doi: 10.1023/A:1021272731737.

Landry, M. R., H. Al-Mutairi, K. E. Selph, S. Christensen, and S. Nunnery. 2001. Seasonal patterns of mesozooplankton abundance and biomass at Station ALOHA. Deep Sea Research Part II: Topical Studies in Oceanography 48:2037–2061. doi: 10.1016/S0967-0645(00)00172-7.

Lattin, G. L., C. J. Moore, A. F. Zellers, S. L. Moore, and S. B. Weisberg. 2004. A comparison of neustonic plastic and zooplankton at different depths near the southern California shore. Marine Pollution Bulletin 49:291–294. doi: 10.1016/j.marpolbul.2004.01.020.

Law, K. L., S. Moret-Ferguson, N. A. Maximenko, G. Proskurowski, E. E. Peacock, J. Hafner, and C. M. Reddy. 2010. Plastic accumulation in the North Atlantic Subtropical Gyre. Science 329:1185–1188. doi: 10.1126/science.1192321.

Lebreton, L. C.-M., S. D. Greer, and J. C. Borrero. 2012. Numerical modelling of floating debris in the world’s oceans. Marine Pollution Bulletin 64:653–661. doi: 10.1016/j.marpolbul.2011.10.027.

Lewis, P. N., M. J. Riddle, and S. D. A. Smith. 2005. Assisted passage or passive drift: a comparison of alternative transport mechanisms for non-indigenous coastal species into the Southern Ocean. Antarctic Science 17:183–191.

Lomolino, M. V. 2000. Ecology’s most general, yet protean pattern: the species-area relationship. Journal of Biogeography 27:17–26.

MacArthur, R. H., and E. O. Wilson. 1963. An equilibrium theory of insular zoogeography. Evolution 17:373–387.

Marshall, H. G., and L. Burchardt. 2005. Neuston: Its definition with a historical review regarding its concept and community structure. Archiv für Hydrobiologie 164:429–448. doi: 10.1127/0003-9136/2005/0164-0429.

Martinez, E., K. Maamaatuaiahutapu, and V. Taillandier. 2009. Floating marine debris surface drift: convergence and accumulation toward the South Pacific subtropical gyre. Marine Pollution Bulletin 58:1347–1355. doi: 10.1016/j.marpolbul.2009.04.022.

Mato, Y., T. Isobe, H. Takada, H. Kanehiro, C. Ohtake, and T. Kaminuma. 2001. Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. Environmental Science & Technology 35:318–324.

Matsumura, S., and K. Nasu. 1997. Distribution of floating debris in the North Pacific Ocean: sighting surveys 1986-1991. Pages 15–24 *in* J. Coe and D. Rogers, editors. Marine debris: sources, impact and solutions. Springer, New York.

Maximenko, N., J. Hafner, and P. Niiler. 2012. Pathways of marine debris derived from trajectories of Lagrangian drifters. Marine Pollution Bulletin 65:51–62. doi: 10.1016/j.marpolbul.2011.04.016.

McDermid, K. J., and T. L. McMullen. 2004. Quantitative analysis of small-plastic debris on beaches in the Hawaiian archipelago. Marine Pollution Bulletin 48:790–794.

McGowan, J. A., and P. W. Walker. 1979. Structure in the copepod community of the North Pacific Central Gyre. Ecological Monographs 49:195–226.

Meeker, J. D., S. Sathyanarayana, and S. H. Swan. 2009. Phthalates and other additives in plastics: human exposure and associated health outcomes. Philosophical Transactions of the Royal Society B: Biological Sciences 364:2097–2113. doi: 10.1098/rstb.2008.0268.

Montevecchi, W. A. 1991. Incidence and types of plastic in gannets' nests in the northwest Atlantic. Canadian Journal of Zoology 69:295–297. doi: 10.1139/z91-047.

Moore, C. J. 2003, November. Trashed: Across the Pacific Ocean, plastics plastics, everywhere. Natural History 112. Retrieved May 25, 2012, from http://www.mindfully.org/Plastic/Ocean/Moore-Trashed-PacificNov03.htm.

Moore, C. J., S. L. Moore, M. K. Leecaster, and S. B. Weisberg. 2001. A comparison of plastic and plankton in the North Pacific central gyre. Marine Pollution Bulletin 42:1297–1300. doi: 10.1016/S0025-326X(01)00114-X.

Moore, C. J., S. L. Moore, S. B. Weisberg, G. L. Lattin, and A. F. Zellers. 2002. A comparison of neustonic plastic and zooplankton abundance in southern California's coastal waters. Marine Pollution Bulletin 44:1035–1038. doi: 10.1016/S0025-326X(02)00150-9.

Moser, M. L., and D. S. Lee. 1992. A fourteen-year survey of plastic ingestion by western North Atlantic seabirds. Colonial Waterbirds 15:83–94. doi: 10.2307/1521357.

Newman, W. A., and D. P. Abbott. 1980. Cirripedia: The Barnacles. Pages 504–535 *in* R. H. Morris, D. P. Abbott, and E. C. Haderlie, editors. Intertidal Invertebrates of California. Stanford University Press, Stanford.

Ng, K. L., and J. P. Obbard. 2006. Prevalence of microplastics in Singapore's coastal marine environment. Marine Pollution Bulletin 52:761–767. doi: 10.1016/j.marpolbul.2005.11.017.

Oehlmann, J., U. Schulte-Oehlmann, W. Kloas, O. Jagnytsch, I. Lutz, K. O. Kusk, L. Wollenberger, E. M. Santos, G. C. Paull, K. J. W. Van Look, and C. R. Tyler. 2009. A critical analysis of the biological impacts of plasticizers on wildlife. Philosophical Transactions of the Royal Society B: Biological Sciences 364:2047–2062. doi: 10.1098/rstb.2008.0242.

Ogata, Y., H. Takada, K. Mizukawa, H. Hirai, S. Iwasa, S. Endo, Y. Mato, M. Saha, K. Okuda, A. Nakashima, M. Murakami, N. Zurcher, R. Booyatumanondo, M. P. Zakaria, L. Q. Dung, M. Gordon, C. Miguez, S. Suzuki, C. Moore, H. K. Karapanagioti, S. Weerts, T. McClurg, E. Burres, W. Smith, M. Van Velkenburg, J. S. Lang, R. C. Lang, D. Laursen, B. Danner, N. Stewardson, and R. C. Thompson. 2009. International Pellet Watch: Global monitoring of persistent organic pollutants (POPs) in coastal Waters. 1. Initial phase data on PCBs, DDTs, and HCHs. Marine Pollution Bulletin 58:1437–1446. doi: 10.1016/j.marpolbul.2009.06.014.

Paffenhofer, G.-A., and K. B. Van Sant. 1985. The feeding response of a marine planktonic copepod to quantity and quality of particles. Marine Ecology Progress Series 27:55–65.

Pew Oceans Commission. 2003. America's Living Oceans: Charting a Course for Sea Change. Pew Oceans Commission, Arlington, VA.

Pichel, W. G., J. H. Churnside, T. S. Veenstra, D. G. Foley, K. S. Friedman, R. E. Brainard, J. B. Nicoll, Q. Zheng, and P. Clemente-Colon. 2007. Marine debris collects within the North Pacific Subtropical Convergence Zone. Marine Pollution Bulletin 54:1207–1211. doi: 10.1016/j.marpolbul.2007.04.010.

Pister, B. 2009. Urban marine ecology in southern California: the ability of riprap structures to serve as rocky intertidal habitat. Marine Biology 156:861–873. doi: 10.1007/s00227-009-1130-4.

Ribic, C. A., S. B. Sheavly, D. J. Rugg, and E. S. Erdmann. 2010. Trends and drivers of marine debris on the Atlantic coast of the United States 1997–2007. Marine Pollution Bulletin 60:1231–1242. doi: 10.1016/j.marpolbul.2010.03.021.

Ribic, C. A., S. B. Sheavly, D. J. Rugg, and E. S. Erdmann. 2012. Trends in marine debris along the U.S. Pacific Coast and Hawai'i 1998–2007. Marine Pollution Bulletin 64:994–1004. doi: 10.1016/j.marpolbul.2012.02.008.

Rios, L. M., C. Moore, and P. R. Jones. 2007. Persistent organic pollutants carried by synthetic polymers in the ocean environment. Marine Pollution Bulletin 54:1230–1237. doi: 10.1016/j.marpolbul.2007.03.022.

Robards, M. D., P. Gould, and J. Platt. 1997. The highest global concentrations and increased abundance of oceanic plastic debris in the North Pacific: evidence from seabirds. Pages 71–80 *in* J. Coe and D. Rogers, editors. Marine debris: sources, impact and solutions. Springer, New York.

Sergio, F., J. Blas, G. Blanco, A. Tanferna, L. López, J. A. Lemus, and F. Hiraldo. 2011. Raptor nest decorations are a reliable threat against conspecifics. Science 331:327 –330. doi: 10.1126/science.1199422.

Sievert, P. R., and L. Sileo. 1993. The effects of ingested plastic on growth and survival of albatross chicks. *in* K. Vermeer, K. T. Briggs, K. H. Morgan., and D. Siegel-Causey, editors. The status, ecology, and conservation of marine birds of the North Pacific. Canadian Wildlife Service Special Publications, Ottawa.

Sileo, L., P. Sievert, and M. Samuel. 1990. Causes of mortality of albatross chicks at Midway Atoll. Journal of Wildlife Diseases 26:329–338.

Spear, L. B., D. G. Ainley, and C. A. Ribic. 1995. Incidence of plastic in seabirds from the tropical pacific, 1984-1991: Relation with distribution of species, sex, age, season, year and body weight. Marine Environmental Research 40:123–146. doi: 10.1016/0141-1136(94)00140-K.

Sverdrup, H. U., M. W. Johnson, and R. H. Fleming. 1946. The Oceans - Their Physics, Chemistry, and General Biology. Prentice-Hall, Inc.

Talsness, C. E., A. J. M. Andrade, S. N. Kuriyama, J. A. Taylor, and F. S. vom Saal. 2009. Components of plastic: experimental studies in animals and relevance for human health. Philosophical Transactions of the Royal Society B: Biological Sciences 364:2079–2096. doi: 10.1098/rstb.2008.0281.

Teuten, E. L., J. M. Saquing, D. R. U. Knappe, M. A. Barlaz, S. Jonsson, A. Bjorn, S. J. Rowland, R. C. Thompson, T. S. Galloway, R. Yamashita, D. Ochi, Y. Watanuki, C. Moore, V. Pham Hung, T. S. Tana, M. Prudente, R.

Boonyatumanond, M. P. Zakaria, K. Akkhavong, Y. Ogata, H. Hirai, S. Iwasa, K. Mizukawa, Y. Hagino, A. Imamura, M. Saha, and H. Takada. 2009. Transport and release of chemicals from plastics to the environment and to wildlife. Philosophical Transactions of the Royal Society of London B 364:2027–2045. doi: 10.1098/rstb.2008.0284.

Thiel, M., and L. Gutow. 2005a. The ecology of rafting in the marine environment II: The rafting organisms and community. Oceanography and Marine Biology: An Annual Review 43:279–418.

Thiel, M., and L. Gutow. 2005b. The ecology of rafting in the marine environment I: The floating substrata. Oceanography and Marine Biology: An Annual Review 42:181–263.

Thiel, M., and P. A. Haye. 2006. The ecology of rafting in the marine environment III: Biogeographical and evolutionary consequences. Oceanography and Marine Biology: An Annual Review 44:323–429.

Thiel, M., I. Hinojosa, N. Vásquez, and E. Macaya. 2003. Floating marine debris in coastal waters of the SE-Pacific (Chile). Marine Pollution Bulletin 46:224–231. doi: 10.1016/S0025-326X(02)00365-X.

Thompson, R. C., Y. Olsen, R. P. Mitchell, A. Davis, S. J. Rowland, A. W. G. John, D. McGonigle, and A. E. Russell. 2004. Lost at sea: Where is all the plastic? Science 304:838. doi: 10.1126/science.1094559.

Tyrrell, M. C., and J. E. Byers. 2007. Do artificial substrates favor nonindigenous fouling species over native species? Journal of Experimental Marine Biology and Ecology 342:54–60.

Uneputty, P., and S. M. Evans. 1997. The impact of plastic debris on the biota of tidal flats in Ambon Bay (eastern Indonesia). Marine Environmental Research 44:233–242. doi: 10.1016/S0141-1136(97)00002-0.

University of Southern Mississippi. 2005. Polymer Science Learning Center. Retrieved March 26, 2010, from http://pslc.ws/.

Van, A., C. M. Rochman, E. M. Flores, K. L. Hill, E. Vargas, S. A. Vargas, and E. Hoh. 2012. Persistent organic pollutants in plastic marine debris found on beaches in San Diego, California. Chemosphere 86:258–263. doi: 10.1016/j.chemosphere.2011.09.039.

Venrick, E. L., T. W. Backman, W. C. Bartram, C. J. Platt, M. S. Thornhill, and R. E. Yates. 1973. Man-made objects on the surface of the central North Pacific ocean. Nature 241:271–271. doi: 10.1038/241271a0.

Venrick, E. L., J. A. McGowan, D. R. Cayan, and T. L. Hayward. 1987. Climate and chlorophyll-a: Long-term trends in the central North Pacific Ocean. Science 238:70–72. doi: 10.1126/science.238.4823.70.

Watters, D. L., M. M. Yoklavich, M. S. Love, and D. M. Schroeder. 2010. Assessing marine debris in deep seafloor habitats off California. Marine Pollution Bulletin 60:131–138. doi: 10.1016/j.marpolbul.2009.08.019.

Wegner, A., E. Besseling, E. m. Foekema, P. Kamermans, and A. a. Koelmans. 2012. Effects of nanopolystyrene on the feeding behavior of the blue mussel (Mytilus edulis L.). Environmental Toxicology and Chemistry 31:2490–2497. doi: 10.1002/etc.1984.

Wei, C.-L., G. T. Rowe, C. C. Nunnally, and M. K. Wicksten. 2012. Anthropogenic “litter” and macrophyte detritus in the deep Northern Gulf of Mexico. Marine Pollution Bulletin 64:966–973. doi: 10.1016/j.marpolbul.2012.02.015.

Wilson, D. S. 1973. Food size selection among copepods. Ecology 54:909–914.

Winston, J. E. 1982. Drift plastic - an expanding niche for a marine invertebrate. Marine Pollution Bulletin 13:348–351.

Winston, J. E., M. R. Gregory, and L. Stevens. 1997. Encrusters, epibionts, and other biota associated with pelagic plastics: a review of biological, environmental, and conservation issues. Pages 81–98 *in* J. M. Coe and D. B. Rogers, editors. Marine debris: sources, impact and solutions. Springer, New York.

Wong, C. S., D. R. Green, and W. J. Cretney. 1974. Quantitative tar and plastic waste distributions in Pacific Ocean. Nature 247:30–32. doi: doi:10.1038/247030a0.

Yamashita, R., H. Takada, M. Fukuwaka, and Y. Watanuki. 2011. Physical and chemical effects of ingested plastic debris on short-tailed shearwaters, Puffinus tenuirostris, in the North Pacific Ocean. Marine Pollution Bulletin 62:2845–2849. doi: 10.1016/j.marpolbul.2011.10.008.

Yamashita, R., and A. Tanimura. 2007. Floating plastic in the Kuroshio Current area, western North Pacific Ocean. Marine Pollution Bulletin 54:485–488.

Ye, S., and A. L. Andrady. 1991. Fouling of floating plastic debris under Biscayne Bay exposure conditions. Marine Pollution Bulletin 22:608–613. doi: 10.1016/0025-326X(91)90249-R.

Zaitsev, Y. P. 1971. Marine Neustonology. Translated from the Russian by A. Mercado. Keter Press, Jerusalem.

Zankai, N. P. 1991. Feeding of nauplius stages of Eudiaptomus gracilis on mixed plastic beads. Journal of Plankton Research 13:437 –453. doi: 10.1093/plankt/13.2.437.

CHAPTER 2: Scales of spatial heterogeneity of plastic marine debris in the northeast Pacific Ocean

Abstract

Plastic debris has been documented in many marine ecosystems, including remote coastlines, the water column, the deep sea, and subtropical gyres. The North Pacific Subtropical Gyre (NPSG), colloquially called the "Great Pacific Garbage Patch," has been an area of particular scientific and public concern. However, quantitative assessments of the extent and variability of plastic in the NPSG have been limited. Here, we quantify the distribution, abundance, and size of plastic in the NPSG, California Current, and transition region, over multiple spatial scales. Samples were collected in summer 2009 using surface and subsurface plankton net tows for small particles ("microplastic") and quantitative visual observations for larger objects ("macroplastic"). Samples were collected in fall 2010 using surface net tows only. We documented widespread, though spatially and temporally variable, plastic pollution in the NPSG and adjacent water masses. The median microplastic numerical concentration in summer 2009 was 0.448 particles m^{-2} with 98% of surface tows containing plastic, and in fall 2010 was 0.021 particles m^{-2} with 100% of tows containing plastic. Plastic concentration was broadly correlated with water mass but showed no distinct spatial pattern due to high submesoscale variability. An inverse correlation with wind speed affected detectability of plastic at the sea surface. The numerical majority of objects were small particles collected with nets, but the majority of debris surface area was found in large objects assessed visually. Microplastic particles in the NSPG were more circular than particles in the transition region or California Current, suggesting greater weathering of particles in the gyre. Plastic to plankton ratio varied with water mass and time of day. Our findings suggest that accurate assessment of oceanic plastic debris must account for spatial variability. These have implications for evaluating impacts of public policy, industry programs, or consumer behavior designed to reduce debris input into the ocean.

Introduction

Plastic debris has been documented in a wide variety of marine ecosystems, including the coastlines of remote islands (Donohue et al. 2001, Ivar do Sul et al. 2009), the coastal water column (Thiel et al. 2003, Collignon et al. 2012), the deep sea (Galgani et al. 1995, Watters et al. 2010, Wei et al. 2012), and subtropical gyres (Matsumura and Nasu 1997, Moore et al. 2001, Law et al. 2010). Environmental impacts of large pieces of debris, termed “macroplastic,” include habitat alteration and damage (Uneputty and Evans 1997, Donohue et al. 2001, Watters et al. 2010), entanglement (Laist 1997), and ingestion by megafauna such as cetaceans, seabirds, and sea turtles (Bugoni et al. 2001, Young et al. 2009, Jacobsen et al. 2010). Colonization of floating debris may also transport rafting species, leading to bioinvasions (Winston et al. 1997, Barnes 2002). Environmental impacts of small plastic particles less than 5 mm in diameter, termed “microplastic,” (Arthur et al. 2008) include ingestion by a number of organisms, including seabirds (Spear et al.

1995, Robards et al. 1997), fishes (Boerger et al. 2010, Possatto et al. 2011, Davison and Asch 2011) and marine invertebrates (Thompson et al. 2004, Browne et al. 2008, Graham and Thompson 2009, Murray and Cowie 2011), accumulation of toxins (Mato et al. 2001, Teuten et al. 2009, Rios et al. 2010), and alteration of the pelagic habitat through the addition of hard substrate (Goldstein et al. 2012).

Plastic pollution has rapidly increased over the past several decades (Barnes et al. 2009). Floating plastic was first documented in the North Pacific and North Atlantic subtropical gyres in the early 1970s, with observations of both large plastic objects such as bottles (Venrick et al. 1973) and small plastic particles (Carpenter and Smith 1972, Wong et al. 1974, Colton et al. 1974). Plastic debris abundance increased between the late 1960s through the 1990s as documented by at-sea surveys (Day and Shaw 1987, Goldstein et al. 2012), seabird ingestion studies in the Arctic and Atlantic (Moser and Lee 1992, Robards et al. 1997), a Continuous Plankton Recorder study in the northeast Atlantic (Thompson et al. 2004), and coastal deposition on remote islands (Barnes 2005). Since the 1990s, there is some question about the increasing trend in plastic density, as spatial and temporal heterogeneity make shorter-term trends difficult to discern (Barnes et al. 2009). Using archived samples, Gilfillan et al. (2009) detected widespread plastic micro-debris in the southern California Current during winter cruises in 1984, 1994, and 2007, but did not find a significant increase over time. Visual observations (Barnes and Milner 2005) and neuston tows (Law et al. 2010) in the Atlantic did not detect an increase in oceanic plastic debris since the 1980s. Densities of debris on the coastline appear to have remained constant since the 1990s (Barnes et al. 2009, Ribic et al. 2010), with the exception of some types of

Pacific debris, which decreased (Ribic et al. 2012). In addition, incidence of plastic ingestion in North Pacific procellariiform seabirds rose between 1984 and 1990 but declined afterwards (Spear et al. 1995).

The spatial distribution of plastic marine debris is influenced by multiple interacting factors. Both continental and oceanic sources of marine debris vary regionally (Derraik 2002, Barnes et al. 2009). Over ocean basins, spatial patterns of debris are influenced by interacting large-scale atmospheric and oceanic circulation patterns, leading to particularly high accumulations of floating debris in the subtropical gyres (Martinez et al. 2009, Maximenko et al. 2012). Over regional scales, convergences such as the North Pacific Subtropical Convergence Zone and the Kuroshio Extension Recirculation Gyre collect debris (Pichel et al. 2007, Howell et al. 2012). Higher densities of debris in coastal waters may also be associated with human population centers (Matsumura and Nasu 1997, Thiel et al. 2003, Browne et al. 2011). Locally, wind patterns affect the distribution of debris by differentially moving or mixing particles of different densities (Browne et al. 2010, Kukulka et al. 2012).

High spatial variance in debris has made assessment of temporal trends difficult (Ryan et al. 2009). For this study, we tested the hypothesis that the distribution, abundance and size of microplastic differ amongst the North Pacific Subtropical Gyre (NPSG), California Current, and transition region between them. We also hypothesized that wind-induced mixing reduces plastic concentration at the sea surface. More exploratory aspects of this study include combining plankton net samples of microplastic with quantitative visual observations of macroplastic to provide the first continuous size spectra of plastic marine debris, and comparing the mass of microplastic debris with concurrently measured biomass of zooplankton.

Materials and Methods

Net samples

In August 2009, samples (N = 119) were collected on the Scripps Environmental Accumulation of Plastic Expedition (SEAPLEX) cruise on the R/V *New Horizon*. Samples on SEAPLEX were taken at predetermined times with the exception of three intensively sampled stations in the NPSG targeted at high-plastic areas and one reference station in the California Current. In October 2010, samples (N = 28) were collected on the EX1006 leg of the Always Exploring Expedition on the NOAA ship *Okeanos Explorer*. Samples on EX1006 were taken at predetermined times. Both sets of samples were collected using a standard manta net (0.86 x 0.2 m) with 333 µm mesh (Brown and Cheng 1981), towed for 15 minutes at 0.7-1 m s^{-1}. Water volume flowing through the net was measured with a calibrated General Oceanics analog flowmeter. The manta net samples the two-dimensional air-sea interface so concentrations are preferentially given in square meters, but when conversion to cubic meters is necessary, the depth sampled is assumed to be the 0.2 m dimension of the net opening (Kramer et al. 1972). The SEAPLEX samples were fixed in 1.8% formaldehyde buffered with sodium borate, and the EX1006 samples were fixed in 95% ethanol.

Subsurface samples were collected on SEAPLEX using a CalCOFI bongo net (pair of circular frames 71 cm in diameter, 202 µm mesh). The bongo net was deployed in an oblique tow with a maximum depth of 210 meters for 15 minutes. As with the manta tow, water through the net was measured with a calibrated flowmeter. Upon retrieval the nets were washed carefully and the contents of one net preserved in 1.8% formaldehyde buffered with sodium borate.

Each sample was sorted for microplastic at 6-12x magnification under a Wild M-5 dissecting microscope, and plastic particles removed for further analysis. Plastic particles were soaked in deionized water to remove salts, dried at 60°C, and stored in a vacuum desiccator. Dry mass was measured on an analytical balance. Particles were then digitally imaged with a Zooscan digital scanner with a resolution of 10.6 μm (Gilfillan et al. 2009, Gorsky et al. 2010). The total number of particles as well as two-dimensional surface area, feret diameter, and circularity of each particle were measured using NIH ImageJ-based tools in the Zooprocess software, and calibrated against manual measurements (Gilfillan et al. 2009, Gorsky et al. 2010). Feret diameter is the longest distance between any two points along the boundary of an object, and is closely related to total length (Gilfillan et al. 2009, Gorsky et al. 2010). Circularity is defined as 4π area*perimeter^{-2}, which ranges from 0 to 1 with 1.0 indicating a perfectly circular object (Gilfillan et al. 2009).

Dry mass of zooplankton was obtained from preserved manta tow samples (Omori and Ikeda 1984). After fixation in 1.8% formaldehyde for 24 months, samples were split in a Folsom splitter, filtered onto 202 μm Nitex mesh disks and rinsed with isotonic ammonium formate. Filters were dried for 24 hours at 60°C and placed in a vacuum dessicator until weighing. Filters were weighed to the nearest 0.0001 gram on the same analytical balance as the plastic samples. A 20% correction factor was applied in order to compensate for the biomass lost by preservation (Omori 1978, Omori and Ikeda 1984). Plastic to plankton ratios were calculated by dividing microplastic dry mass by zooplankton dry mass.

Visual observations

Visual observer counts for macrodebris on SEAPLEX were conducted by a single observer (A.J.T) at 10 m eye height above sea level, while the vessel was transiting between stations. The observer surveyed on one side of the track-line, based on sighting conditions (e.g., glare and wind). All marine debris sighted to the horizon was counted and assigned to one of three pre-determined size classes based on its larger dimension: small (2–10 cm), medium (10–30 cm), large (> 30 cm). The color of each piece and a description were also recorded. Distance sampling methods were used in order to calculate estimated densities of each debris size class along the track-line. Additional details on visual counts can be found in Titmus & Hyrenbach 2011.

To compare visual observations with net tow observations, visual observations were combined in over-the-ground bins of 900 meter length. The average net tow also covered 900 meters of over-the-ground distance. To calculate two-dimensional area, visual objects were assumed to be circular.

Submesoscale sampling schemata

Two submesoscale sampling protocols were used on the SEAPLEX cruise. First a grid pattern was deployed on August 12, 2009 centered around 30° 48.6’ N, 139° 45.9’ W. The grid consisted of 16 manta tows 10 km apart in a 4 by 4 grid pattern. The second was a line pattern deployed on August 15, 2009 proceeding west from 34° 3.4’ N, 141° 22.4’ W. The line consisted of four stations of five repeated manta tows, with stations 18 km apart. Visual transect sampling of plastic macrodebris was performed between tow stations. Plastic concentrations were compared between tow stations with visual observations taken less than 10 km away.

Oceanographic context

Stations from both cruises were assigned to an oceanographic water mass based on surface water temperature and salinity, as measured by the ship underway system. Depth profile information was not available so these assignments should be viewed as approximations. On both the R/V *New Horizon* and NOAA Ship *Okeanos Explorer*, surface temperature and conductivity were measured with a Seabird SBE-45 thermosalinograph, and fluorescence with a Turner Designs 10-AU field fluorometer.

For the purposes of this analysis, the California Current was defined as having a surface temperature less than 19°C and surface salinity less than 33.5 psu (Lynn and Simpson 1987). The transition region was defined as having a surface temperature of 19-22°C and surface salinity of 33.5-34.8 psu (Roden 1980, Lynn and Simpson 1987). The NPSG was defined as having surface temperatures greater than 22°C and salinity greater than 34.8 psu (Roden 1980, Niiler and Reynolds 1984).

Sea surface temperature was mapped over the study area using monthly composites of remotely sensed data from MODIS-Aqua and MODIS-Terra. Chlorophyll was mapped using monthly composites of SeaWiFS Level-2. Both sets of maps were created by Mati Kahru (Scripps Institution of Oceanography, UCSD) (Kahru 2011).

True wind data were collected on the R/V *New Horizon* during SEAPLEX using an RM Young 85000 ultrasonic anemometer mounted in the starboard side of the ship's superstructure 11 m above the waterline. Data were downloaded from the Scripps Institution of Oceanography MetAcq System where true wind was derived from ship heading, course over ground, speed, and relative wind speed (Smith et al. 1999). True wind data were collected on the NOAA Ship Okeanos Explorer during EX1006 using an RM Young 05106 aerovane mounted atop the ship's superstructure 17.7 m above the waterline. Data were downloaded from the ship SCS data system where true wind was derived from ship heading, course over ground, speed, and relative wind speed (Smith et al. 1999).

To compare the particle concentration to true wind speed, the particle concentration anomaly was compared to the true wind speed anomaly for each cruise. The anomaly was the difference between individual measurements of the particle concentration and the overall mean particle concentration, or between the individual true wind speed measurements and the mean true wind speed for the entire time series. Wind speed data recorded during particle sampling (manta net tows) were extracted from the full record of true wind data from each cruise and used in these analyses.

Fisch (2010) documented potential differences in wind speed between the sensor types used in these two cruises, finding that the ultrasonic anemometer measurements can be 0.3 m s^{-1} faster than the aerovane for average speed and 1.0 m s^{-1} faster at maximum speeds (Fisch 2010). We sampled a range of wind speeds within the average wind speeds experienced in the Fisch study. Therefore, while intercalibration between the two ships was not conducted, it is assumed that it may be possible that the ultrasonic anemometer data from the SEAPLEX cruise may be 0.3 m/s faster than the aerovane data from the EX1006.

Variograms

The semivariogram, often abbreviated variogram, describes how data covary with distance (Kaluzny et al. 1998). The semivariogram is calculated as

$$\gamma(h) = \frac{1}{2\,|N(h)|} \sum_{N(h)} (z_i - z_j)^2 \tag{1}$$

where *N(h)* is the set of all pairwise Euclidean distances $i - j = h$, $|N(h)|$ is the number of distinct pairs in *N(h)*, and z_i and z_j are data values at spatial locations *i* and *j,* respectively (Kaluzny et al. 1998). Semivariogram interpretation is based on the principle that pairs of samples that are closer to each other are more similar than pairs of samples farther apart. The semivariogram function should therefore increase with distance (Yoder et al. 1987, Doney et al. 2003). Above a certain distance, sample pairs may no longer be correlated, and the semivariogram function may reach a steady value, or “sill.” To aid in interpretation, the empirical semivariogram generated by equation 1 can be fitted with a simple statistical model (Kaluzny et al. 1998).

We calculated variograms for surface plastic abundance, temperature, salinity, and chlorophyll-*a* fluorescence for 119 stations in summer 2009. Because the standard variogram equation is sensitive to skewness in the data, we calculated empirical variograms using the robust variogram estimator (Cressie and Hawkins 1980). This method is based on the square root of the absolute value of the data value differences, $|z_i - z_j|^{1/2}$, rather than the squares of the differences.

$$\gamma(h) = \frac{\frac{1}{2}\left(\frac{1}{N(h)}\sum_{N(h)} | z_i - z_j |^{1/2}\right)^4}{\left(0.457 + \frac{0.494}{N(h)}\right)}$$

(2)

Variograms were computed with the geoR package (version 1.7-1) (Ribeiro and Diggle 2001) and fitted with a Gaussian distribution.

Analysis

We computed all statistics using the R statistical environment (version R-2.13.1) (R Development Core Team 2011). Data were non-normal so nonparametric tests (Mann-Whitney U, Kolmogorov-Smirnov test, Spearman rank correlation) were used. The statistical power of the Mann-Whitney U test for detecting differences in microplastic numerical concentration measurements was calculated by multiplying the summer 2009 data (N = 119) by a factor of increase (e.g., 20%, 30%, etc.) and testing for differences before and after this increase using Monte Carlo simulations (1000 simulations per test) (Mumby 2002). Figures 2.1, 2.3 and 2.5 were created in Surfer 8 (Golden Software) and the remaining figures in R. All figures were formatted in Adobe Illustrator CS5.1. Data from this study are deposited with the California Current Ecosystem LTER DataZoo (URL placeholder).

Results

Interannual abundance and distribution of neustonic plastic

Oceanographic conditions varied between the two sampling years (Fig 2.1). In summer 2009, the transition region was further north, and the highest plastic density occurred in the warmer, less productive NPSG waters (Fig 2.1A, B, 2E). In fall 2010, the transition region was further south, and the highest plastic density occurred in the transition region with slightly cooler water and higher productivity (Fig 2.1C, D, 2F).

Significantly more particles were found in Summer 2009 than in Fall 2010 (Fig 2.2A, B; Kolmogorov-Smirnov test, $p < 0.001$), and median particle density was an order of magnitude higher in summer 2009 (Table 2.1). The size spectra of particles was also significantly different between summer 2009 and fall 2009, with more small particles found at the surface in summer (Fig 2.2C, D; Kolmogorov-Smirnov test, $p < 0.001$). The overall seasonal difference in microplastic concentrations across all regions sampled between summer 2009 and fall 2010 was driven by changes in abundance in the NPSG (Table 2.2, Mann-Whitney U, $p < 0.001$). There was no significant difference between plastic particle concentrations by year in either the California Current or transition region (Mann-Whitney U, $p = 0.187$ and $p = 0.306$, respectively).

In summer 2009, the highest plastic concentrations were found in the NPSG water mass (Fig 2.2E). Plastic densities were significantly different among water masses in summer 2009 (Kruskal-Wallis rank sum test chi-squared = 53.147, $p < 0.001$). Post-hoc analysis with the Nemenyi-Damico-Wolfe-Dunn test (Hothorn et al.

2008) found that plastic concentrations between the NPSG and the California Current and transition region were statistically distinct, but that there was no difference between the California Current and transition region (Table 2.3). In contrast, the highest plastic concentrations in fall 2010 were found in the transition region (Fig 2.2F). While plastic densities were significantly different among water masses (Kruskal-Wallis rank sum test $\chi^2 = 8.330$, $p = 0.016$), the Nemenyi-Damico-Wolfe-Dunn test found that the transition region and California Current had significantly different concentrations of plastic, but that NPSG plastic concentration was not significantly different than plastic concentrations in either the transition region or California Current water masses (Table 2.3).

We conducted a power analysis on the summer 2009 dataset to estimate the range of sample sizes that would be necessary to detect changes in plastic abundance of a specified magnitude (Fig 2.3). For example, using a power of 80%, plastic abundance would need to increase by 90% to be detectable with a sample size of $N = 100$. Under the same adequacy, detection of a 50% increase in microplastic would require a sample size of $N = 240$.

In both years, microplastic concentration was inversely related to wind speed. We compared particle abundance anomalies (No. m^{-2}) and mean hourly wind anomalies ($m\ s^{-1}$) as a function of time for the summer 2009 data within the NPSG, and for the complete fall 2010 dataset. Both comparisons illustrated that negative particle concentration anomalies were associated with positive wind anomalies (Fig 2.4). In summer 2009, a negative relationship was observed for 56 instances out of 90 points, and in fall 2010, for 18 of the 28 data points. Spearman's rank correlation of particle concentration and wind speed for both cruises showed a significant negative correlation ($p < 0.05$).

Spatial scales of plastic variation

Plastic concentrations were variable over relatively small spatial scales. In the grid sampling pattern (Fig. 2.5), median particle density (and 5-95 percentiles, followed by maximum value) was 0.832 particles m^{-2} (0.390-2.023; 3.202). The coefficient of variation was 71.2%. The grid pattern had significantly more plastic in the southern section than in the northern section (Spearman's rank correlation $p = 0.044$), but no longitudinal pattern (Spearman's rank correlation $p = 0.900$). In the line sampling pattern (Table 2.4), both visual counts and net sampled concentrations of plastic were highly variable. Concentrations of net sampled plastic microdebris were two orders of magnitude higher than visual counts of plastic microdebris.

In the variograms, there was no correlation between lag distance and surface microplastic concentration (Fig 2.6A). In contrast, the semivariance of temperature, salinity, and fluorescence all increased with lag distance, but none reached a sill (Fig 6B-D).

Abundance and distribution of plastic in summer 2009

Depth distribution

In summer 2009 in both the California Current and the NPSG, significantly higher particle densities were found in the neuston than in the integrated water column from the sea surface to 210 m (Fig 2.7). In the California Current station and all three

NPSG stations with paired neuston and subsurface sampling, the median neuston concentration was two orders of magnitude higher than subsurface concentration. The differences between the neuston and subsurface stations were statistically significant (Table 2.5).

Surface distribution of micro- vs. macrodebris

Plastic concentrations as detected in visual observations and plankton tows within 25 km of each other were positively correlated over the cruise track (Fig 2.8, Spearman's rank correlation $p < 0.0005$, $R^2 = 0.394$). The median plastic concentration in plankton tows was 0.3860 particles m^{-2} for plastic particles captured in a 333 μm net. The median plastic concentration detected by visual observation was 0.0001 particles m^{-2} for objects with a maximum diameter greater than 2 cm.

Microdebris and macrodebris were not well correlated on smaller (10 km) spatial scales (Fig 2.8, filled circles). Microplastic was statistically distinct between the four stations with repeated tows and visual observations (Kruskal-Wallis, $p = 0.002$). Post-hoc analysis with the Nemenyi-Damico-Wolfe-Dunn test revealed that this was caused by differences between the two stations with the lowest and highest concentrations of microplastic ($p < 0.001$), and that no other pairwise comparisons were statistically significant ($p > 0.05$). No stations had statistically distinct levels of macrodebris (Kruskal-Wallis test, $p > 0.05$).

Size distribution of debris

In all water masses in summer 2009, plastic debris less than 333 μm was by far the most numerically abundant (Fig 2.9). However, the majority of the two-dimensional area of plastic debris was found in the large, relatively rare items. While the overall patterns remained the same across water masses, both the number and percentage of area accounted for by small visually observed items (3.1-78.5 cm^2) increased from the California Current through the transition region to the NPSG. The sum of the two-dimensional surface area for all plastic debris observed in summer 2009 was 23 m^2 for the minimum visual estimate, and 14,746 m^2 for the maximum estimated, over the total of 94.4 km^2 sampled.

To test whether the roundness of microdebris particles was correlated with particle size, we compared particle circularity with feret diameter. The overall relationship was negative (Fig 2.10), indicating that larger particles were more irregular or elongate while smaller particles were more circular. When particles were divided by water mass, particles of equivalent diameter from the NPSG were the most circular and particles from the California Current were the least circular. For the largest microdebris particles (> 5 mm), this relationship did not hold, but these particle circularities were based on small sample sizes ($N < 10$ particles). For feret diameter, the NPSG was statistically distinct from both the transition region and the California Current (Nemenyi-Damico-Wolfe-Dunn test $p < 0.001$), but the transition region and California Current were not different from each other ($p = 0.145$). For circularity, the California Current was statistically distinct from both the transition region and the NPSG (Nemenyi-Damico-Wolfe-Dunn test $p < 0.001$), but the transition region and NPSG were not different from each other ($p = 0.819$).

Plastic to plankton ratio

Plastic to plankton (PZ) ratios for summer 2009 were correlated with plastic density (Fig 2.11, Spearman's rank correlation, $p < 0.001$, $R^2 = 0.375$), with the lowest ratios found in the California Current during crepuscular time periods (median = 0.002) and the highest in the NPSG during the day (median = 2.823). PZ ratios were not significantly correlated with zooplankton dry mass (Spearman's rank correlation, $p = 0.150$, $R^2 = 0.018$). PZ ratios were significantly different between the NPSG and the two other water masses (Nemenyi-Damico-Wolfe-Dunn test $p < 0.001$) but not between California Current and transition region (Nemenyi-Damico-Wolfe-Dunn test $p = 0.581$). Within water masses, PZ ratios were not significantly different by time of day with the exception of the NPSG day vs. night samples ($p < 0.001$).

Discussion

This study documents widespread, though spatially and temporally variable plastic pollution in the northeast Pacific Ocean. The highest concentrations of microplastic were found at the surface in the NPSG and transition region water masses. However, debris was highly variable between years and within water masses. To our knowledge, this is the first time that quantitative observations on pelagic microplastic and macroplastic have been combined into a complete size spectrum.

The median concentration of NPSG microplastic measured in this study in summer 2009 (0.619 particles m^{-2}/3.095 particles m^{-3}) is higher than maximum values from some past studies. Two previous studies in the NPSG found maximum values of 0.3168 particles m^{-2} (Day et al. 1990) and 0.3343 particles m^{-2} (Moore et al. 2001). Our median value is similar to the maximum value of 3.141 particles m^{-3} found in the southern region of the California Current (Gilfillan et al. 2009). However, a similar study conducted in the Bering Sea and southern California Current found a maximum microplastic concentration of only 0.4061 particles m^{-3} (Doyle et al. 2011). Plastic concentrations reported in this study are also high compared to the maximum value of 0.580 particles m^{-2} reported from the North Atlantic Subtropical Gyre (Law et al. 2010). This difference may be partially due to the summer 2009 sampling scheme, which deliberately targeted high-plastic areas. Calm, glassy conditions (Beaufort Sea State 1-2) during the summer 2009 may also have allowed less buoyant particles to rise to the air-sea interface (Kukulka et al. 2012). Additionally, seasonal, annual, and decadal-scale changes in oceanographic conditions can influence oceanographic conditions and therefore the abundance and location of plastic debris (Morishige et al. 2007, Pichel et al. 2007, Howell et al. 2012).

For similar reasons, the percentage of tows that contained microplastic debris is substantially higher than those reported in previous studies. In this study, 98.3% of surface tows from summer 2009 and 100% of surface tows from fall 2010 contained plastic. In contrast, for samples taken in 2006 and 2007, Doyle et al. reported values of 25% and 40% from the Bering Sea, 8.75% for a cruise off the northern US west coast, and 66-84% off southern California (Doyle et al. 2011). Likewise, Gilfillan et al. reported 56-68% for three southern California cruises (Gilfillan et al. 2009), and Law et al. reported 62% for the North Atlantic (Law et al. 2010).

The difference in offshore surface plastic concentration, size, and water mass association between summer 2009 and fall 2010 may be influenced by seasonal changes in oceanographic and atmospheric conditions. The study area contains two interacting convergence zones – the North Pacific Subtropical Convergence Zone (NPCZ) and the North Pacific Subtropical High (Howell et al. 2012). Both of these features act as debris accumulation zones on the large scale (Moore et al. 2001, Morishige et al. 2007, Pichel et al. 2007), but seasonal and mesoscale variation, such as eddy formation, can lead to local variation in convergence (Roden 1991). Coupled atmospheric-oceanic phenomena such as El Nino-Southern Oscillation may also affect the distribution of debris (Matsumura and Nasu 1997, Morishige et al. 2007). Using remotely sensed data, we observed a shift in the latitude of the frontal region between years. This shift in the frontal region may account for the difference in both overall plastic abundance and plastic association with water masses, since both cruises sampled similar geographic coordinates. Our microplastic sampling resolution was too low to resolve local convergences/divergences associated with fronts and eddies, though such features are generally weaker in the summer and fall months (Roden 1980, Howell et al. 2012).

Microplastic patterns were patchy on both the submesoscale and over both cruise tracks. In the two submesoscale sampling experiments, both performed in summer 2009, microplastic concentrations were highly variable. Over the summer 2009 cruise track, there was no scale-dependence of spatial patterns of microplastic abundance, in contrast to temperature, salinity, and chlorophyll-*a* fluorescence. Ryan et al. (2009) attributed the high variability of plastic debris concentrations to “multiple diffuse and point-source inputs and the non-random transportation of debris by winds and currents (Ryan et al. 2009).” Other beach and at-sea studies have also found substantial variability, attributed to proximity to populated areas (Browne et al. 2011), regional oceanographic conditions such as upwelling (Ribic et al. 2012), or large-scale oceanographic changes such as the ENSO cycle (Morishige et al. 2007). While existing methods are sufficient to identify large-scale variability such as between water masses, the within-station variability demonstrated in this study suggests that more replications are necessary to detect temporal trends.

The detection of high-plastic areas also varied with methodology. Visually detected macroplastic density was correlated with net tow collected microplastic density over the entire cruise track, but macroplastic and microplastic were not well correlated on the 10 km scale. The lack of correlation between macroplastic and microplastic at the smaller scale may be attributed to differences in the forces that move the different types of debris. For example, in estuarine benthic debris, Browne et al. (2010) found that low density macrodebris moved with the wind, but low density microdebris did not (Browne et al. 2010). In addition, Pichel et al. (2007) used wind-driven Ekman drift in association with high convergence as a factor in predicting macrodebris locations in the North Pacific (Pichel et al. 2007). Within the NPSG in the absence of strong surface currents, low level winds may disproportionately affect macrodebris causing a spatial mismatch with associated concentrations of microdebris. Additionally, extremely high densities of marine debris as observed in the NPSG may have resulted in underestimates of macroplastic density in the smallest observable size class (2-10 cm). Visual underestimates in density would likely be resolved by restricting observations to certain types or size classes of macrodebris, or by observing over smaller defined strip widths along the cruise track.

We found a negative exponential relationship between size and particle abundance in both micro- and macrodebris. This relationship has been found in some (Shaw and Day 1994, Lattin et al. 2004, Gilfillan et al. 2009, Doyle et al. 2011), but not all studies of sea surface microplastic (Moore et al. 2001, 2002, Yamashita and Tanimura 2007, Moret-Ferguson et al. 2010). Numerically dominant small particles may be more important for risks that depend on encounter frequency, such as ingestion (Boerger et al. 2010, Davison and Asch 2011), microbial growth (Lobelle and Cunliffe 2011), and ecotoxicity (Derraik 2002, Teuten et al. 2009, Andrady 2011, Cole et al. 2011). However, large items may be more important for risks that are surface area dependent, such as entanglement (Laist 1997) and the transport of potentially invasive species (Barnes et al. 2009, Gregory 2009), and such risks may potentially be mitigated by targeted removal of large objects.

Calm conditions may have contributed to our finding that microplastic was more abundant in the neuston than in the sub-surface water column, since minimal wind mixing may have allowed less buoyant particles to rise to the surface. Based on analysis of two cruises with different wind environments (fall 2010 experienced higher winds than summer 2009), samples with fewer plastic particles were observed when wind speeds were higher. Since this pattern was observed both between water masses and within the NPSG water mass, the primary factor affecting particle concentration may be wind. Similarly, Kukulka et al. (2012) found an inverse relationship between wind speed and surface plastic concentration in the North Atlantic Subtropical Gyre. Based on those data and a one-dimensional column model, they estimated that 54% of plastic pieces are mixed below surface tow depths under average wind conditions. Doyle et al. (2011) found a similar pattern off southern California, though Lattin et al. 2004 found more debris closer to the benthos in Santa Monica Bay, California (Lattin et al. 2004).

Our use of a non-closing net and oblique tow technique means that the depth from which particles were collected is not known. However, on the same cruise, plastic particles were found in the stomachs of 4.8% of the planktivorous mesopelagic fishes that live below the sea surface (non-vertically migratory taxa (Davison and Asch 2011)). Since these particles were too large to have been ingested by these fishes' prey, this result suggests that some plastic particles are sinking outside the euphotic zone. Plastic particle sinking may also be influenced by biofouling-induced changes in density (Moret-Ferguson et al. 2010), although plastic has not been documented to be a significant component of the material collected in sediment traps (Law et al. 2010). Both these studies and the findings reported here emphasize the need for more detailed observations of the vertical distribution of plastic during various wind conditions.

The increased circularity of microplastic with smaller particle size was described in Gilfillan et al. (2009) as a process in which "larger marine debris items with an irregular shape become progressively smaller and rounded through time via mechanical breakdown." While degradation of plastic in seawater is extremely slow compared to degradation of plastic in air (Andrady 2011), greater circularity of NPSG particles may be associated with increased time at sea (Gilfillan et al. 2009). While this trend would not hold for samples containing a high percentage of the preproduction plastic pellets known as "nurdles," such pellets were a small percentage of the total microplastic considered in this analysis.

Past studies have used the ratio of dry plastic mass to zooplankton biomass (PZ) to assess risk of debris ingestion by marine planktonic filter feeders (Moore et al.

2001, 2002, Lattin et al. 2004). This approach is problematic for a number of reasons described in Doyle et al. (2011), including variance of both plastic and zooplankton in space and time, selective sampling by nets, and selective feeding by zooplankton. Our data confirm that this ratio is conflated with large-scale patterns of plastic abundance and, to a lesser extent, with time of day. Though PZ ratio was not significantly correlated with zooplankton biomass over our sampling region, ephemeral high-biomass events may influence it. For example, PZ ratios in the transition region during our sampling period spanned seven orders of magnitude due to a salp aggregation and spatially patchy microplastic.

While PZ ratio does not assess the likelihood of zooplankton ingestion of microplastic, PZ ratio may be useful in assessing microplastic remediation schemes. For example, based on our median NPSG PZ ratio of 1.368, approximately 731 mg of dry zooplankton biomass would be removed from the NPSG for each gram of plastic removed. This corresponds to approximately 330 mg of carbon removed, assuming carbon content is 0.40 of total zooplankton dry mass (Beers 1966). Since overall productivity in the NPSG is estimated to be only 473 mg C m^{-2} day^{-1} (Karl 1999), a remediation scheme that removed significant amounts of microplastic would likely have a substantial impact on surrounding plankton standing stocks and, consequently, on nutrient dynamics.

Public concern about plastic debris in marine ecosystems has grown in recent years, resulting in several governmental and non-governmental reports (National Research Council 2009, STAP 2011, Stevenson, C. 2011, Wurpel et al. 2011). However, the efficacy of changes in public policy, industry, or consumer behavior will be difficult to determine without accurate assessment of debris quantities. This will require spatial variability to be taken into account, both so that there is sufficient power to resolve trends and so that the differing spatial patterns between size classes of debris can be resolved. Because logistical limitations on sampling design (e.g., limited ship time) makes basin-scale debris assessment difficult, future studies may benefit from working with existing oceanographic monitoring programs such as the Hawaiian Oceanographic Time-Series (HOTS) or the California Cooperative Oceanographic Fisheries Investigations (CalCOFI), or by focusing on submesoscale features likely to accumulate high concentrations of debris.

Acknowledgments

We are grateful for assistance from the captain, crews, and science parties of the R/V *New Horizon* and NOAA Ship *Okeanos Explorer*, particularly S. Oakes. Logistical and laboratory support were provided by A. Hays and D. Abramenkoff of NOAA Southwest Fisheries Science Center, A. Townsend and L. Sala of the SIO Pelagic Invertebrates Collection, and L. Gilfillan. The following laboratory volunteers provided valuable assistance in sorting plankton samples: O. Benge, C.L. Cameron, P. Chung, D. Dufour, A.P-H. Fan, G.C. Gawad, A. Greco, R.Z. Hill, C. Nickels, E. Raudzens, E. Reed, M. Rosenberg, M. Ryder, A. Salas, S. Strutt, T. Trinh, and A. Warneke.

Funding for the SEAPLEX cruise was provided by University of California Ship Funds, Project Kaisei/Ocean Voyages Institute, AWIS-San Diego, and NSF IGERT Grant No. 0333444. EX1006 samples courtesy of the NOAA Okeanos

Explorer Program, 2010 Always Exploring expedition. EX1006 supplies and M.C.G.'s travel were provided by NOAA National Marine Fisheries Service. Laboratory supplies, support, and some analytical equipment were provided by the SIO Pelagic Invertebrate Collection and the California Current Ecosystem LTER site supported by NSF. M.C.G. was supported by California Department of Boating and Waterways (Contract 05-106-115), NSF GK-12 Grant No. 0841407 and donations from Jim & Kris McMillan, Jeffrey & Marcy Krinsk, Lyn & Norman Lear, Ellis Wyer, and an anonymous donor. A.J.T. was supported by the National Fish and Wildlife Foundation Marine Debris Programs (Grant 2007-0088-007).

Chapter 2 has been submitted to PLoS ONE and is presented as part of this dissertation with the acknowledgement of the study co- authors Andrew J. Titmus and Michael Ford. The dissertation author was the primary investigator and is the primary author of this material.

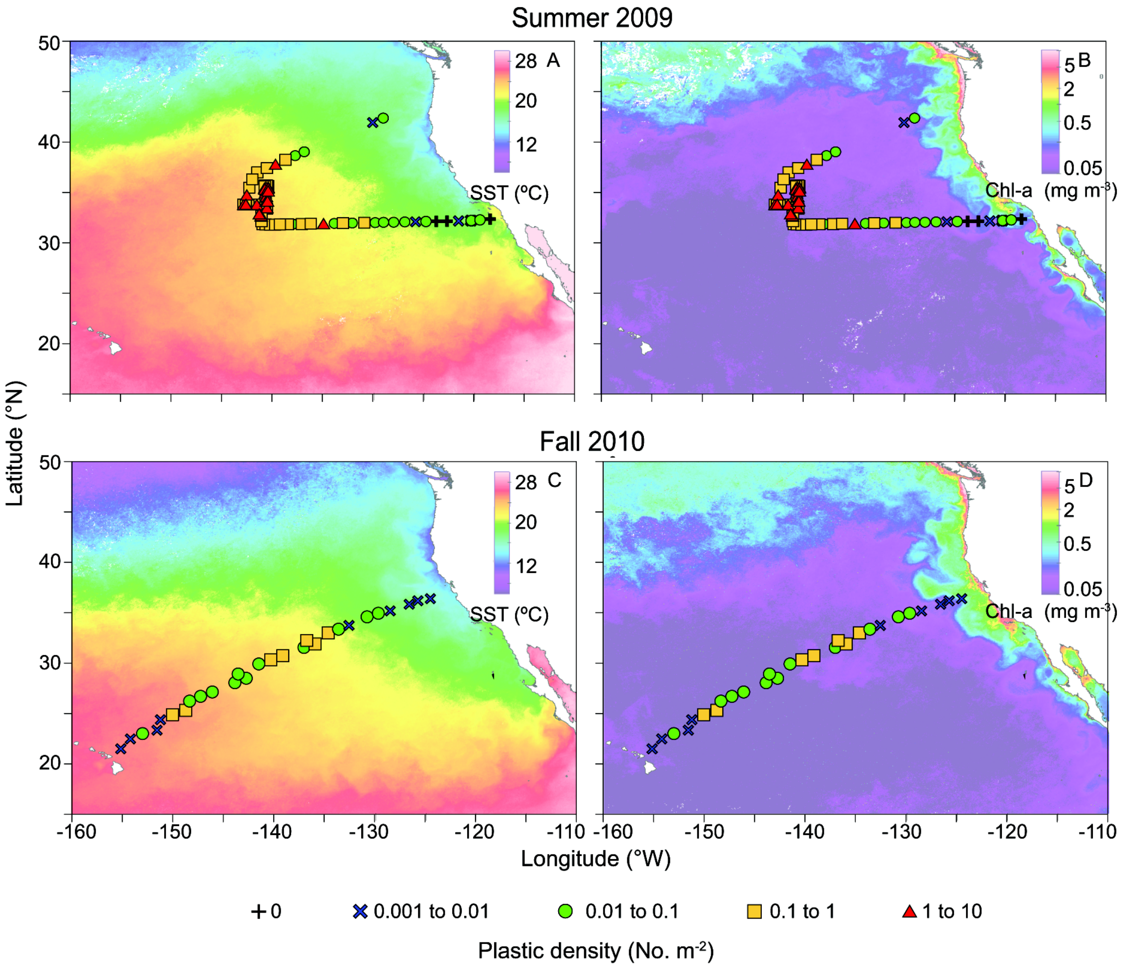


Figure 2.1. Microplastic numerical abundance superimposed on sea surface temperature and chlorophyll-*a*

Temperature maps are monthly composites of MODIS-Aqua and MODIS-Terra data, and chlorophyll-*a* maps are monthly composites of SeaWiFS Level-2 data. A) Microplastic numerical abundance and sea surface temperature in summer 2009; B) Microplastic numerical abundance and chorophyll-*a* in summer 2009; C) Microplastic numerical abundance and sea surface temperature in fall 2010; D) Microplastic numerical abundance and chlorophyll-*a* in fall 2010. White pixels denote no data due to cloud cover.

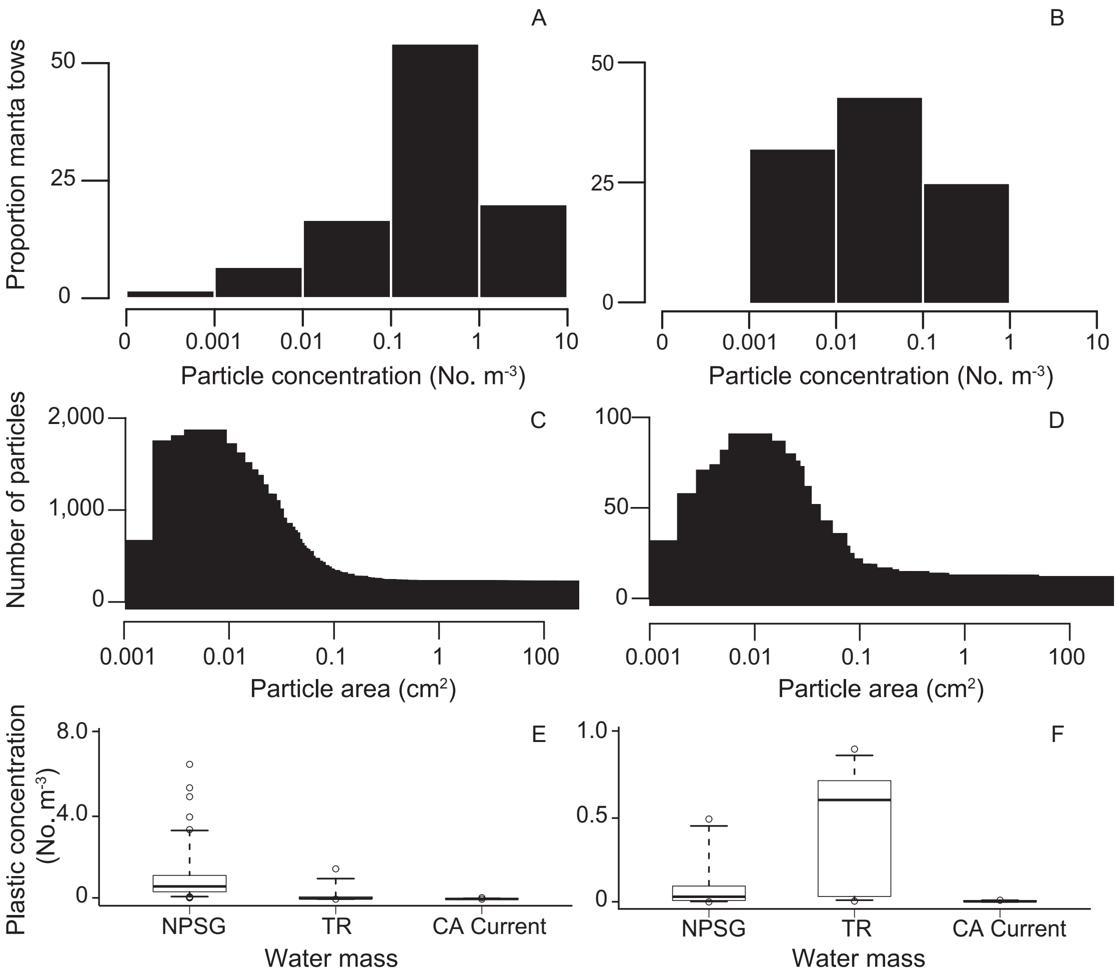


Figure 2.2. Microplastic numerical abundance and size spectra
Histogram of particle numerical abundance collected in manta tows in A) summer 2009 and B) fall 2010; histogram of particle cross-sectional areas in C) summer 2009 and D) fall 2010; and microplastic numerical abundance by water mass in E) summer 2009 and F) fall 2010. NPSG = North Pacific Subtropical Gyre, TR = transition region, CA Current = California Current. Box plot whiskers are 95% confidence intervals and open circles are outlying data points.

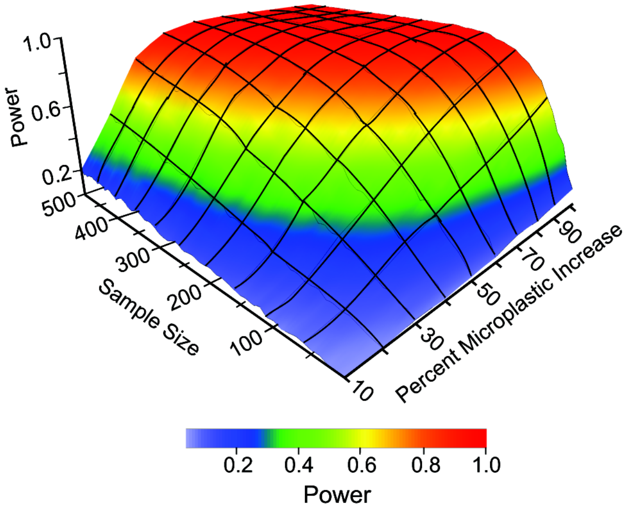


Figure 2.3. Power analysis of summer 2009 microplastic concentration
Power was calculated by multiplying the summer 2009 data (N = 119) by a factor of increase (e.g., 20%) and comparing the two data sets using Monte Carlo simulations (1000 simulations per test) of the Mann-Whitney U test.

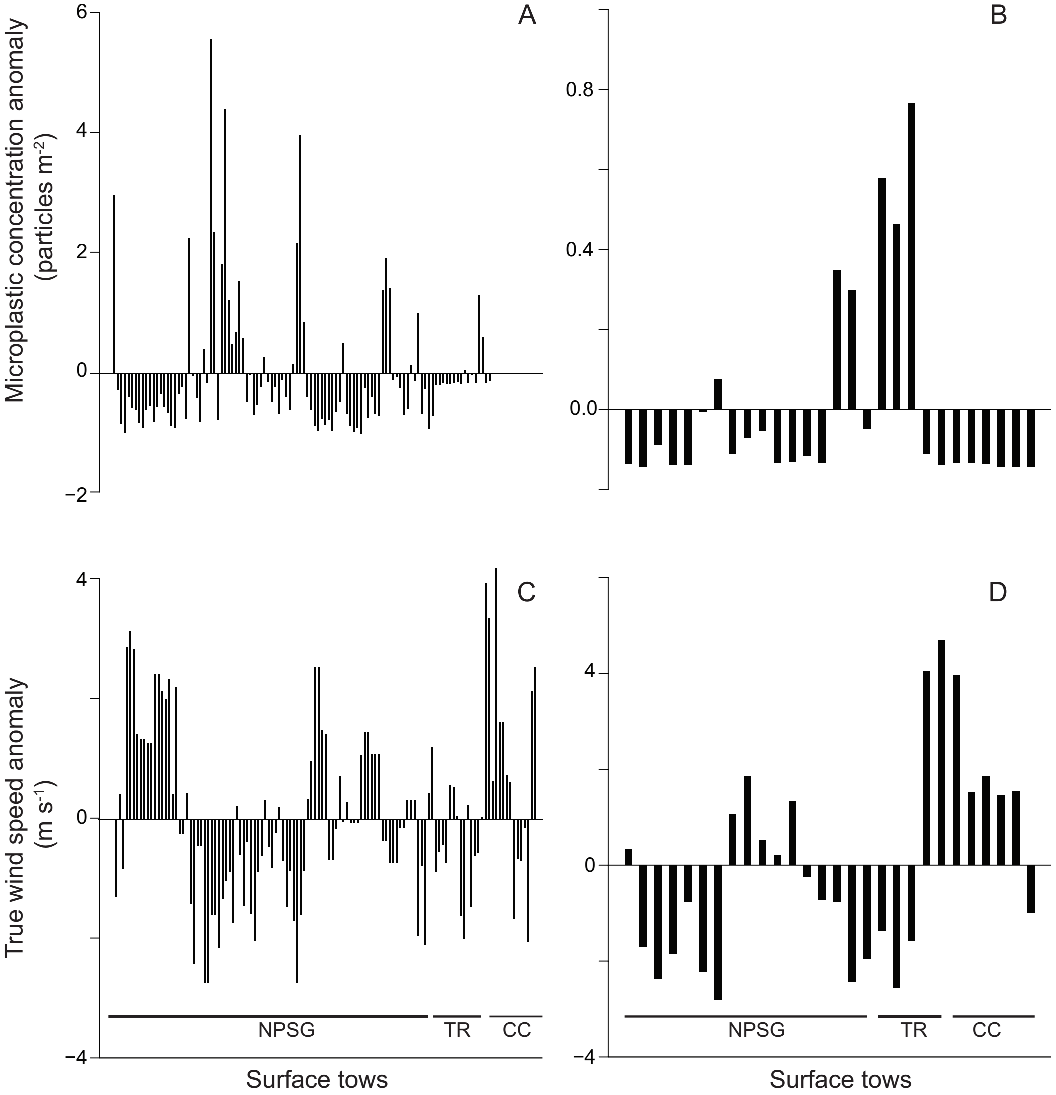


Figure 2.4. Particle anomaly and wind speed anomaly as a function of time
Particle anomalies during A) summer 2009 and B) fall 2010, and true wind speed anomalies during C) summer 2009 and D) fall 2010. Particle density was measured in surface manta net tows, and wind speed recorded during particle sampling. Sample sizes for summer 2009 is N = 119 and for fall 2010 N = 28. Abbreviations are North Pacific Subtropical Gyre (NPSG), transition region (TR), and California Current (CC).

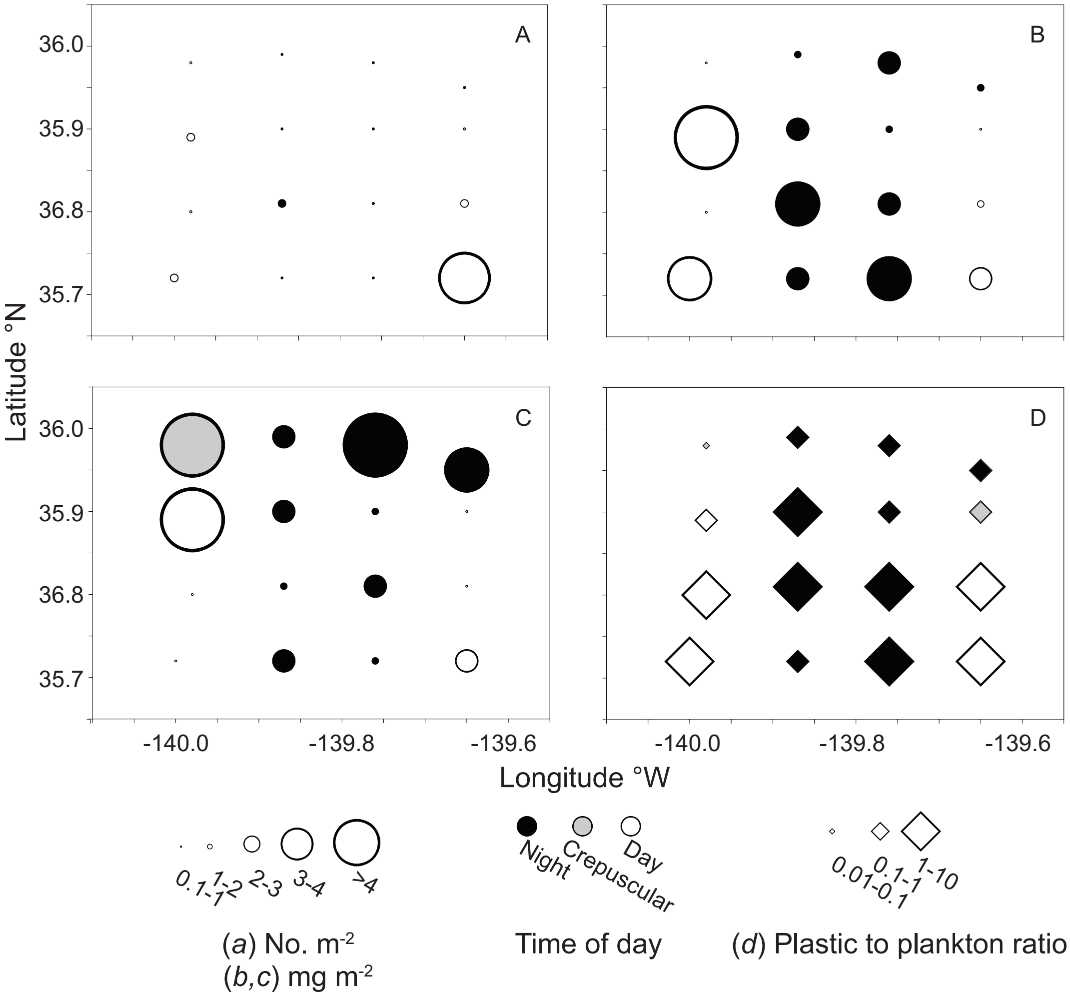


Figure 2.5. Submesoscale variation in microplastic, zooplankton, and plastic to plankton ratio

A) Microplastic numerical concentration (No. m^{-2}); B) Microplastic mass concentration (mg m^{-2}) ; C) Zooplankton biomass concentration (mg m^{-2}) ; D) Ratio of microplastic dry mass to zooplankton dry mass.

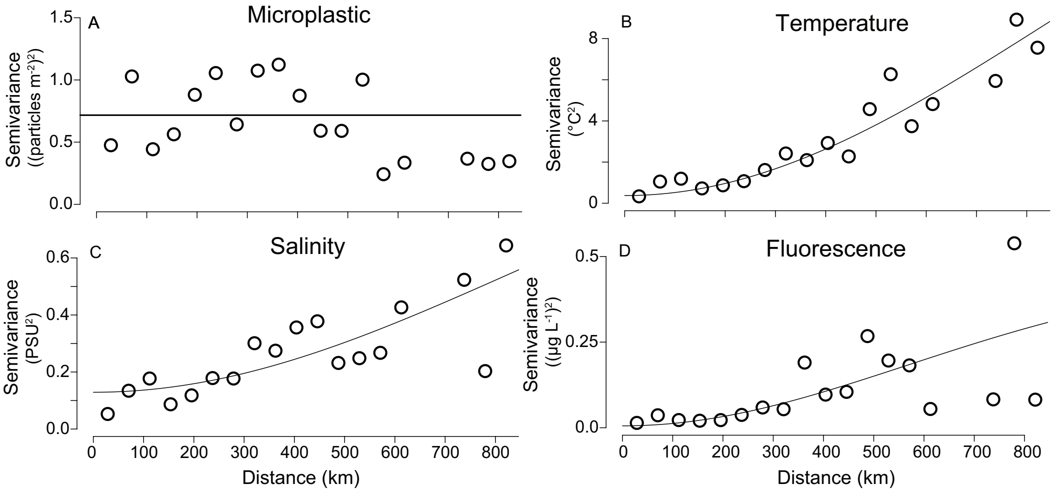


Figure 2.6. Scale-dependence of variance in microplastic concentration and surface biophysical variables

Dots are the values of the empirical semivariogram and the lines are a description of the data trends. A) Microplastic numerical concentration; B) sea surface temperature; C) sea surface salinity; C) sea surface fluorescence. Data are shown for summer 2009 only.

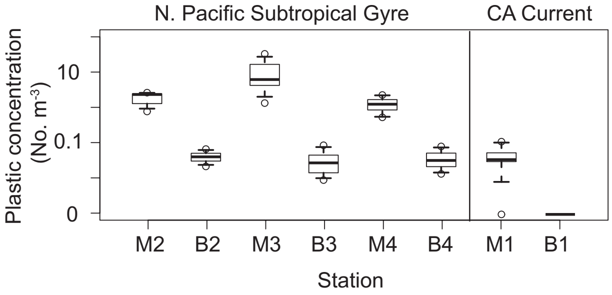


Figure 2.7. Numerical concentrations of microplastic from neuston samples and sub-surface samples
M indicates manta tows, B indicates bongo tows, and the number refers to the station. Sample sizes are N = 9 (manta tows) and N = 6 (bongo tows) for all groups.

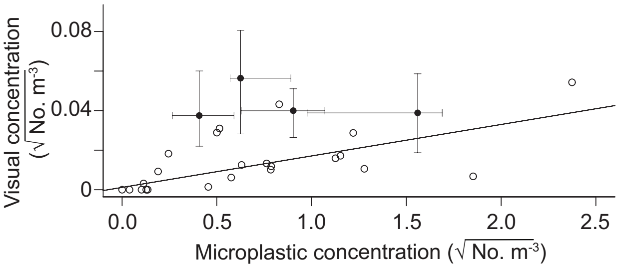


Figure 2.8. Comparison of plastic debris concentrations from visual and net tow data
Hollow circles indicate observations within 25 km of each other, and solid circles indicate stations with repeated samples taken within 10 km. Lines with solid circles are 95% confidence intervals. Regression line fit using Theil-Sen single median method.

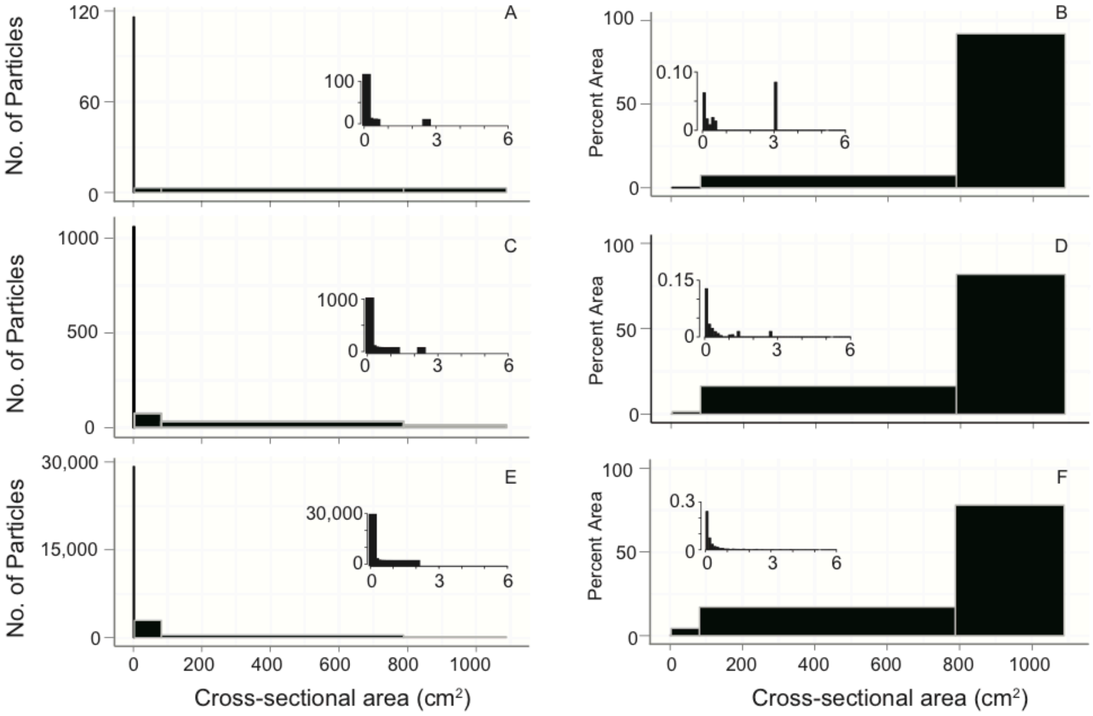


Figure 2.9. Numerical abundance and percent cross-sectional area of plastic debris by size and water mass

Insets are an enlargement of the left side of x-axis from 0 to 6 cm^2. Numerical abundance of plastic debris by debris size in the A) California Current; C) transition region; and E) NPSG. Percentage total debris area by debris size in the B) California Current; D) transition region; and F) NPSG. N = 34,233.

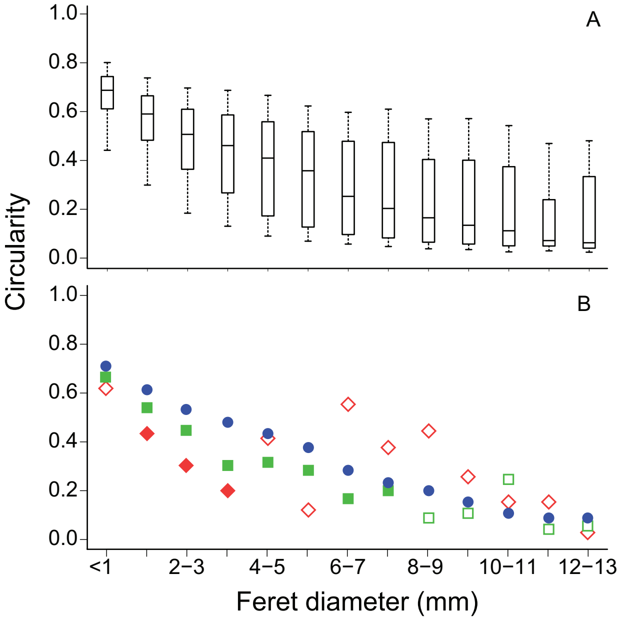


Figure 2.10. Circularity vs. feret diameter in microplastic particles
A) All particles collected in summer 2009 and fall 2010. Lines indicate 95% confidence intervals and open circles are outlying data points. B) Median particle circularity by water mass. Red diamonds = California Current, green squares = transition region, and blue circles = NPSG. Unfilled symbols indicate N < 10.

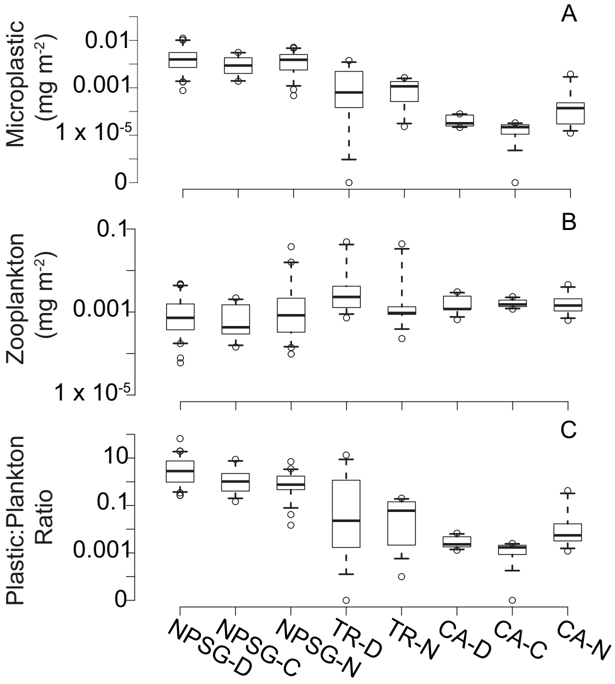


Figure 2.11. Plastic to plankton ratios by water mass and time of day
A) Dry mass of microplastic; B) Dry biomass zooplankton; C) Plastic to plankton ratios. Dry masses are given in mg m^{-2}. Water mass abbreviations are North Pacific Subtropical Gyre (NPSG), transition region (TR), and California Current (CC). Time of day is abbreviated to D = day, C = crepuscular, and N = night. Only data from summer 2009 data are shown. Sample sizes are as follows: NPSG-D = 48, NPSG-C = 12, NPSG-N = 30, TR-D = 9, TR-N = 6, CC-D = 5, CC-C = 3, CC-N = 6.

Table 2.1. Microplastic numerical concentration (particles m^{-2}) in summer 2009 and fall 2010

Summer 2009 N = 119, fall 2010 N = 28.

	Median	**5th-95th percentile**	**Maximum**
Summer 2009	0.448	0.007-3.211	6.553
Fall 2010	0.021	0.002-0.682	0.910

Table 2.2. Microplastic numerical concentration by water mass in summer 2009 and fall 2010

Median values, the 5th and 95th percentiles of the data, and the maximum data value are given for the California Current (CC), transition region (TR), and North Pacific Subtropical Gyre (NPSG). N values are summer/fall. P-values are given for two-tailed Mann-Whitney tests.

Water mass	Summer 2009 median (5-95 CI; maximum)	Fall 2010 median (5-95 CI; maximum)	N	p-value
CC	0.009 (0.001-0.041; 0.072)	0.005 (0.002-0.012; 0.012)	14/6	0.187
TR	0.033 (0.003-0.999; 1.473)	0.608 (0.012-0.873; 0.910)	15/5	0.306
NPSG	0.619 (0.126-3.339; 6.553)	0.032 (0.004-0.453; 0.494)	90/17	<0.001

Table 2.3. P-values showing statistical differences in plastic abundance between water masses

Test used was a Nemenyi-Damico-Wolfe-Dunn test. Alpha values are pairwise comparisons. NPSG = North Pacific Subtropical Gyre, TR = transition region, CA Current = California Current.

	CC	**NPSG**
Summer 2009 NPSG	<0.0001	-
Summer 2009 TR	0.443	<0.0001
Fall 2010 NPSG	0.202	-
Fall 2010 TR	0.005	0.862

Table 2.4. Numerical concentrations of plastic debris from visual observations and net tows
Macrodebris concentrations from the visual observer were not statistically different among stations (Kruskal-Wallis test $p > 0.05$). Microdebris concentration from the net tows were statistically different among stations (Kruskal-Wallis test $p = 0.002$), which was caused by the difference between station 1 and 3 (Nemenyi-Damico-Wolfe-Dunn test, $p < 0.001$). Microplastic concentrations between the other net tow stations were not significantly different (Nemenyi-Damico-Wolfe-Dunn test, $p > 0.05$).

Station	**Mean numerical concentration of debris (No. m^{-2}), followed by coefficient of variation**	
	Visual observer (macrodebris)	**Net tow (microdebris)**
1	0.002 (73.9)	0.181 (70.0)
2	0.003 (62.8)	0.511 (43.6)
3	0.002 (63.7)	1.957 (47.2)
4	0.002 (64.9)	0.758 (44.6)

Table 2.5. Plastic abundance in surface (0-0.2 m) vs. subsurface (0-210 m) tows One station was in the California Current (CC) and the other three in the NPSG. P-values are given for two-tailed Mann-Whitney U tests.

Water mass and station	Median surface concentration (particles m^{-3})	Median subsurface concentration (particles m^{-3})	p-value
CC – Station 1	0.036	0.000	0.002
NPSG – Station 2	2.314	0.040	0.001
NPSG – Station 3	6.146	0.027	0.001
NPSG – Station 4	1.227	0.031	0.001

References

Andrady, A. L. 2011. Microplastics in the marine environment. Marine Pollution Bulletin 62:1596–1605. doi: 10.1016/j.marpolbul.2011.05.030.

Arthur, C., J. Baker, and Bamford, H. (Eds.). 2008. Proceedings of the International Research Workshop on the Occurrence, Effects, and Fate of Microplastic Marine Debris. United States Dept of Commerce.

Barnes, D. K. A. 2002. Invasions by marine life on plastic debris. Nature 416:808–809. doi: 10.1038/416808a.

Barnes, D. K. A. 2005. Remote islands reveal rapid rise of southern hemisphere sea debris. The Scientific World Journal 5:915–921. doi: 10.1100/tsw.2005.120.

Barnes, D. K. A., F. Galgani, R. C. Thompson, and M. Barlaz. 2009. Accumulation and fragmentation of plastic debris in global environments. Philosophical Transactions of the Royal Society of London B 364:1985–1998. doi: 10.1098/rstb.2008.0205.

Barnes, D. K. A., and P. Milner. 2005. Drifting plastic and its consequences for sessile organism dispersal in the Atlantic Ocean. Marine Biology 146:815–825. doi: 10.1007/s00227-004-1474-8.

Beers, J. R. 1966. Studies on the chemical composition of the major zooplankton groups in the Sargasso Sea off Bermuda. Limnology and Oceanography 11:520–528.

Boerger, C. M., G. L. Lattin, S. L. Moore, and C. J. Moore. 2010. Plastic ingestion by planktivorous fishes in the North Pacific Central Gyre. Marine Pollution Bulletin 60:2275–2278. doi: 10.1016/j.marpolbul.2010.08.007.

Brown, D. M., and L. Cheng. 1981. New net for sampling the ocean surface. Marine Ecology Progress Series 5:225–227. doi: 10.3354/meps005225.

Browne, M. A., P. Crump, S. J. Niven, E. Teuten, A. Tonkin, T. Galloway, and R. Thompson. 2011. Accumulation of microplastic on shorelines woldwide: sources and sinks. Environmental Science & Technology 45:9175–9179. doi: 10.1021/es201811s.

Browne, M. A., A. Dissanayake, T. S. Galloway, D. M. Lowe, and R. C. Thompson. 2008. Ingested microscopic plastic translocates to the circulatory system of the mussel, Mytilus edulis (L). Environmental Science & Technology 42:5026–31. doi: 10.1021/es800249a.

Browne, M. A., T. S. Galloway, and R. C. Thompson. 2010. Spatial patterns of plastic debris along estuarine shorelines. Environmental Science & Technology 44:3404–3409. doi: 10.1021/es903784e.

Bugoni, L., L. Krause, and M. V. Petry. 2001. Marine debris and human impacts on sea turtles in southern Brazil. Marine Pollution Bulletin 42:1330–1334. doi: 10.1016/S0025-326X(01)00147-3.

Carpenter, E. J., and K. L. Smith. 1972. Plastics on the Sargasso Sea surface. Science 175:1240. doi: 10.1126/science.175.4027.1240.

Cole, M., P. Lindeque, C. Halsband, and T. S. Galloway. 2011. Microplastics as contaminants in the marine environment: A review. Marine Pollution Bulletin 62:2588–2597. doi: 10.1016/j.marpolbul.2011.09.025.

Collignon, A., J.-H. Hecq, F. Glagani, P. Voisin, F. Collard, and A. Goffart. 2012. Neustonic microplastic and zooplankton in the North Western Mediterranean Sea. Marine Pollution Bulletin 64:861–864. doi: 10.1016/j.marpolbul.2012.01.011.

Colton, J. B., F. D. Knapp, and B. R. Burns. 1974. Plastic particles in surface waters of the northwestern Atlantic. Science 185:491–497. doi: 10.1126/science.185.4150.491.

Cressie, N., and D. Hawkins. 1980. Robust estimation of the variogram: I. Mathematical Geology 12:115–125. doi: 10.1007/BF01035243.

Davison, P., and R. G. Asch. 2011. Plastic ingestion by mesopelagic fishes in the North Pacific Subtropical Gyre. Marine Ecology Progress Series 432:173–180. doi: 10.3354/meps09142.

Day, R. H., and D. G. Shaw. 1987. Patterns in the abundance of pelagic plastic and tar in the north Pacific Ocean, 1976-1985. Marine Pollution Bulletin 18:311–316. doi: 10.1016/S0025-326X(87)80017-6.

Day, R. H., D. G. Shaw, and S. E. Ignell. 1990. The quantitative distribution and characteristics of neuston plastic in the North Pacific Ocean, 1984-1988. Pages 247–266 Proceedings of the Second International Conference on Marine Debris, April 2-7, 1989, Honolulu, Hawaii. U. S. Department of Commerce, NOAA Technical Memorandum, NMFS, NOAA-TM-NMFS-SWFC-154.

Derraik, J. G. B. 2002. The pollution of the marine environment by plastic debris: a review. Marine Pollution Bulletin 44:842–852. doi: 10.1016/S0025-326X(02)00220-5.

Doney, S. C., D. M. Glover, S. J. McCue, and M. Fuentes. 2003. Mesoscale variability of Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite ocean color:

global patterns and spatial scales. Journal of Geophysical Research 108:3024. doi: 200310.1029/2001JC000843.

Donohue, M. J., R. C. Boland, C. M. Sramek, and G. A. Antonelis. 2001. Derelict fishing gear in the northwestern Hawaiian Islands: diving surveys and debris removal in 1999 confirm threat to coral reef ecosystems. Marine Pollution Bulletin 42:1301–1312. doi: 10.1016/S0025-326X(01)00139-4.

Doyle, M. J., W. Watson, N. M. Bowlin, and S. B. Sheavly. 2011. Plastic particles in coastal pelagic ecosystems of the Northeast Pacific ocean. Marine Environmental Research 71:41–52. doi: 10.1016/j.marenvres.2010.10.001.

Fisch, G. 2010. Comparisons between aerovane and sonic anemometer wind measurements at Alcantara Launch Center. Journal of Aerospace Technology and Management 2:105–110. doi: DOI: 10.5028/jatm.2010.0201105110.

Galgani, F., S. Jaunet, A. Campillo, X. Guenegen, and E. His. 1995. Distribution and abundance of debris on the continental shelf of the North-Western Mediterranean Sea. Marine Pollution Bulletin 30:713–717.

Gilfillan, L. R., M. D. Ohman, M. J. Doyle, and W. Watson. 2009. Occurrence of plastic micro-debris in the southern California Current system. CalCOFI Report 50:123–133.

Goldstein, M. C., M. Rosenberg, and L. Cheng. 2012. Increased oceanic microplastic debris enhances oviposition in an endemic pelagic insect. Biology Letters 8:817–820. doi: 10.1098/rsbl.2012.0298.

Gorsky, G., M. D. Ohman, M. Picheral, S. Gasparini, L. Stemmann, J.-B. Romagnan, A. Cawood, S. Pesant, C. Garcia-Comas, and F. Prejger. 2010. Digital zooplankton image analysis using the ZooScan integrated system. Journal of Plankton Research 32:285–303. doi: 10.1093/plankt/fbp124.

Graham, E. R., and J. T. Thompson. 2009. Deposit- and suspension-feeding sea cucumbers (Echinodermata) ingest plastic fragments. Journal of Experimental Marine Biology and Ecology 368:22–29. doi: 10.1016/j.jembe.2008.09.007.

Gregory, M. R. 2009. Environmental implications of plastic debris in marine settings-entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. Philosophical Transactions of the Royal Society B 364:2013–2025. doi: 10.1098/rstb.2008.0265.

Hothorn, T., K. Hornik, M. A. van de Wiel, and A. Zeileis. 2008. Implementing a class of permutation tests: the coin package. Journal of Statistical Software 28:1–23.

Howell, E. A., S. J. Bograd, C. Morishige, M. P. Seki, and J. J. Polovina. 2012. On North Pacific circulation and associated marine debris concentration. Marine Pollution Bulletin 65:16–22. doi: 10.1016/j.marpolbul.2011.04.034.

Ivar do Sul, J. A., A. Spengler, and M. F. Costa. 2009. Here, there and everywhere. Small plastic fragments and pellets on beaches of Fernando de Noronha (Equatorial Western Atlantic). Marine Pollution Bulletin 58:1236–1238. doi: 10.1016/j.marpolbul.2009.05.004.

Jacobsen, J. K., L. Massey, and F. Gulland. 2010. Fatal ingestion of floating net debris by two sperm whales (Physeter macrocephalus). Marine Pollution Bulletin 60:765–767. doi: 10.1016/j.marpolbul.2010.03.008.

Kahru, M. 2011, April 5. Full-resolution satellite time series of the California Current area. Retrieved March 14, 2012, from http://spg.ucsd.edu/Satellite_Projects/CAL/.

Kaluzny, S. P., S. C. Vega, T. P. Cardoso, and A. A. Shelly. 1998. S+ Spatial Stats. Springer, New York.

Karl, D. M. 1999. A sea of change: Biogeochemical variability in the North Pacific Subtropical Gyre. Ecosystems 2:181–214. doi: 10.1007/s100219900068.

Kramer, D., M. J. Kalin, E. G. Stevens, J. R. Thrallkill, and J. R. Zweifel. 1972. Collecting and processing data on fish eggs and larvae in the California Current region. U.S. Department of Commerce, NOAA Technical Report NMFS Circular 370:1–38.

Kukulka, T., G. Proskurowski, S. Morét-Ferguson, D. W. Meyer, and K. L. Law. 2012. The effect of wind mixing on the vertical distribution of buoyant plastic debris. Geophysical Research Letters 39:6 pp. doi: 201210.1029/2012GL051116.

Laist, D. 1997. Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. Pages 99–140 *in* J. Coe and D. Rogers, editors. Marine debris: sources, impact and solutions. Springer, New York.

Lattin, G. L., C. J. Moore, A. F. Zellers, S. L. Moore, and S. B. Weisberg. 2004. A comparison of neustonic plastic and zooplankton at different depths near the southern California shore. Marine Pollution Bulletin 49:291–294. doi: 10.1016/j.marpolbul.2004.01.020.

Law, K. L., S. Moret-Ferguson, N. A. Maximenko, G. Proskurowski, E. E. Peacock, J. Hafner, and C. M. Reddy. 2010. Plastic accumulation in the North Atlantic Subtropical Gyre. Science 329:1185–1188. doi: 10.1126/science.1192321.

Lobelle, D., and M. Cunliffe. 2011. Early microbial biofilm formation on marine plastic debris. Marine Pollution Bulletin 62:197–200. doi: 10.1016/j.marpolbul.2010.10.013.

Lynn, R. J., and J. J. Simpson. 1987. The California Current system: the seasonal variability of its physical characteristics. Journal of Geophysical Research 92:12,947–12,966. doi: 198710.1029/JC092iC12p12947.

Martinez, E., K. Maamaatuaiahutapu, and V. Taillandier. 2009. Floating marine debris surface drift: convergence and accumulation toward the South Pacific subtropical gyre. Marine Pollution Bulletin 58:1347–1355. doi: 10.1016/j.marpolbul.2009.04.022.

Mato, Y., T. Isobe, H. Takada, H. Kanehiro, C. Ohtake, and T. Kaminuma. 2001. Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. Environmental Science & Technology 35:318–324.

Matsumura, S., and K. Nasu. 1997. Distribution of floating debris in the North Pacific Ocean: sighting surveys 1986-1991. Pages 15–24 *in* J. Coe and D. Rogers, editors. Marine debris: sources, impact and solutions. Springer, New York.

Maximenko, N., J. Hafner, and P. Niiler. 2012. Pathways of marine debris derived from trajectories of Lagrangian drifters. Marine Pollution Bulletin 65:51–62. doi: 10.1016/j.marpolbul.2011.04.016.

Moore, C. J., S. L. Moore, M. K. Leecaster, and S. B. Weisberg. 2001. A comparison of plastic and plankton in the North Pacific central gyre. Marine Pollution Bulletin 42:1297–1300. doi: 10.1016/S0025-326X(01)00114-X.

Moore, C. J., S. L. Moore, S. B. Weisberg, G. L. Lattin, and A. F. Zellers. 2002. A comparison of neustonic plastic and zooplankton abundance in southern California’s coastal waters. Marine Pollution Bulletin 44:1035–1038. doi: 10.1016/S0025-326X(02)00150-9.

Moret-Ferguson, S., K. L. Law, G. Proskurowski, E. K. Murphy, E. E. Peacock, and C. M. Reddy. 2010. The size, mass, and composition of plastic debris in the western North Atlantic Ocean. Marine Pollution Bulletin 60:1873–1878. doi: 10.1016/j.marpolbul.2010.07.020.

Morishige, C., M. J. Donohue, E. Flint, C. Swenson, and C. Woolaway. 2007. Factors affecting marine debris deposition at French Frigate Shoals, Northwestern Hawaiian Islands Marine National Monument, 1990-2006. Marine Pollution Bulletin 54:1162–1169. doi: 10.1016/j.marpolbul.2007.04.014.

Moser, M. L., and D. S. Lee. 1992. A fourteen-year survey of plastic ingestion by western North Atlantic seabirds. Colonial Waterbirds 15:83–94. doi: 10.2307/1521357.

Mumby, P. J. 2002. Statistical power of non-parametric tests: A quick guide for designing sampling strategies. Marine Pollution Bulletin 44:85–87. doi: 10.1016/S0025-326X(01)00097-2.

Murray, F., and P. R. Cowie. 2011. Plastic contamination in the decapod crustacean Nephrops norvegicus (Linnaeus, 1758). Marine Pollution Bulletin 62:1207–1217. doi: 10.1016/j.marpolbul.2011.03.032.

National Research Council. 2009. Tackling Marine Debris in the 21st Century. National Academies Press, Washington DC. Retrieved from http://www.nap.edu/catalog/12486.html.

Niiler, P. P., and R. W. Reynolds. 1984. The three-dimensional circulation near the eastern North Pacific subtropical front. Journal of Physical Oceanography 14:217–230. doi: 10.1175/1520-0485(1984)014<0217:TTDCNT>2.0.CO;2.

Omori, M. 1978. Some factors affecting on dry weight, organic weight and concentrations of carbon and nitrogen in freshly prepared and in preserved zooplankton. Internationale Revue der gesamten Hydrobiologie und Hydrographie 63:261–269. doi: 10.1002/iroh.19780630211.

Omori, M., and T. Ikeda. 1984. Methods in Marine Zooplankton Ecology. Wiley-Interscience, New York.

Pichel, W. G., J. H. Churnside, T. S. Veenstra, D. G. Foley, K. S. Friedman, R. E. Brainard, J. B. Nicoll, Q. Zheng, and P. Clemente-Colon. 2007. Marine debris collects within the North Pacific Subtropical Convergence Zone. Marine Pollution Bulletin 54:1207–1211. doi: 10.1016/j.marpolbul.2007.04.010.

Possatto, F. E., M. Barletta, M. F. Costa, J. A. Ivar do Sul, and D. V. Dantas. 2011. Plastic debris ingestion by marine catfish: An unexpected fisheries impact. Marine Pollution Bulletin 62:1098–1102. doi: 10.1016/j.marpolbul.2011.01.036.

R Development Core Team. 2011. R: A language and environment for statistical computing. Vienna, Austria. Retrieved from http://www.r-project.org.

Ribeiro, P. J., and P. J. Diggle. 2001. geoR: a package for geostatistical analysis. R-NEWS 1:15–18.

Ribic, C. A., S. B. Sheavly, D. J. Rugg, and E. S. Erdmann. 2010. Trends and drivers of marine debris on the Atlantic coast of the United States 1997–2007. Marine Pollution Bulletin 60:1231–1242. doi: 10.1016/j.marpolbul.2010.03.021.

Ribic, C. A., S. B. Sheavly, D. J. Rugg, and E. S. Erdmann. 2012. Trends in marine debris along the U.S. Pacific Coast and Hawai'i 1998–2007. Marine Pollution Bulletin 64:994–1004. doi: 10.1016/j.marpolbul.2012.02.008.

Rios, L., P. Jones, C. Moore, and U. Narayan. 2010. Quantitation of persistent organic pollutants adsorbed on plastic debris from the Northern Pacific Gyre's "eastern garbage patch". Journal of Environmental Monitoring 12:2226–2236. doi: 10.1039/c0em00239a.

Robards, M. D., P. Gould, and J. Platt. 1997. The highest global concentrations and increased abundance of oceanic plastic debris in the North Pacific: evidence from seabirds. Pages 71–80 *in* J. Coe and D. Rogers, editors. Marine debris: sources, impact and solutions. Springer, New York.

Roden, G. I. 1980. On the subtropical frontal zone north of Hawaii during winter. Journal of Physical Oceanography 10:342–362. doi: 10.1175/1520-0485(1980)010<0342:OTSFZN>2.0.CO;2.

Roden, G. I. 1991. Subarctic-subtropical transition zone of the North Pacific: large-scale aspects and mesoscale structure. Pages 1–38 Biology, Oceanography, and Fisheries of the North Pacific Transition Zone and Subarctic Frontal Zone.

Ryan, P. G., C. J. Moore, J. A. van Franeker, and C. L. Moloney. 2009. Monitoring the abundance of plastic debris in the marine environment. Philosophical Transactions of the Royal Society B 364:1999–2012. doi: 10.1098/rstb.2008.0207.

Shaw, D. G., and R. H. Day. 1994. Colour- and form-dependent loss of plastic micro-debris from the North Pacific Ocean. Marine Pollution Bulletin 28:39–43.

Smith, S. R., M. A. Bourassa, and R. J. Sharp. 1999. Establishing More Truth in True Winds. Journal of Atmospheric and Oceanic Technology 16:939–952. doi: 10.1175/1520-0426(1999)016<0939:EMTITW>2.0.CO;2.

Spear, L. B., D. G. Ainley, and C. A. Ribic. 1995. Incidence of plastic in seabirds from the tropical pacific, 1984-1991: Relation with distribution of species, sex, age, season, year and body weight. Marine Environmental Research 40:123–146. doi: 10.1016/0141-1136(94)00140-K.

STAP. 2011. Marine Debris as a Global Environmental Problem: Introducing a solutions based framework focused on plastic. Page 28. STAP Information Document, Scientific and Technical Advisory Panel, Global Environment Facility, Washington DC. Retrieved from http://www.unep.org/stap/Portals/61/pubs/STAP%20MarineDebris%20-%20website.pdf.

Stevenson, C. 2011. Plastic Debris in the California Marine Ecosystem: A Summary of Current Research, Solution Strategies and Data Gaps. Page 82. California Ocean Science Trust. Retrieved from http://calost.org/science-initiatives/?page=marine-debris.

Teuten, E. L., J. M. Saquing, D. R. U. Knappe, M. A. Barlaz, S. Jonsson, A. Bjorn, S. J. Rowland, R. C. Thompson, T. S. Galloway, R. Yamashita, D. Ochi, Y. Watanuki, C. Moore, V. Pham Hung, T. S. Tana, M. Prudente, R. Boonyatumanond, M. P. Zakaria, K. Akkhavong, Y. Ogata, H. Hirai, S. Iwasa, K. Mizukawa, Y. Hagino, A. Imamura, M. Saha, and H. Takada. 2009. Transport and release of chemicals from plastics to the environment and to wildlife. Philosophical Transactions of the Royal Society of London B 364:2027–2045. doi: 10.1098/rstb.2008.0284.

Thiel, M., I. Hinojosa, N. Vásquez, and E. Macaya. 2003. Floating marine debris in coastal waters of the SE-Pacific (Chile). Marine Pollution Bulletin 46:224–231. doi: 10.1016/S0025-326X(02)00365-X.

Thompson, R. C., Y. Olsen, R. P. Mitchell, A. Davis, S. J. Rowland, A. W. G. John, D. McGonigle, and A. E. Russell. 2004. Lost at sea: Where is all the plastic? Science 304:838. doi: 10.1126/science.1094559.

Titmus, A. J., and K. D. Hyrenbach. 2011. Habitat associations of floating debris and marine birds in the North East Pacific Ocean at coarse and meso spatial scales. Marine Pollution Bulletin 62:2496–2506. doi: 10.1016/j.marpolbul.2011.08.007.

Uneputty, P., and S. M. Evans. 1997. The impact of plastic debris on the biota of tidal flats in Ambon Bay (eastern Indonesia). Marine Environmental Research 44:233–242. doi: 10.1016/S0141-1136(97)00002-0.

Venrick, E. L., T. W. Backman, W. C. Bartram, C. J. Platt, M. S. Thornhill, and R. E. Yates. 1973. Man-made objects on the surface of the central North Pacific ocean. Nature 241:271–271. doi: 10.1038/241271a0.

Watters, D. L., M. M. Yoklavich, M. S. Love, and D. M. Schroeder. 2010. Assessing marine debris in deep seafloor habitats off California. Marine Pollution Bulletin 60:131–138. doi: 10.1016/j.marpolbul.2009.08.019.

Wei, C.-L., G. T. Rowe, C. C. Nunnally, and M. K. Wicksten. 2012. Anthropogenic “litter” and macrophyte detritus in the deep Northern Gulf of Mexico. Marine Pollution Bulletin 64:966–973. doi: 10.1016/j.marpolbul.2012.02.015.

Winston, J. E., M. R. Gregory, and L. Stevens. 1997. Encrusters, epibionts, and other biota associated with pelagic plastics: a review of biological, environmental, and conservation issues. Pages 81–98 *in* J. M. Coe and D. B. Rogers, editors. Marine debris: sources, impact and solutions. Springer, New York.

Wong, C. S., D. R. Green, and W. J. Cretney. 1974. Quantitative tar and plastic waste distributions in Pacific Ocean. Nature 247:30–32. doi: doi:10.1038/247030a0.

Wurpel, G., Van den Akker, J., Pors, J., and Ten Wolde, A. 2011. Plastics do not belong in the ocean: towards a roadmap for a clean North Sea. Page 104. IMSA Amsterdam. Retrieved from http://www.plasticmarinelitter.eu/media/publications.

Yamashita, R., and A. Tanimura. 2007. Floating plastic in the Kuroshio Current area, western North Pacific Ocean. Marine Pollution Bulletin 54:485–488.

Yoder, J. A., C. R. McClain, Jackson O. Blanton, and L.-Y. Oey. 1987. Spatial scales in CZCS-chlorophyll imagery of the southeastern U. S. continental shelf. Limnology and Oceanography 32:929–941. doi: 10.4319/lo.1987.32.4.0929.

Young, L. C., C. Vanderlip, D. C. Duffy, V. Afanasyev, and S. A. Shaffer. 2009. Bringing home the trash: do colony-based differences in foraging distribution lead to increased plastic ingestion in Laysan albatrosses? PLoS One 4:Article No.: e7623. doi: 10.1371/journal.pone.0007623.

CHAPTER 3: Composition and weathering of oceanic microplastic

Abstract

Small plastic particles a few millimeters in diameter, termed “microplastic,” comprise the vast numerical majority of debris in the ocean. However, there is currently no method for estimating how long a given object or microplastic particle has resided in the ocean, which is critical to assessing the efficacy of plastic pollution mitigation programs. This study compared microplastics naturally weathered in the ocean with microplastics degraded under known experimental conditions, using Fourier-transform infrared spectroscopy to assess plastic type and weathering-related chemical changes. Composition of oceanic microplastic varied with location, with a greater proportion of polypropylene (PP) found in the California Current and a greater proportion of polyethylene, particularly high-density polyethylene (HDPE), found offshore in the North Pacific Subtropical Gyre. Low-density polyethylene (LDPE) and HDPE oceanic microplastic had higher carbonyl indices than any of the experimentally weathered microplastic. PP oceanic microplastic had higher carbonyl indices than sunlight/seawater experimentally weathered microplastic, but lower carbonyl indices than the sunlight-only experimentally weathered microplastic. These findings suggest that changes in microplastic composition over the eastern North Pacific may be explained by differential rates of weathering between plastic types, and

that carbonyl has the potential to be combined with other analyses in order to qualitatively estimate weathering time.

Introduction

Small plastic particles a few millimeters in diameter were discovered in the subtropical gyres in the early 1970s (Carpenter and Smith 1972, Wong et al. 1974), and have since been found on the surface waters of much of the world ocean (Morris 1980, Thompson et al. 2004, Gilfillan et al. 2009, Law et al. 2010). These particles, termed "microplastic," comprise the vast numerical majority of debris in the ocean, though the shape of the particle size distributions has differed between studies (Hidalgo-Ruz et al. 2012). Microplastic can either enter the ocean as small particles ("primary microplastics") or form from the breakdown of larger items ("secondary microplastics;" Cole et al. 2011). Primary microplastics include preproduction pellets (Ogata et al. 2009), microfibers from clothing (Browne et al. 2011), microspheres from facial cleansers (Fendall and Sewell 2009), and burrowing isopod damage to polystyrene floats (Davidson 2012). Secondary microplastics form from the photo-mechanical degradation of larger objects. When an object is exposed to UV light, free radicals are formed through the breaking of either carbon-carbon bonds (Norrish type I) or carbon-oxygen bonds (Norrish type II degradation; Albertsson et al. 1987). After contact with oxygen, these radicals form hydroperoxides and carbonyl groups (Albertsson et al. 1987). The repeated breaking of the polymer backbone causes flaking, cracking, and brittleness on the object surface (Cooper and Corcoran 2010). The surface layer is removed by mechanical forces such as waves or contact with the benthos, which releases secondary microplastic into the environment and exposes new areas of the original object to sunlight, starting the degradation process again (Gregory and Andrady 2003).

The most important process controlling the rate of secondary microplastic in the marine environment is heat (Andrady 2011). While plastics may degrade in less than 50 years in certain terrestrial environments (Kyrikou and Briassoulis 2007), this relatively rapid rate of degradation is unlikely to occur in the ocean, where plastic weathers more slowly due to a lack of thermal buildup and the blocking of UV light by biofouling organisms (Andrady 1989, 2011, O'Brine and Thompson 2010). For example, dry polyethylene exposed to sunlight for a year became brittle after only 6 months, while polyethylene in seawater did not become brittle after 12 months (Andrady 2003b).

Determining the residence time of plastic in the ocean is a significant challenge. Though plastic has been detected in the ocean for over forty years (Carpenter and Smith 1972, Venrick et al. 1973), the time in which a given particle has been in the ocean is difficult to determine. Anecdotal evidence, such as finding a 1980s-era action figure washed up on Midway Island, suggests that plastic may remain in the open ocean for a substantial period (Alt 2008). In 2009, a National Research Council report noted that "[u]nderstanding these lag processes is an important element in predicting the amount of time that may be required to detect changes in the quantity of debris introduced into the marine environment and thus the effectiveness of management measures intended to reduce debris discharges (National Research Council 2009).” While many studies have examined how plastic in the environment degrades, there is currently no method for estimating how long a given object or microplastic particle has circulated in the ocean.

In this study, I asked the following questions: a) What is the composition of pelagic microplastic in the northeast Pacific? b) Can the known weathering time of plastic particles under experimental conditions be used to estimate the unknown weathering time of plastic particles collected from the ocean?

Methods

Oceanic particles

In August 2009, samples were collected on the Scripps Environmental Accumulation of Plastic Expedition (SEAPLEX) cruise on the R/V *New Horizon* (Fig 3.1a). Samples were collected using a standard manta net (0.86 x 0.2 m; Brown and Cheng 1981) with 333 μm mesh, towed for 15 minutes at 0.7-1 m s^{-1}. Water volume flowing through the net was measured with a calibrated General Oceanics analog flowmeter. Samples were fixed in 1.8% formaldehyde buffered with sodium borate.

Each sample was sorted for microplastic at 6-12x magnification under a Wild M-5 dissecting microscope. Plastic particles were removed, dried at 60°C, and stored in glass vials. If there were fewer than 50 particles per sample, the entire sample was analyzed. If there were more than 50 particles per sample, the sample was split using the quartering method (ASTM Standard C702/C702M-11 2011) until an aliquot of 30-50 particles was obtained. The aliquot of particles was then soaked for 12 hours in

10% hydrochloric acid to remove calcium carbonate deposits, rinsed in deionized water, re-dried at 60°C, and stored in glass vials.

For the purposes of this analysis, the California Current was defined as having a surface temperature less than 19°C and surface salinity less than 33.5 psu (Lynn and Simpson 1987). The North Pacific Subtropical Gyre (NPSG) was defined as having surface temperatures greater than 22°C and salinity greater than 34.8 psu (Roden 1980, Niiler and Reynolds 1984). The intermediate region was defined as having a surface temperature of 19-22°C and surface salinity of 33.5-34.8 psu (Roden 1980, Lynn and Simpson 1987). Because only surface data were used, these water masses should be viewed as approximations rather than absolute oceanographic definitions (Goldstein et al. 2012b).

Weathering experiment

Beginning in December 2010, preproduction pellets of six common consumer thermoplastic resins (Andrady 2003a) were exposed to either sunlight, seawater, or combined sunlight and seawater. The resin types were as follows: polyethylene terephthalate (PET; Resin ID #1), high density polyethylene (HDPE; Resin ID #2), polyvinyl chloride (PVC; Resin ID #3), low density polyethylene (LDPE; Resin ID #4), polypropylene (PP; Resin ID #5), and polystyrene (PS; Resin ID #6).

For the sunlight treatment, 250 mL of each type of preproduction pellets (N=2) were placed in Pyrex glass trays on the roof of Hubbs Hall at the Scripps Institution of Oceanography, La Jolla, California (Fig 3.1b). Each tray was covered by fiberglass screening (2 mm mesh size) to prevent pellet loss.

For the seawater and sunlight/seawater treatments, 250 mL of each type of preproduction pellet were placed in 75.7 liter (20 gallon) “long” aquaria with flowing seawater (N=2 for each treatment; Fig 3.1c). To keep plastic types separate, aquarium divider screens were installed. Each plastic type was randomly assigned to a location in the tank. The plastic location assignments were repeated between treatments, so that one seawater and one sunlight/seawater tank utilized one set of plastic type locations, and the other seawater tank and sunlight/seawater tank utilized a second set of plastic type locations. Local seawater from the Scripps seawater system was continually added to each partition via a sprinkle bar set over the tank, and drained through a screen-covered stand pipe set into one end of the tank. The seawater-only treatment tanks were placed in an indoor experimental aquarium room and covered in opaque black plastic sheeting, which was only removed when the tanks were being sampled. The sunlight/seawater treatment tanks were placed on the same roof as the sunlight treatments, and the tops of the aquaria were covered with fiberglass screen to prevent pellet loss. All immersion treatments used natural seawater from the Scripps pier seawater intake, filtered through a sand filter.

The experiment was sampled monthly by removing ten pellets from each replicate. After removal, pellets were gently wiped to remove epiphytes, rinsed with deionized water, dried at 60°C for 24 hours, and stored in glass vials in the dark until FTIR analysis. Three time points were selected for analysis: T_0=unweathered particles, T_1=9 months, and T_2=18 months of weathering time. Only HDPE, LDPE and PP were analyzed for the experimental study.

Fourier-Transform Infrared Spectroscopy and weathering indices

Both ocean-collected samples and weathering experiment samples were analyzed using a Fourier-Transform Infrared Spectrometer with an attenuated total reflectance (ATR) diamond crystal attachment (Nicolet 6700 with Smart-iTR). All spectra were taken at 4 cm^{-1} resolution. The FTIR spectra for particles collected from the ocean were compared to both published standards (Forrest et al. 2007) and in-house standards for the 6 common consumer plastic types listed above (Fig 3.2a-c). LDPE was distinguished from HDPE by examining the peak at 1377 cm^{-1}, with the presence of a peak denoting LDPE (Fig 3.3a) and the absence denoting HDPE (Fig 3.3b; Lobo and Bonilla 2003). If polyethylene type could not be positively determined, the sample was classified as unknown PE, which occurred in 3.8% of polyethylene samples.

For weathering samples, 5 particles were randomly subsampled from the 10 particles collected at each time point. Depending on particle shape, either 2 or 3 spectra were obtained from different locations on each particle. No effect of location was discerned, so spectra were treated as independent.

Three likely areas of weathering-related change in infrared spectra were identified from the literature: carbonyl (1690-1810 cm^{-1}), hydroxyl (3100-3700 cm^{-1}), and carbon double bonds (1600-1680 cm^{-1}; Albertsson et al. 1987, Pavia et al. 2008, Rajakumar et al. 2009). An additional area of change in spectra, carbon-oxygen bonds, was located empirically (1000-1300 cm^{-1} ; Pavia et al. 2008).

Indices of carbonyl, hydroxyl, double bonds, and carbon-oxygen bonds were calculated as the maximum absorbance value for the peak to the value of a reference peak. Several different reference peaks have been used previously, including 974 cm^{-1} and 2720 cm^{-1} for PP (Livanova and Zaikov 1992, Rabello and White 1997, Rajakumar et al. 2009) and 1465 cm^{-1} and 2020 cm^{-1} for PE (Albertsson et al. 1987, Roy et al. 2011). I selected 1375 cm^{-1} for PE (Andrady et al. 1993b) and 2720 cm^{-1} for PP (Livanova and Zaikov 1992, Rabello and White 1997) because these peaks are thought to remain unchanged by weathering.

Indices were therefore calculated as the ratio of the maximum peak absorbance in the following area: carbonyl (LDPE/HDPE 1690-1810 cm^{-1} /1350-1400 cm^{-1}; PP 1690-1810 cm^{-1} /2700-2750 cm^{-1}), hydroxyl (LDPE/HDPE 3100-3700 cm^{-1}/1350-1400 cm^{-1}; PP 3100-3700 cm^{-1}/2700-2750 cm^{-1}), double bond (LDPE/HDPE 1600-1680 cm^{-1}/1350-1400 cm^{-1}; PP 1600-1680 cm^{-1}/2700-2750 cm^{-1}), and carbon-oxygen (LDPE/HDPE 1000-1300 cm^{-1} /1350-1400 cm^{-1}; PP 1000-1300 cm^{-1} /2700-2750 cm^{-1}).

Before calculating the indices, all spectra were corrected by subtracting the minimum absorbance value recorded in that spectra from all wavepoints, then normalizing to the maximum absorption value (Workman, Jr and Springsteen 1998). Baselines were corrected using the R package ChemoSpec (Hanson 2012).

Results

Oceanic plastic type

The composition of microplastic debris varied with location (Fig 3.4, chi-squared test of independence $p<0.001$). Surface layer oceanic microplastic was comprised of polyethylene (PE), polypropylene (PP), and polystyrene (PS). Most PE could be further identified as high-density polyethylene (HDPE) and low-density polyethylene (LDPE).

The largest proportion of California Current microplastic was PP, while the largest proportion of microplastic in the intermediate region and NPSG was LDPE (Fig 3.4a). Relatively more HDPE was found in the NPSG than in the intermediate region (Fig 3.4b,c; chi-squared test of independence p=0.020). PS was a small proportion of total plastic at all sites.

Weathering experiment

Of the four weathering indices, the hydroxyl, double bond, and carbon-oxygen indices showed no clear change with time across plastic types. In LDPE and HDPE, values for these indices increased between T_0 and T_1, and then decreased between T_1 and T_2 (data not shown). PP values had extremely high variation, making patterns difficult to discern (data not shown). In contrast, the carbonyl index showed a clearer relationship with time across plastic types. Carbonyl index values in the LDPE and HDPE sunlight-only and sunlight/seawater treatments increased with time (Fig 3.5a,b; Nemenyi-Damico-Wolfe-Dunn test $p<0.05$), with the exception of the HDPE exposed to sunlight only, which decreased between T_1 and T_2 ($p<0.001$). Carbonyl did not increase in the seawater-only treatments ($p>0.05$). For PP, carbonyl increased in the light and sunlight/seawater treatments (Fig 3.5c; $p<0.05$), but not in the seawater treatment ($p=0.295$).

To further explore whether the carbonyl index could relate to weathering, carbonyl index values from the weathering experiments were compared with values from ocean-collected particles of the same plastic type. For HDPE and PP, there were no significant carbonyl differences in ocean particles by collection area (California Current, transition region, and NPSG; Kruskal-Wallis test $p>0.1$). For LDPE, there was a significant difference by collection area (Kruskal-Wallis $p=0.002$), which post-hoc testing revealed to be solely between the transition region and California Current (Nemenyi-Damico-Wolfe-Dunn $p<0.001$). Because there was no clear spatial pattern in carbonyl index value among water masses, ocean particles from all water masses were combined in the following analysis.

LDPE and HDPE ocean particles had higher carbonyl indices than any of the experimentally weathered particles (Fig 3.5a,b; Nemenyi-Damico-Wolfe-Dunn test $p<0.001$). PP ocean particles were higher than the seawater or sunlight/seawater treatments, but lower than the sunlight-only treatment ($p<0.05$, Fig 3.5c). In LDPE, carbonyl formation was apparent in the sunlight treatment and in the ocean particles, but not in the seawater and sunlight/seawater treatments (Fig 3.5d). In HDPE, carbonyl formation was only apparent in the ocean particles (Fig 3.5e). In PP, carbonyl formation was apparent only in the sunlight treatment (Fig 3.5f). No difference in the shapes of spectra was observed between ocean particles and treatments in the hydroxyl, double bond, and CO areas (data not shown).

Discussion

This study documents spatial changes in pelagic microplastic composition in the eastern North Pacific. Carbonyl content was found to be a useful index of degradation in both oceanic particles and particles of known weathering time. While there was substantial variance, ocean particles on the whole contained more carbonyl than particles weathered in sunlight and seawater for 18 months. To my knowledge this is the first direct comparison between microplastics naturally weathered in the ocean and microplastics degraded under known experimental conditions.

The changes in microplastic composition over the eastern North Pacific may be explained by differential rates of weathering. The proportion of PP and PS in pelagic microplastic decreased with distance from the coast, potentially due to faster breakdown in these compounds than in PE. This inference is supported by laboratory studies, primarily on plastic films, that found that PP films weather more quickly than PE films (Gijsman et al. 1999). In addition, while PE weathering is a linear function of time, PP weathering accelerates after an initial exposure period (Shyichuk et al. 2005). PS also weathers more quickly than PE. For example, when consumer products were exposed to quasi-natural air and seawater weathering conditions, expanded polystyrene foam was the only plastic type to degrade faster in seawater than in air (Andrady 1989). The relatively high proportion of HDPE to LDPE in the NPSG may also be explained by differential weathering, since HDPE weathers more slowly than LDPE (Gulmine et al. 2003). However, future studies are required, particularly of sub-333 µm particles not sampled in this study. For example, it is possible that PP and PS items simply degrade into smaller particles than LDPE and HDPE items, and are therefore not sampled by standard-mesh zooplankton nets.

Results from the weathering experiment also support differential weathering rates of different plastic types, although most changes were seen only in the sunlight-exposed particles. After 18 months, carbonyl formation in sunlight-exposed particles was most pronounced in PP, visible in LDPE, but not detectable in HDPE. However, the decrease between 9 and 18 months of weathering suggests that HDPE carbonyl dynamics may be non-linear. These patterns suggest that the predominance of NPSG plastic is more weathered than California Current or intermediate region plastic.

The physical oceanography of the North Pacific and the shape of the particles themselves provides additional supporting evidence that the more weathered particles are likely to be found offshore. Models of the North Pacific large-scale circulation predict that floating objects from around the Pacific basin will not stay in the boundary currents, but will accumulate within the NPSG within 5-10 years of release (Kubota 1994, Maximenko et al. 2012). Particles can also become entrained in additional accumulation zones within the NPSG, such as the atmospheric high pressure zones found in the eastern and western portions of the NPSG (Howell et al. 2012). Additionally, a previous study of microplastic found that particles in the NPSG are also more rounded than particles of equivalent diameter found in the California Current or transition area, suggesting that they are more weathered (Goldstein et al. 2012b).

However, the weathering of plastic in seawater is substantially more complicated than weathering in the laboratory or terrestrial environments. Over multiple studies, plastic in seawater has been found to degrade much more slowly than plastics exposed to air (Pegram and Andrady 1989, Andrady 1989, 2011, Andrady et al. 1993a, Gregory and Andrady 2003). Because plastic degradation rate is determined by heat and oxygen, the relatively lower temperatures in the marine environment may significantly retard degradation (Gregory and Andrady 2003), though oxygen levels should not be limiting on the ocean's surface. Plastic weathering in the marine environment may be further slowed by encrustation by fouling organisms, which reduces the UV light that reaches the plastic surface (Ye and Andrady 1991, O'Brine and Thompson 2010). In the weathering experiments presented here, both reduced temperature and a high degree of algal fouling explain why carbonyl levels in sunlight/seawater samples are more similar to seawater-only samples than to sunlight-only samples.

Interpreting carbonyl formation in weathered particles was made more difficult by the importance of finding a consistent reference peak. In most LDPE and HDPE weathered particles, the baseline of the spectra was distorted, particularly between 400-1500 cm^{-1} (Supplemental Figures S3.1,S3.2), which is the region where most published reference peaks for polyethylene are found (Albertsson et al. 1987, Andrady et al. 1993b). Because the distortion was non-linear, it could not be improved by baseline correction. A similar distortion was observed in published spectra of ocean-weathered polyethylene particles (Cooper and Corcoran 2010), making it less likely that the distortion in this study was a specific methodological problem. While the nature of the distortion is unknown, it is possible that more advanced pre-processing of spectra could improve the detection of differences between spectra. Several types of distortion can occur in FTIR-ATR spectroscopy, caused by instrumental effects, sample thickness, temperature, humidity, and light scattering (Miljković et al. 2012). Mathematical methods exist for correcting for these distortions, but because of their complexity they were beyond the scope of this study (Romeo and Diem 2005, Kohler et al. 2009).

The rate of plastic weathering also depends on the additives in a given plastic product. The preproduction pellets used in the weathering experiment presented here contained no additives, which causes them to weather more quickly than most consumer products. Products often contain pigments and UV stabilizers that alter heat absorption and impede oxygen diffusion (Pickett 2000). For example, objects with dark pigment absorb more solar light than light-colored plastics, leading to more rapid degradation (Searle 2003). In addition, most consumer plastics that are expected to be exposed to sunlight contain UV-absorbing compounds that absorb and dissipate the energy from UV light, though these compounds gradually diminish over time (Pickett 2000). The interaction between object color and additives is unknown in the environment (Searle 2003). The majority of pelagic microplastic is white or transparent, but it is unclear whether this pattern is causing by differential weathering rates or by selective ingestion by marine biota (Shaw and Day 1994).

In many plastic weathering studies, an increase in carbonyl compounds is linked directly to degree of weathering (Albertsson et al. 1987, Livanova and Zaikov 1992, Andrady et al. 1993b, Rabello and White 1997, Rajakumar et al. 2009, Roy et al. 2011), though there is some variation with temperature (Satoto et al. 1997). However, this relationship may be more complicated in oceanic microplastic. Carbonyl compounds are initially formed through the abiotic Norrish mechanism of degradation, which requires only exposure to UV light and oxygen (Albertsson et al. 1987). However, once carbonyl groups have been produced, they are accessible to microbes, which metabolize them with an end product of carbon dioxide and water (Albertsson et al. 1987, Balasubramanian et al. 2010). Biofilm formation on oceanic plastic is very common (Leonas and Gorden 1996, Moret-Ferguson et al. 2010), though the link between biofilm-dwelling microbes and plastic degradation is unknown (Eubeler et al. 2009). While interaction with oceanic microbes does not appear to lead to significant plastic mass loss (e.g., 1 % over 6 months; Sudhakar et al. 2007), these processes can cause the carbonyl content of ocean-exposed plastics to decrease over long-term exposure (Artham et al. 2009, Muthukumar et al. 2011). Microbial metabolism may explain the relatively low carbonyl content of many of the oceanic particles examined in this analysis.

Plastic weathers so slowly in the ocean that it has been suggested that microplastics cannot form in the ocean at all, but instead must form through the weathering of beach litter (Andrady 2011). Beach litter is exposed to substantially higher temperatures as well as mechanical processes that produce fractures and grooves, enhancing oxidative weathering (Corcoran et al. 2009, Cooper and Corcoran 2010). Microplastic collected from the ocean can have substantial surface rugosity (M.C. Goldstein pers. obs.), but the specific origin of these features is unknown. This complicated interaction between temperature, fouling, color, UV stabilizers, and microbes may explain the wide range of carbonyl values observed in the oceanic particles.

Carbonyl dynamics alone are likely insufficient to determine the weathering time for a given microplastic particle, but the results of this study suggest that carbonyl could be combined with other analyses to estimate weathering time. For example, while carbonyl levels on oceanic particles were low as compared to sunlight-weathered particles, they were still higher than sunlight/seawater weathered particles after 18 months. Since surface circulation models estimate that plastic may take several years to be entrained in the NPSG (Kubota 1994, Maximenko et al. 2012), 18 months is shorter than the likely weathering time of particles found in the NPSG. Greater understanding of oceanic plastic weathering may also be gained by examining a finer temporal resolution. Though the weathering experiment has been sampled bimonthly, only three time points were analyzed for this study. The weathering experiment presented here is ongoing, and future changes may be forthcoming.

Oceanic microplastic in the central Pacific has increased by two orders of magnitude over the past four decades (Goldstein et al. 2012a). Basic estimates of "residence time" are necessary to understand the source of pelagic microplastic. If NPSG plastic is indeed more weathered than plastic in the California Current and transition area, as suggested by this study, NPSG microplastic particles may be more likely to originate from coastal sources than from accidental or illegal discharge at sea. If true, this would have significant implications for selecting effective mitigation strategies, such as a focus on prevention and beach cleanups rather than at-sea debris removal. Since plastic abundance is highly variable in space and time (Morishige et al. 2007, Goldstein et al. 2012b, Kukulka et al. 2012), a method of estimating plastic weathering time is necessary to determine whether mitigation programs are decreasing the abundance of "new", relatively unweathered plastic particles. While a method to definitively measure oceanic plastic weathering does not yet exist, the results presented here suggest that a qualitative method may be achievable. Future studies should consider more detailed measures of carbonyl dynamics in ocean-weathered particles, along with additional metrics of weathering such as tensile properties and molecular weight (Shah et al. 2008).

Acknowledgements

I thank Pacific Plastics Injection Molding, Damar Plastics, P. Dinger, and C. Rochman for their donation of preproduction plastic pellets. G. Arrhenius, M.J. Sailor, and A. Potocny made the FTIR work possible. I am grateful to K.E. Armaiz for assistance in the laboratory, P. Zerofski for help with experimental setup, and M.D. Ohman for his advice throughout the project. Funding for the SEAPLEX cruise was provided by University of California Ship Funds, Project Kaisei/Ocean Voyages Institute, AWIS-San Diego, and NSF IGERT Grant No. 0333444. I was supported by NSF GK-12 Grant No. 0841407 and donations from Jim & Kris McMillan, Jeffrey & Marcy Krinsk, Lyn & Norman Lear, Ellis Wyer, and an anonymous donor.

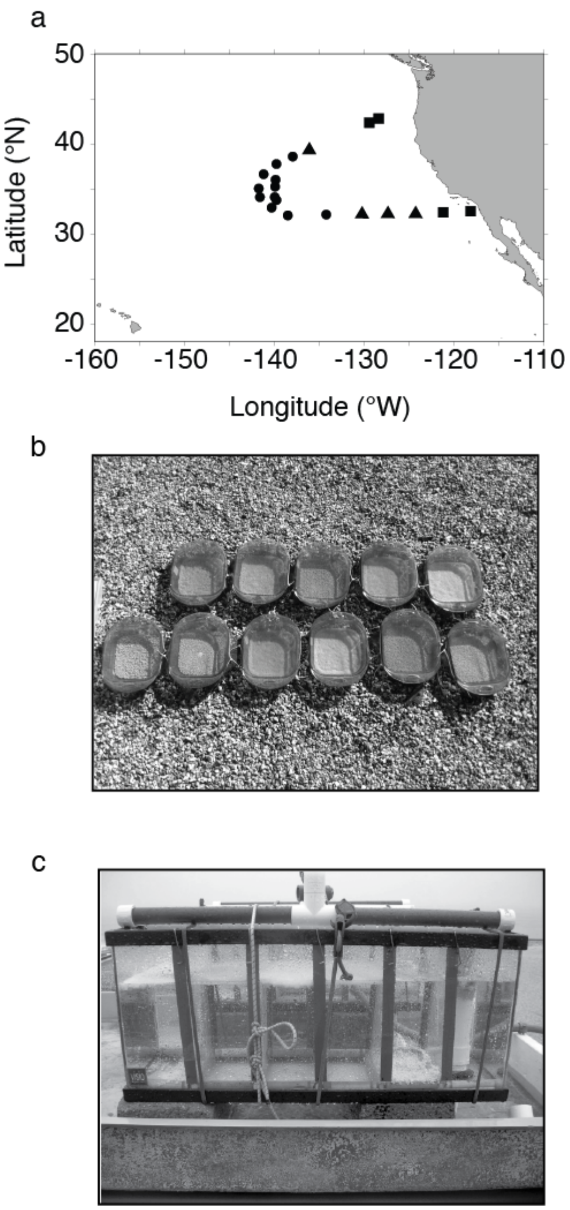


Figure 3.1. Sampling sites and weathering experiment setup
a) Locations sampled for oceanic microplastic debris in August 2009. Shape indicates approximate water mass based on surface characteristics. Squares indicate the California Current stations, triangles indicate the intermediate region stations, and circles indicate the NPSG stations. b) Plastic particles in the weathering experiment, sunlight-only treatment. c) Plastic particles in the weathering experiment, sunlight/seawater treatment. The seawater-only treatment was in identical tanks, but were covered to minimize light.

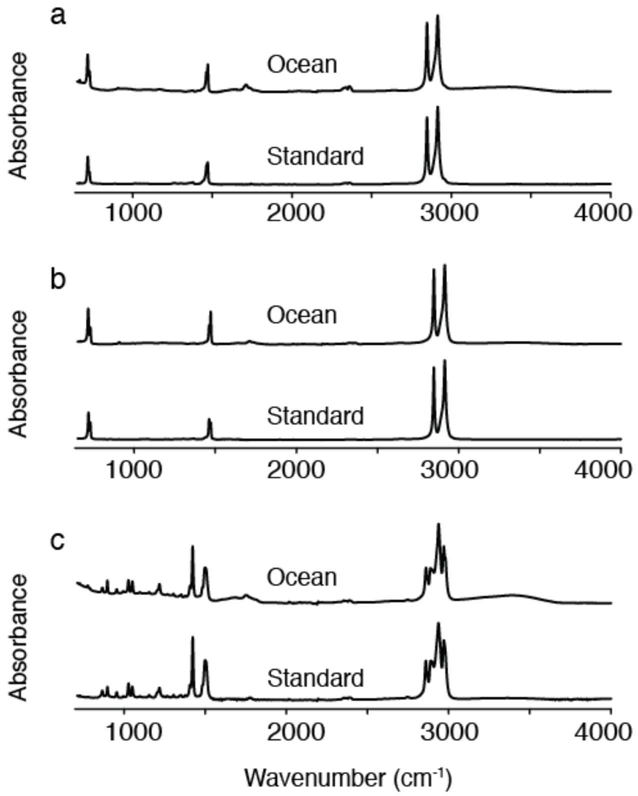


Figure 3.2. FTIR spectra comparing microplastic collected from the ocean to laboratory standards
a) Low-density polyethylene (LDPE), b) High-density polyethylene (HDPE), c) Polypropylene (PP).

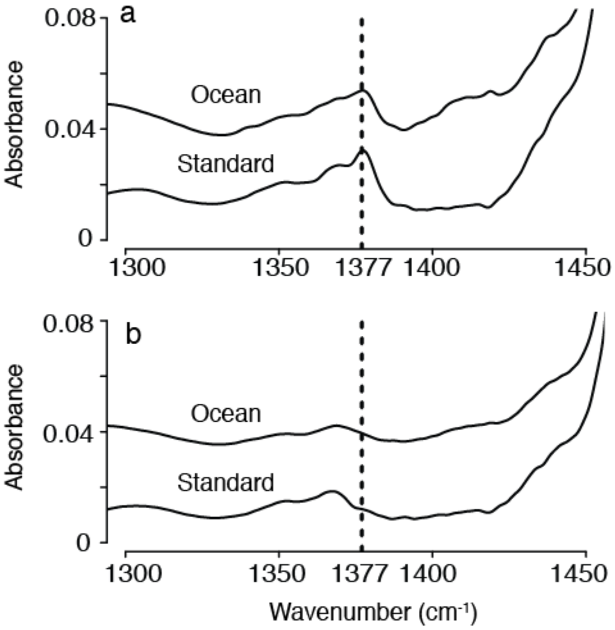


Figure 3.3. Portion of FTIR spectra comparing microplastic collected from the ocean to laboratory standards
a) Low-density polyethylene (LDPE), b) High-density polyethylene (HDPE).

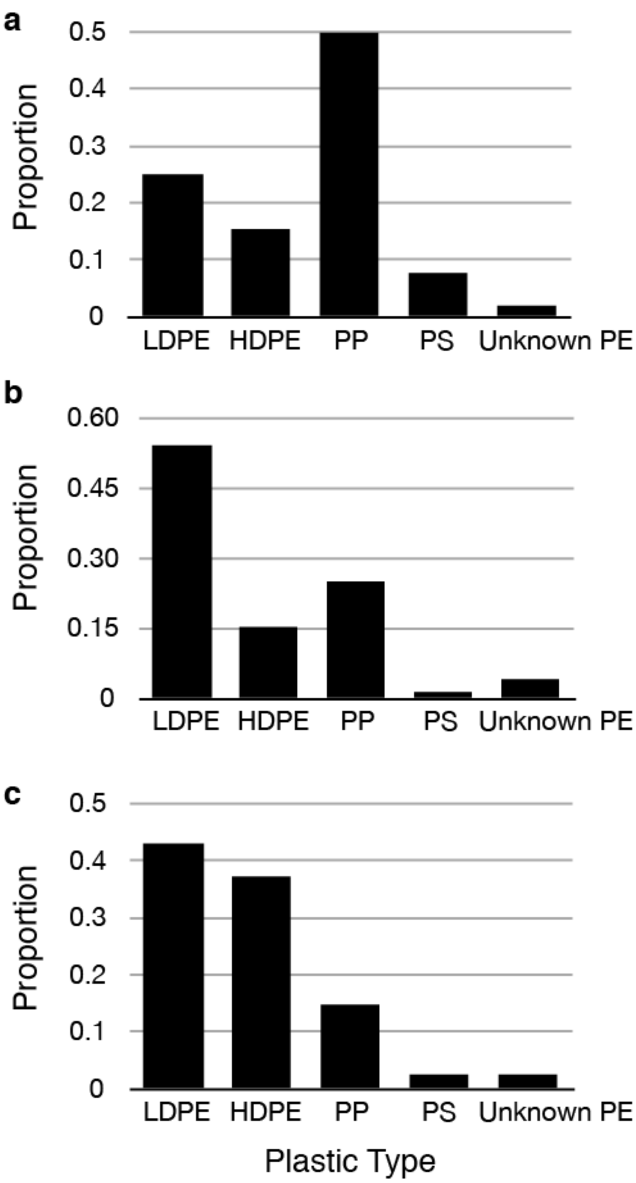
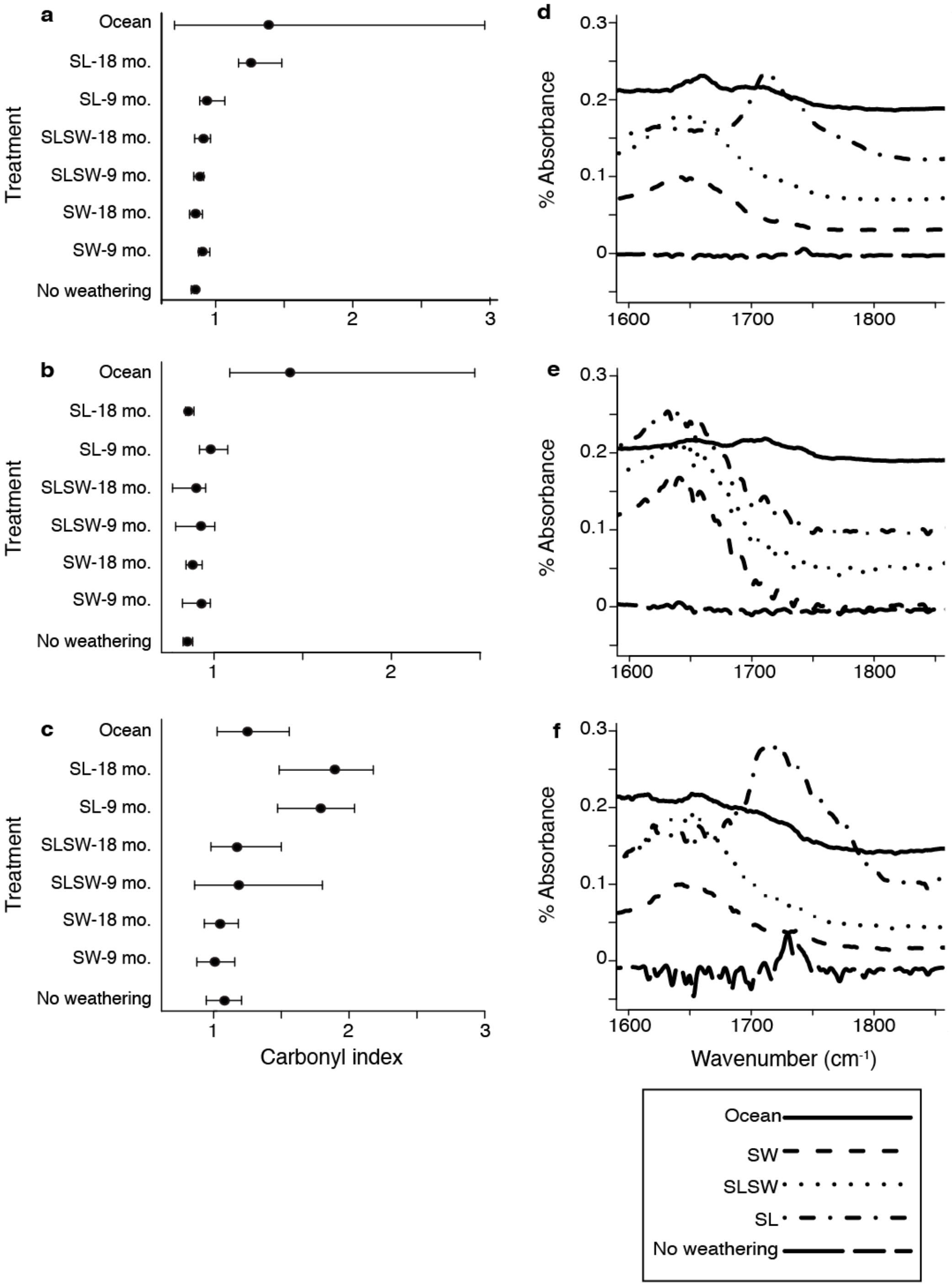


Figure 3.4. Composition of microplastic
in the a) California Current (N=52), b) intermediate region (N=72), and c) NPSG (N=433). Abbreviations are as follows: low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), and unknown polyethylene (unknown PE).

Figure 3.5. Carbonyl content in oceanic particles and in the weathering experiment

Panels on the left show the median carbonyl index value with 95% confidence intervals for unweathered particles, particles exposed to seawater for 9 and 18 months (SW-9 mo., SW-18 mo.), particles exposed to sunlight for 9 and 18 months (SL-9 mo., SL-18 mo.), particles exposed to sunlight and seawater for 9 and 18 months (SLSW-9 mo., SLSW-18 mo.), and particles collected from the ocean. Plastic types are: a) low-density polyethylene (LDPE), b) high-density polyethylene (HDPE), c) polypropylene (PP). Panels on the right show the median infrared spectra from 1600-1850 cm^{-1} for unweathered particles, particles weathered for 18 months (abbreviations as above), and ocean particles. This region of the spectra includes the carbonyl peak between 1690 and 1810 cm^{-1} (Pavia et al. 2008). Plastic types are d) LDPE, e) HDPE, and f) PP. Sample sizes are as follows: a) Ocean N=243, SL-18 mo. N=30, SL-9 mo. N=29, SLSW-18 mo N=29, SLSW 9-mo. N=30, SW 18-mo. N=30, SW 9 mo N=30, no weathering N=15. b) Ocean N=170, N=20 for all others. c) Ocean N=106, SL-18 mo. N=30, SL-9 mo. N=20, SLSW-18 mo N=29, SLSW 9-mo. N=20, SW 18-mo. N=27, SW 9 mo N=20, no weathering N=23.


a
b
c
d
e
f
Ocean
SL-18 mo.
SL-9 mo.
SLSW-18 mo.
SLSW-9 mo.
SW-18 mo.
SW-9 mo.
No weathering
Treatment
1
2
3
Carbonyl index
% Absorbance
0.3
0.2
0.1
0
1600
1700
1800
Wavenumber (cm-1)
Ocean
SW
SLSW
SL
No weathering

References

Albertsson, A.-C., S. O. Andersson, and S. Karlsson. 1987. The mechanism of biodegradation of polyethylene. Polymer Degradation and Stability 18:73–87. doi: 10.1016/0141-3910(87)90084-X.

Alt, M. 2008, March 28. Castaway No. 28. Retrieved October 9, 2012, from http://altjapan.typepad.com/my_weblog/2008/03/castaway-no-28.html.

Andrady, A. 1989. Environmental degradation of plastics under land and marine exposure conditions. Proceedings of the Second International Conference on Marine Debris. United States Dept of Commerce, Honolulu, Hawaii.

Andrady, A. L. 2003a. Common plastics materials. Pages 77–121 *in* A. L. Andrady, editor. Plastics and the Environment. John Wiley & Sons, Inc., Hoboken, NJ.

Andrady, A. L. 2003b. Weathering of polyethylene (LDPE) and enhanced photodegradable polyethylene in the marine environment. Journal of Applied Polymer Science 39:363–370. doi: 10.1002/app.1990.070390213.

Andrady, A. L. 2011. Microplastics in the marine environment. Marine Pollution Bulletin 62:1596–1605. doi: 10.1016/j.marpolbul.2011.05.030.

Andrady, A. L., J. E. Pegram, and Y. Song. 1993a. Studies on enhanced degradable plastics. II. Weathering of enhanced photodegradable polyethylenes under marine and freshwater floating exposure. Journal of Polymers and the Environment 1:117–126. doi: 10.1007/BF01418205.

Andrady, A. L., J. E. Pegram, and Y. Tropsha. 1993b. Changes in carbonyl index and average molecular weight on embrittlement of enhanced-photodegradable polyethylenes. Journal of Polymers and the Environment 1:171–179. doi: 10.1007/BF01458025.

Artham, T., M. Sudhakar, R. Venkatesan, C. Madhavan Nair, K. V. G. K. Murty, and M. Doble. 2009. Biofouling and stability of synthetic polymers in sea water. International Biodeterioration & Biodegradation 63:884–890. doi: 10.1016/j.ibiod.2009.03.003.

ASTM Standard C702/C702M-11. 2011. Practice for reducing samples of aggregate to testing size. ASTM International, West Conshohocken, PA. doi: 10.1520/C0702_C0702M-11.

Balasubramanian, V., K. Natarajan, B. Hemambika, N. Ramesh, C. s. Sumathi, R. Kottaimuthu, and V. Rajesh Kannan. 2010. High-density polyethylene (HDPE)-degrading potential bacteria from marine ecosystem of Gulf of

Mannar, India. Letters in Applied Microbiology 51:205–211. doi: 10.1111/j.1472-765X.2010.02883.x.

Brown, D. M., and L. Cheng. 1981. New net for sampling the ocean surface. Marine Ecology Progress Series 5:225–227. doi: 10.3354/meps005225.

Browne, M. A., P. Crump, S. J. Niven, E. Teuten, A. Tonkin, T. Galloway, and R. Thompson. 2011. Accumulation of microplastic on shorelines woldwide: sources and sinks. Environmental Science & Technology 45:9175–9179. doi: 10.1021/es201811s.

Carpenter, E. J., and K. L. Smith. 1972. Plastics on the Sargasso Sea surface. Science 175:1240. doi: 10.1126/science.175.4027.1240.

Cole, M., P. Lindeque, C. Halsband, and T. S. Galloway. 2011. Microplastics as contaminants in the marine environment: A review. Marine Pollution Bulletin 62:2588–2597. doi: 10.1016/j.marpolbul.2011.09.025.

Cooper, D. A., and P. L. Corcoran. 2010. Effects of mechanical and chemical processes on the degradation of plastic beach debris on the island of Kauai, Hawaii. Marine Pollution Bulletin 60:650–654. doi: 10.1016/j.marpolbul.2009.12.026.

Corcoran, P. L., M. C. Biesinger, and M. Grifi. 2009. Plastics and beaches: A degrading relationship. Marine Pollution Bulletin 58:80–84. doi: 10.1016/j.marpolbul.2008.08.022.

Davidson, T. M. 2012. Boring crustaceans damage polystyrene floats under docks polluting marine waters with microplastic. Marine Pollution Bulletin. doi: 10.1016/j.marpolbul.2012.06.005.

Eubeler, J. P., M. Bernhard, S. Zok, and T. P. Knepper. 2009. Environmental biodegradation of synthetic polymers I. Test methodologies and procedures. Trends in Analytical Chemistry 28:1057–1072. doi: 10.1016/j.trac.2009.06.007.

Fendall, L. S., and M. A. Sewell. 2009. Contributing to marine pollution by washing your face: Microplastics in facial cleansers. Marine Pollution Bulletin 58:1225–1228. doi: 10.1016/j.marpolbul.2009.04.025.

Forrest, M., Y. Davies, and J. Davies. 2007. Rapra Collection of Infrared Spectra of Rubbers, Plastics and Thermoplastic Elastomers, 3rd edition. Smithers Rapra Technology.

Gijsman, P., G. Meijers, and G. Vitarelli. 1999. Comparison of the UV-degradation chemistry of polypropylene, polyethylene, polyamide 6 and polybutylene terephthalate. Polymer Degradation and Stability 65:433–441. doi: 10.1016/S0141-3910(99)00033-6.

Gilfillan, L. R., M. D. Ohman, M. J. Doyle, and W. Watson. 2009. Occurrence of plastic micro-debris in the southern California Current system. CalCOFI Report 50:123–133.

Goldstein, M. C., M. Rosenberg, and L. Cheng. 2012a. Increased oceanic microplastic debris enhances oviposition in an endemic pelagic insect. Biology Letters 8:817–820. doi: 10.1098/rsbl.2012.0298.

Goldstein, M. C., A. J. Titmus, and M. Ford. 2012b. Scales of spatial heterogeneity of plastic marine debris in the northeast Pacific Ocean PLOS ONE, submitted.

Gregory, M. R., and A. L. Andrady. 2003. Plastics in the marine environment. Pages 379–401 *in* A. L. Andrady, editor. Plastics and the Environment. John Wiley & Sons, Inc., Hoboken, NJ.

Gulmine, J. V., P. R. Janissek, H. M. Heise, and L. Akcelrud. 2003. Degradation profile of polyethylene after artificial accelerated weathering. Polymer Degradation and Stability 79:385–397. doi: 10.1016/S0141-3910(02)00338-5.

Hanson, B. A. 2012. ChemoSpec: Exploratory Chemometrics for Spectroscopy. R package version 1.51-2. Retrieved from http://academic.depauw.edu/~hanson/ChemoSpec/ChemoSpec.html.

Hidalgo-Ruz, V., L. Gutow, R. C. Thompson, and M. Thiel. 2012. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environmental Science & Technology 46:3060–3075. doi: 10.1021/es2031505.

Howell, E. A., S. J. Bograd, C. Morishige, M. P. Seki, and J. J. Polovina. 2012. On North Pacific circulation and associated marine debris concentration. Marine Pollution Bulletin 65:16–22. doi: 10.1016/j.marpolbul.2011.04.034.

Kohler, A., U. Böcker, J. Warringer, A. Blomberg, S. W. Omholt, E. Stark, and H. Martens. 2009. Reducing inter-replicate variation in Fourier transform infrared spectroscopy by extended multiplicative signal correction. Applied spectroscopy 63:296–305.

Kubota, M. 1994. A mechanism for the accumulation of floating marine debris north of Hawaii. Journal of Physical Oceanography 24:1059–1064.

Kukulka, T., G. Proskurowski, S. Morét-Ferguson, D. W. Meyer, and K. L. Law. 2012. The effect of wind mixing on the vertical distribution of buoyant plastic debris. Geophysical Research Letters 39:6 pp. doi: 201210.1029/2012GL051116.

Kyrikou, I., and D. Briassoulis. 2007. Biodegradation of agricultural plastic films: a critical review. Journal of Polymers and the Environment 15:125–150. doi: 10.1007/s10924-007-0053-8.

Law, K. L., S. Moret-Ferguson, N. A. Maximenko, G. Proskurowski, E. E. Peacock, J. Hafner, and C. M. Reddy. 2010. Plastic accumulation in the North Atlantic Subtropical Gyre. Science 329:1185–1188. doi: 10.1126/science.1192321.

Leonas, K., and R. Gorden. 1996. Bacteria associated with disintegrating plastic films under simulated aquatic environments. Bulletin of Environmental Contamination and Toxicology 56:948–955.

Livanova, N. M., and G. E. Zaikov. 1992. A scale effect in the durability of oriented narrow polypropylene films during oxidation under load. Fracture model of stressed polypropylene films. Polymer Degradation and Stability 36:253–259. doi: 10.1016/0141-3910(92)90064-C.

Lobo, H., and J. V. Bonilla (Eds.). 2003. Handbook of Plastics Analysis, 1st edition. CRC Press.

Lynn, R. J., and J. J. Simpson. 1987. The California Current system: the seasonal variability of its physical characteristics. Journal of Geophysical Research 92:12,947–12,966. doi: 198710.1029/JC092iC12p12947.

Maximenko, N., J. Hafner, and P. Niiler. 2012. Pathways of marine debris derived from trajectories of Lagrangian drifters. Marine Pollution Bulletin 65:51–62. doi: 10.1016/j.marpolbul.2011.04.016.

Miljković, M., B. Bird, and M. Diem. 2012. Line shape distortion effects in infrared spectroscopy. The Analyst 137:3954. doi: 10.1039/c2an35582e.

Moret-Ferguson, S., K. L. Law, G. Proskurowski, E. K. Murphy, E. E. Peacock, and C. M. Reddy. 2010. The size, mass, and composition of plastic debris in the western North Atlantic Ocean. Marine Pollution Bulletin 60:1873–1878. doi: 10.1016/j.marpolbul.2010.07.020.

Morishige, C., M. J. Donohue, E. Flint, C. Swenson, and C. Woolaway. 2007. Factors affecting marine debris deposition at French Frigate Shoals, Northwestern Hawaiian Islands Marine National Monument, 1990-2006. Marine Pollution Bulletin 54:1162–1169. doi: 10.1016/j.marpolbul.2007.04.014.

Morris, R. J. 1980. Plastic debris in the surface waters of the South Atlantic. Marine Pollution Bulletin 11:164–166.

Muthukumar, T., A. Aravinthan, K. Lakshmi, R. Venkatesan, L. Vedaprakash, and M. Doble. 2011. Fouling and stability of polymers and composites in marine environment. International Biodeterioration & Biodegradation 65:276–284. doi: 10.1016/j.ibiod.2010.11.012.

National Research Council. 2009. Tackling Marine Debris in the 21st Century. National Academies Press, Washington DC. Retrieved from http://www.nap.edu/catalog/12486.html.

Niiler, P. P., and R. W. Reynolds. 1984. The three-dimensional circulation near the eastern North Pacific subtropical front. Journal of Physical Oceanography 14:217–230. doi: 10.1175/1520-0485(1984)014<0217:TTDCNT>2.0.CO;2.

O'Brine, T., and R. C. Thompson. 2010. Degradation of plastic carrier bags in the marine environment. Marine Pollution Bulletin 60:2279–2283. doi: 10.1016/j.marpolbul.2010.08.005.

Ogata, Y., H. Takada, K. Mizukawa, H. Hirai, S. Iwasa, S. Endo, Y. Mato, M. Saha, K. Okuda, A. Nakashima, M. Murakami, N. Zurcher, R. Booyatumanondo, M. P. Zakaria, L. Q. Dung, M. Gordon, C. Miguez, S. Suzuki, C. Moore, H. K. Karapanagioti, S. Weerts, T. McClurg, E. Burres, W. Smith, M. Van Velkenburg, J. S. Lang, R. C. Lang, D. Laursen, B. Danner, N. Stewardson, and R. C. Thompson. 2009. International Pellet Watch: Global monitoring of persistent organic pollutants (POPs) in coastal Waters. 1. Initial phase data on PCBs, DDTs, and HCHs. Marine Pollution Bulletin 58:1437–1446. doi: 10.1016/j.marpolbul.2009.06.014.

Pavia, D. L., G. M. Lampman, G. S. Kriz, and J. A. Vyvyan. 2008. Introduction to Spectroscopy, 4th edition. Brooks Cole.

Pegram, J. E., and A. L. Andrady. 1989. Outdoor weathering of selected polymeric materials under marine exposure conditions. Polymer Degradation and Stability 26:333–345. doi: 10.1016/0141-3910(89)90112-2.

Pickett, J. E. 2000. Permanence of UV absorbers in plastics and coatings. Pages 163–190 *in* S. H. Hamid, editor. Handbook of Polymer Degradation, 2nd edition. CRC Press.

Rabello, M. S., and J. R. White. 1997. The role of physical structure and morphology in the photodegradation behaviour of polypropylene. Polymer Degradation and Stability 56:55–73. doi: 10.1016/S0141-3910(96)00202-9.

Rajakumar, K., V. Sarasvathy, A. Thamarai Chelvan, R. Chitra, and C. Vijayakumar. 2009. Natural Weathering Studies of Polypropylene. Journal of Polymers and the Environment 17:191–202. doi: 10.1007/s10924-009-0138-7.

Roden, G. I. 1980. On the subtropical frontal zone north of Hawaii during winter. Journal of Physical Oceanography 10:342–362. doi: 10.1175/1520-0485(1980)010<0342:OTSFZN>2.0.CO;2.

Romeo, M., and M. Diem. 2005. Correction of dispersive line shape artifact observed in diffuse reflection infrared spectroscopy and absorption/reflection (transflection) infrared micro-spectroscopy. Vibrational Spectroscopy 38:129–132. doi: 10.1016/j.vibspec.2005.04.003.

Roy, P. K., P. Surekha, and C. Rajagopal. 2011. Surface oxidation of low-density polyethylene films to improve their susceptibility toward environmental degradation. Journal of Applied Polymer Science 122:2765–2773. doi: 10.1002/app.34097.

Satoto, R., W. S. Subowo, R. Yusiasih, Y. Takane, Y. Watanabe, and T. Hatakeyama. 1997. Weathering of high-density polyethylene in different latitudes. Polymer Degradation and Stability 56:275–279. doi: 10.1016/S0141-3910(96)00213-3.

Searle, N. D. 2003. Environmental effects on polymeric materials. Pages 313–358 *in* A. L. Andrady, editor. Plastics and the Environment. John Wiley & Sons, Inc., Hoboken, NJ.

Shah, A. A., F. Hasan, A. Hameed, and S. Ahmed. 2008. Biological degradation of plastics: A comprehensive review. Biotechnology Advances 26:246–265. doi: 10.1016/j.biotechadv.2007.12.005.

Shaw, D. G., and R. H. Day. 1994. Colour- and form-dependent loss of plastic micro-debris from the North Pacific Ocean. Marine Pollution Bulletin 28:39–43.

Shyichuk, A. V., J. R. White, I. H. Craig, and I. D. Syrotynska. 2005. Comparison of UV-degradation depth-profiles in polyethylene, polypropylene and an ethylene–propylene copolymer. Polymer Degradation and Stability 88:415–419. doi: 10.1016/j.polymdegradstab.2004.12.006.

Sudhakar, M., A. Trishul, M. Doble, K. Suresh Kumar, S. Syed Jahan, D. Inbakandan, R. R. Viduthalai, V. R. Umadevi, P. Sriyutha Murthy, and R. Venkatesan. 2007. Biofouling and biodegradation of polyolefins in ocean waters. Polymer Degradation and Stability 92:1743–1752. doi: 10.1016/j.polymdegradstab.2007.03.029.

Thompson, R. C., Y. Olsen, R. P. Mitchell, A. Davis, S. J. Rowland, A. W. G. John, D. McGonigle, and A. E. Russell. 2004. Lost at sea: Where is all the plastic? Science 304:838. doi: 10.1126/science.1094559.

Venrick, E. L., T. W. Backman, W. C. Bartram, C. J. Platt, M. S. Thornhill, and R. E. Yates. 1973. Man-made objects on the surface of the central North Pacific ocean. Nature 241:271–271. doi: 10.1038/241271a0.

Wong, C. S., D. R. Green, and W. J. Cretney. 1974. Quantitative tar and plastic waste distributions in Pacific Ocean. Nature 247:30–32. doi: doi:10.1038/247030a0.

Workman, Jr, J., and A. Springsteen. 1998. Applied Spectroscopy: A Compact Reference for Practitioners. Academic Press.

Ye, S., and A. L. Andrady. 1991. Fouling of floating plastic debris under Biscayne Bay exposure conditions. Marine Pollution Bulletin 22:608–613. doi: 10.1016/0025-326X(91)90249-R.

Appendix

Figure S3.1. Low-density polyethylene median spectra
LDPE median spectra (black line), with interquartile range (red line) for: a) unweathered particles (N=15), b) particles exposed to sunlight for 9 months (N=29), c) particles exposed to sunlight for 18 months (N=30), d) unweathered particles (N=15), e) particles exposed to seawater for 9 months (N=30), f) particles exposed to seawater for 18 months (N=30), g) unweathered particles (N=15), h) particles exposed to sunlight and seawater for 9 months (N=30), i) particles exposed to sunlight and seawater for 18 months (N=29), and j) particles collected from the ocean (N=243).

LDPE

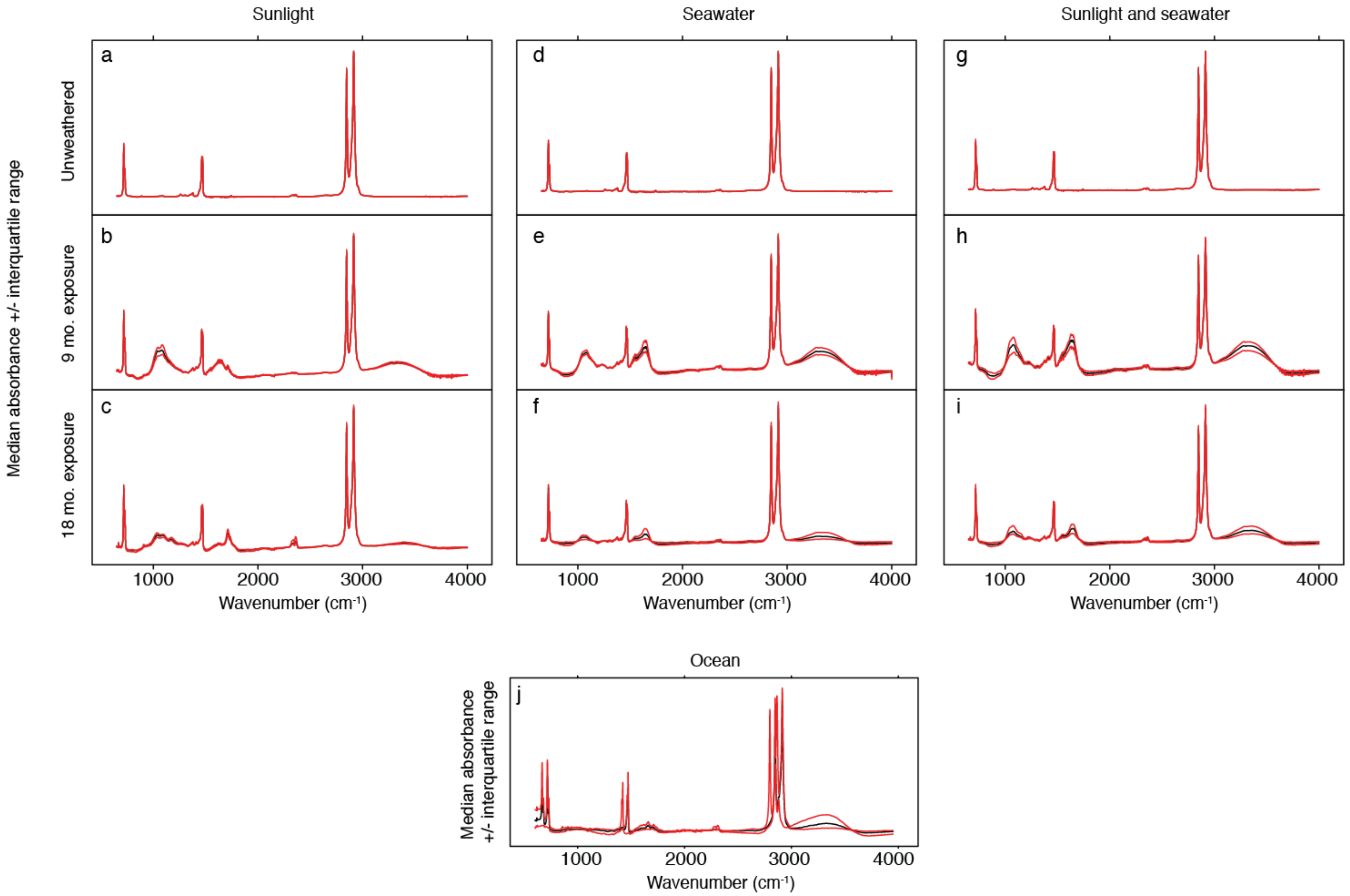

Sunlight
Seawater
Sunlight and seawater
Median absorbance +/- interquartile range
Unweathered
9 mo. exposure
18 mo. exposure
a
b
c
d
e
f
g
h
i
1000
2000
3000
4000
Wavenumber (cm-1)
Ocean
j
Median absorbance +/- interquartile range

Figure S3.2. High-density polyethylene median spectra
HDPE median spectra (black line), with interquartile range (red line) for: a) unweathered particles (N=20), b) particles exposed to sunlight for 9 months (N=20), c) particles exposed to sunlight for 18 months (N=20), d) unweathered particles (N=20), e) particles exposed to seawater for 9 months (N=20), f) particles exposed to seawater for 18 months (N=20), g) unweathered particles (N=20), h) particles exposed to sunlight and seawater for 9 months (N=20), i) particles exposed to sunlight and seawater for 18 months (N=20), and j) particles collected from the ocean (N=170).

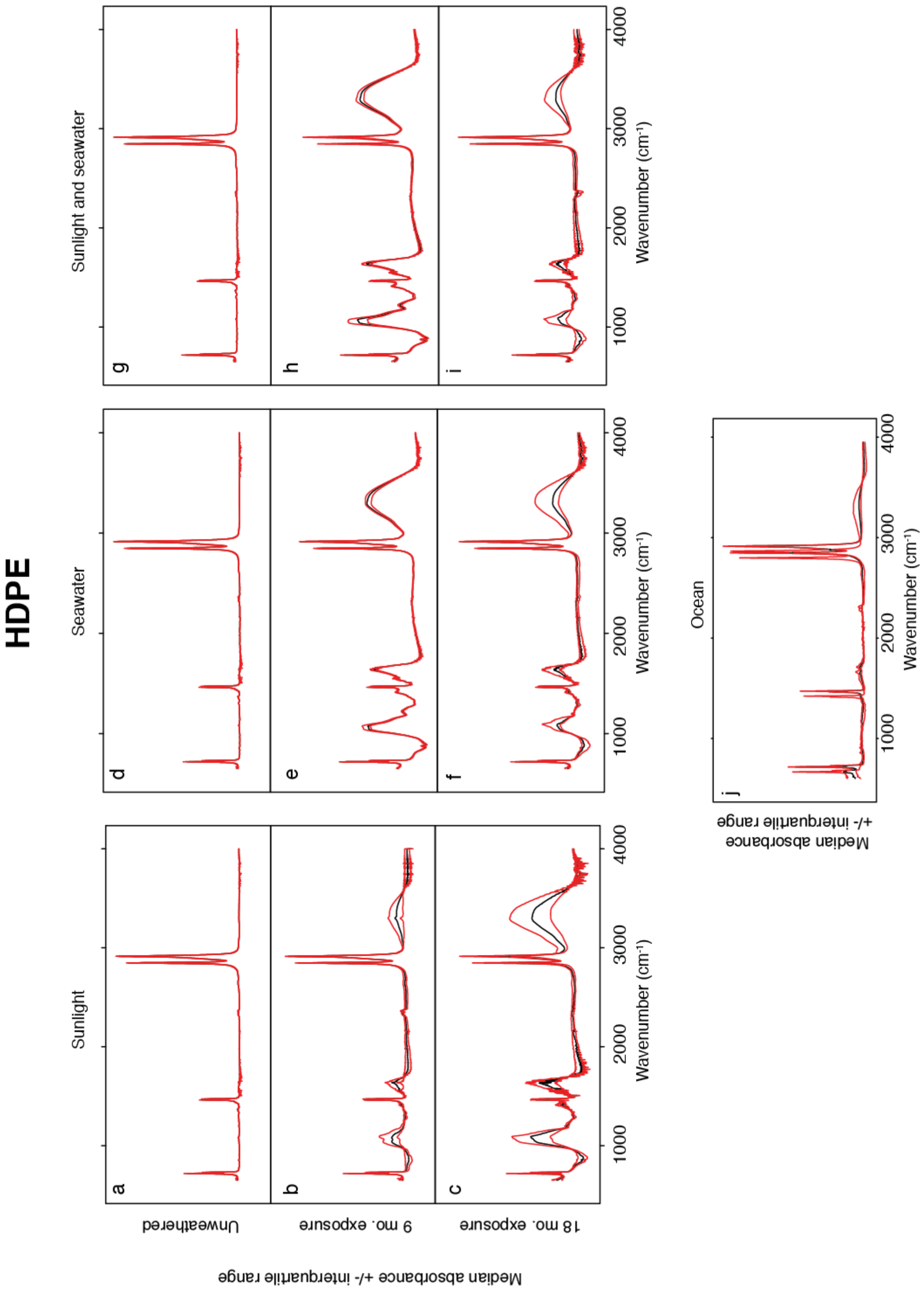
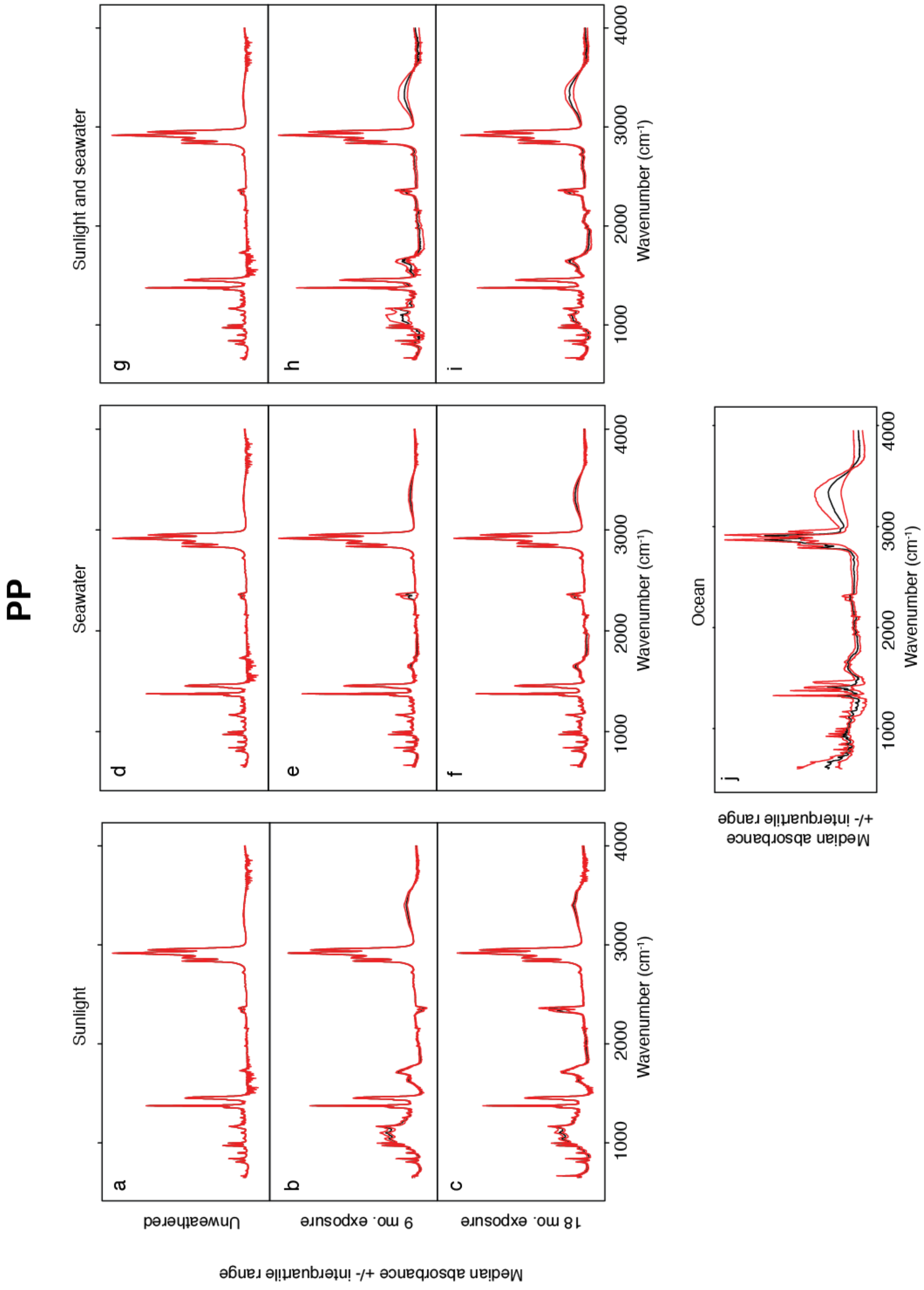

HDPE
Sunlight
Seawater
Sunlight and seawater
Unweathered
9 mo. exposure
18 mo. exposure
Median absorbance +/- interquartile range
a
b
c
d
e
f
g
h
i
1000
2000
3000
4000
Wavenumber (cm-1)
Ocean
j
Median absorbance +/- interquartile range

Figure S3.3. Polypropylene median spectra
PP median spectra (black line), with interquartile range (red line) for: a) unweathered particles (N=23), b) particles exposed to sunlight for 9 months (N=20), c) particles exposed to sunlight for 18 months (N=30), d) unweathered particles (N=23), e) particles exposed to seawater for 9 months (N=20), f) particles exposed to seawater for 18 months (N=27), g) unweathered particles (N=23), h) particles exposed to sunlight and seawater for 9 months (N=20), i) particles exposed to sunlight and seawater for 18 months (N=29), and j) particles collected from the ocean (N=106).


PP
Sunlight
Seawater
Sunlight and seawater
Unweathered
9 mo. exposure
18 mo. exposure
Ocean
Median absorbance +/- interquartile range
a
b
c
d
e
f
g
h
i
j
1000
2000
3000
4000
Wavenumber (cm^{-1})

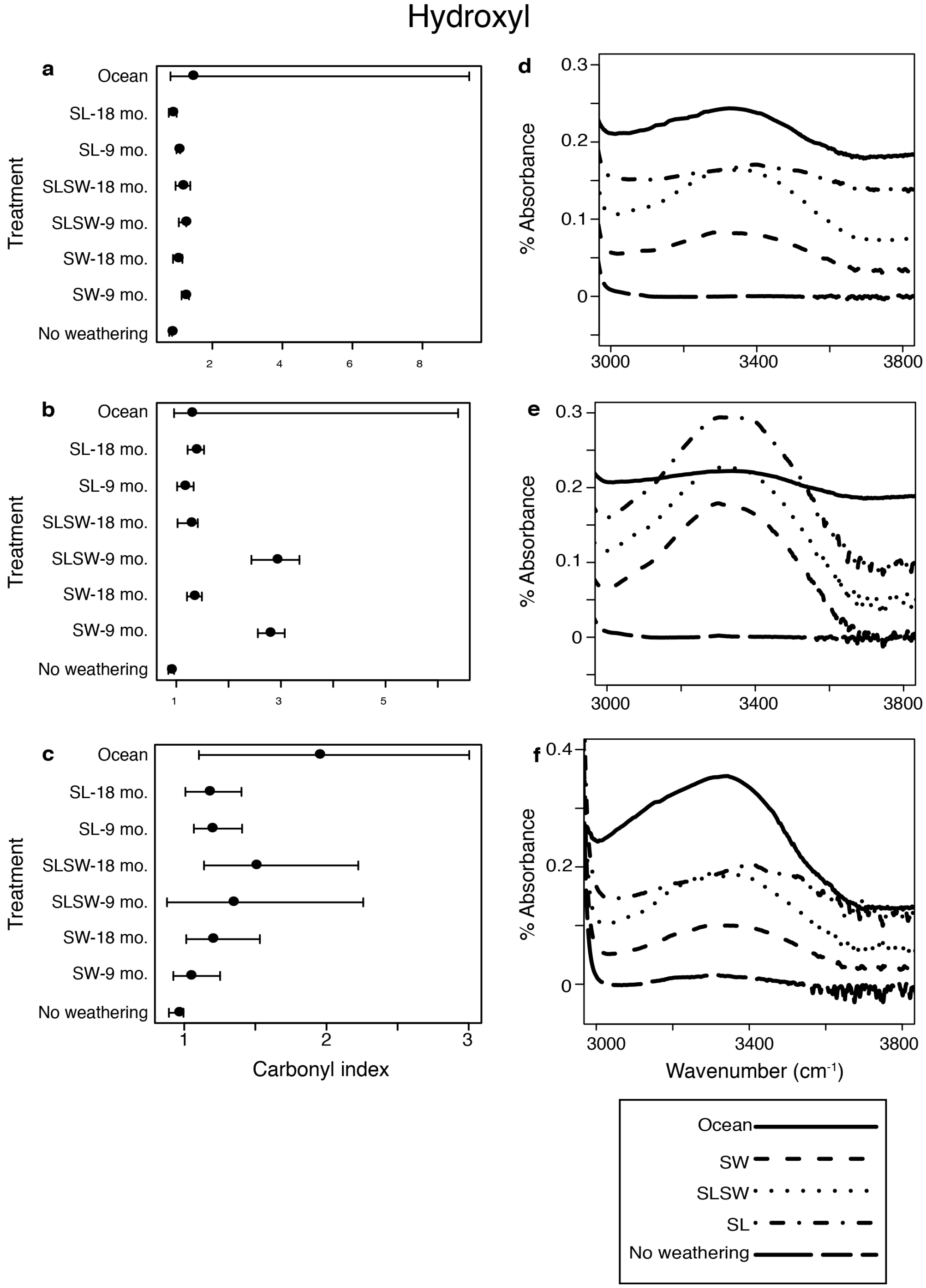


Figure S3.4 Hydroxyl content in oceanic particles and in the weathering experiment

Panels on the left show the median hydroxyl index value with 95% confidence intervals. Panels on the right show the median infrared spectra from 3000-3800 cm^{-1}. See Figure 3.5 for abbreviations. Plastic types are: a,d) low-density polyethylene (LDPE), b.e) high-density polyethylene (HDPE), c.f) polypropylene (PP).

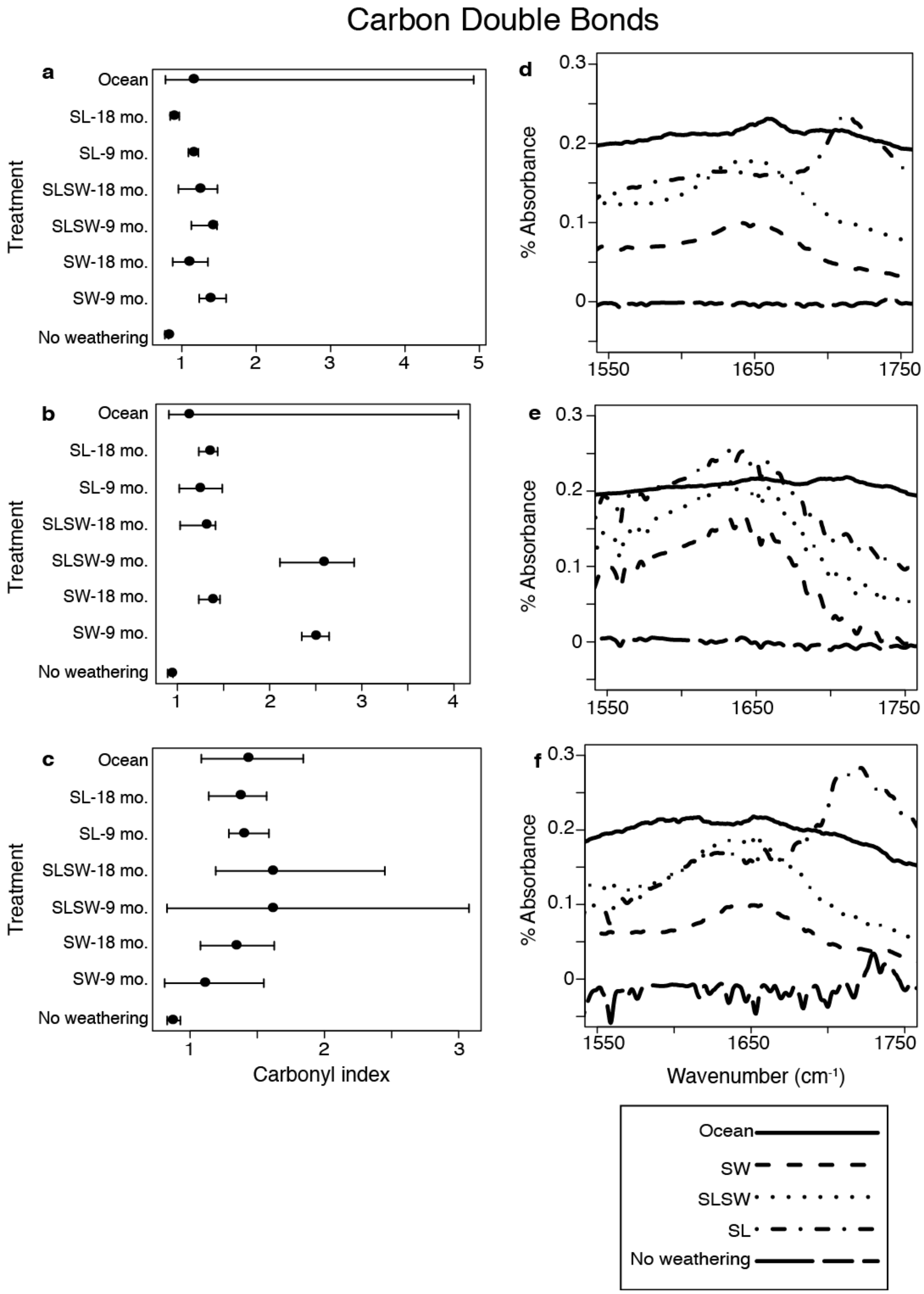


Figure S3.5 Carbon double bond content in oceanic particles and in the weathering experiment

Panels on the left show the median carbon double bond index value with 95% confidence intervals. Panels on the right show the median infrared spectra from 1550-1750 cm^{-1}. See Figure 3.5 for abbreviations. Plastic types are: a,d) low-density polyethylene (LDPE), b.e) high-density polyethylene (HDPE), c.f) polypropylene (PP).

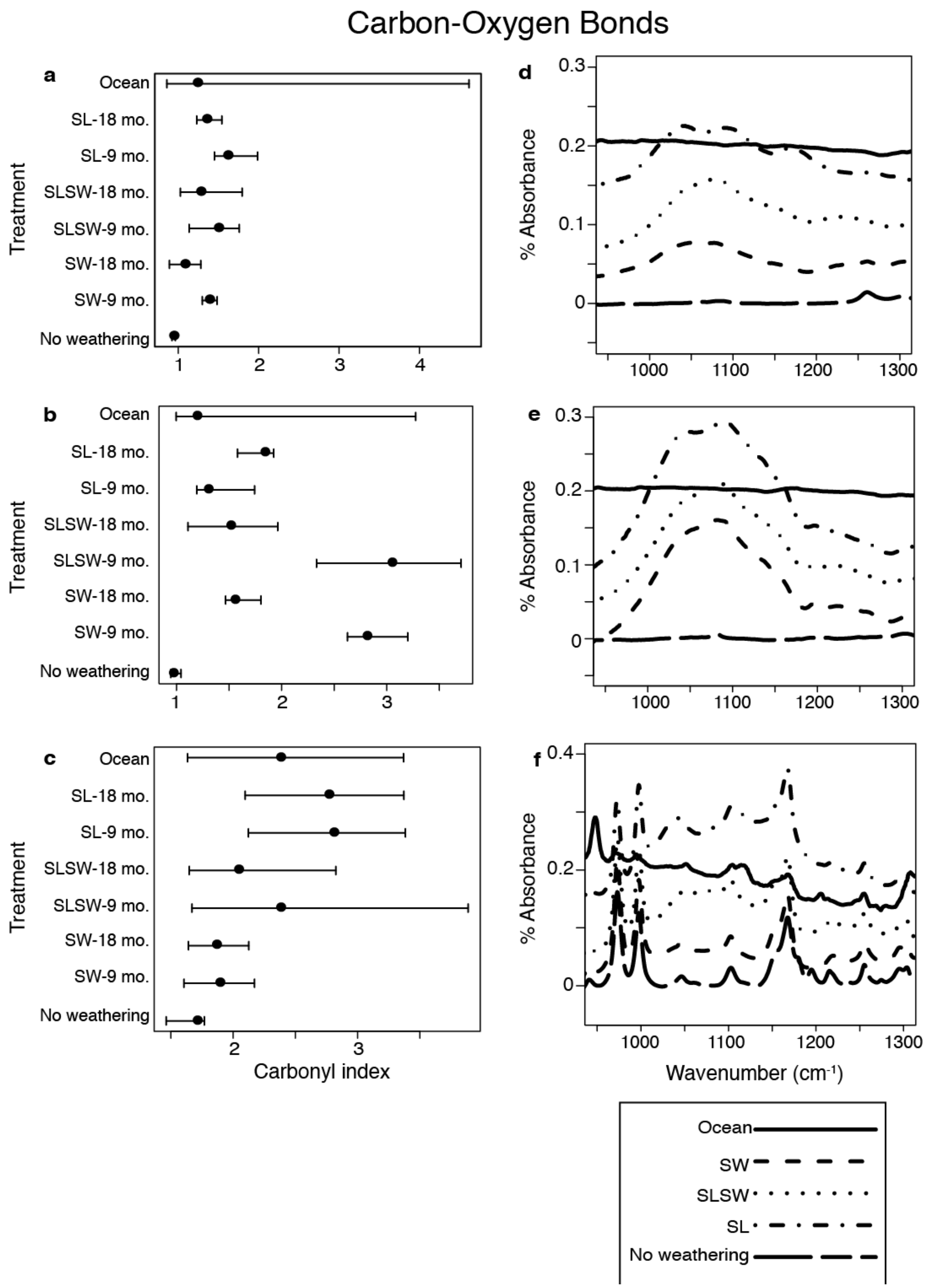


Figure S3.6 Carbon-oxygen bonds in oceanic particles and in the weathering experiment

Panels on the left show the median carbon-oxygen bond index value with 95% confidence intervals. Panels on the right show the median infrared spectra from 3000-3800 cm^{-1}. See Figure 3.5 for abbreviations. Plastic types are: a,d) low-density polyethylene (LDPE), b.e) high-density polyethylene (HDPE), c.f) polypropylene (PP).

CHAPTER 4: Ingestion of microplastic by neustonic marine invertebrates

Abstract

Substantial quantities of small plastic particles, termed “microplastic,” have accumulated in the North Pacific Subtropical Gyre. However, the biological implications of microplastic remain poorly understood. This study evaluated microplastic ingestion in surface-dwelling copepods and rafting gooseneck barnacles (*Lepas* spp.). In a series of incubation experiments, copepods ingested minimal quantities of plastic. However, 32.5 % of opportunistically collected barnacles were found to have plastic particles in their gastrointestinal tract. These results suggest that the plastic-associated rafting assemblages dominated by lepadid barnacles may be more significantly impacted by microplastic ingestion than the neustonic zooplankton.

Introduction

Ingestion of plastic debris occurs in many marine species, including mammals (Eriksson and Burton 2003, Jacobsen et al. 2010), seabirds (Fry et al. 1987, Spear et al. 1995, Avery-Gomm et al. 2012), turtles (Bjorndal et al. 1994, Bugoni et al. 2001), and fishes (Boerger et al. 2010, Possatto et al. 2011, Davison and Asch 2011). One study estimated that more than 267 species have been documented to ingest plastic (Allsopp et al. 2006). Negative effects of plastic ingestion may include intestinal blockage, diminished feeding stimulus, lowered steroid hormone levels, delayed ovulation and reproductive failure (Azzarello and Van Vleet 1987, Derraik 2002).

Because oceanic plastic debris can contain high levels of hydrophobic toxins (Endo et al. 2005, Rios et al. 2010), ingestion of plastic debris may also increase toxic exposure (Teuten et al. 2009).

Since most plastic ingestion has been documented in vertebrates, the extent of plastic ingestion in marine invertebrates remains poorly known. Laboratory experiments suggest that many invertebrates ingest plastic. Suspended plastic microparticles (2-60 µm in diameter) were successfully fed to calanoid copepods, cladocerans, and salps in the context of studying particle size selectivity (Burns 1968, Wilson 1973, Frost 1977, Kremer and Madin 1992). Microplastics were also readily ingested by a variety of benthic invertebrates in laboratory studies (Thompson et al. 2004, Browne et al. 2008, Graham and Thompson 2009). In natural ecosystems, microplastic fibers were found in Norway lobster (*Nephrops norvegicus*; Murray and Cowie 2011), and plastic line in flying squid (*Ommastrephes bartrami*; Day 1988 cited in Laist 1997).

While plastic pollution has been documented in a wide variety of marine ecosystems, particularly high concentrations of microplastic particles less than 5 mm in diameter have been found in the subtropical gyres (Carpenter and Smith 1972, Wong et al. 1974, Day and Shaw 1987, Moore et al. 2001, Law et al. 2010, Goldstein et al. 2012a). In such areas of the ocean, the majority of microplastic floats at the surface (Goldstein et al. 2012b), though wind mixing moves some particles deeper (Kukulka et al. 2012). Therefore, the biota most likely to be impacted by microplastic pollution is the neuston, a specialized community associated with the air-sea interface which includes both zooplankton and substrate-associated rafting organisms (Cheng 1975).

The goals of this study were to investigate microplastic ingestion in the North Pacific Subtropical Gyre (NPSG) neuston. We hypothesized that the incidence of microplastic ingestion would be positively correlated to microplastic concentration. To this end, (a) NPSG zooplankton were incubated at sea with varying quantities of added microplastic; (b) the gut contents of NPSG rafting barnacles were examined for evidence of microplastic ingestion.

Methods

Zooplankton incubation experiments

Zooplankton from the California Current (CC) were collected from a small boat approximately 2 km off Scripps Institution of Oceanography in La Jolla, California. Zooplankton from the NPSG were collected from the Sea Education Association vessel SSV *Robert C. Seamans* (Fig 4.1). For both sets of samples, neustonic zooplankton were collected by towing a 30x45 cm "mini-neuston" net for 15 minutes at 0.5-1 meters s^{-1}. The net consisted of a rectangular frame supported by floats, a 333 µm Nitex net, and a 4 liter solid cod end. After the net was retrieved, the contents of the cod end were immediately transferred into a bucket, diluted, and placed out of the sun.

Prior to incubations, fluorescent polyethylene beads (27-45 µm in diameter; Cospheric Fluorescent Yellow) were soaked in unfiltered local seawater for 3 days. Incubation experiments were performed in 8 one-liter glass jars mounted on a plankton wheel. For the CC samples, the plankton wheel was placed in an 18° C cold room, and for the NPSG samples, the plankton wheel was rotated through a flowing seawater bath. Each jar was filled with unfiltered local seawater.

Ten to twenty actively swimming zooplankton were gently transferred into each jar. Zooplankton were randomly selected, but in practice the vast majority were copepods. Each jar also was also randomly assigned a bead concentration of either 10 beads L^{-1}, 100 beads L^{-1}, or 1000 beads L^{-1}. The copepods were incubated with the beads for 20-22 hours. After this time, the contents of the jars were filtered onto a 20 μm Nitex filter and frozen at -20° C. An incubation was defined as successful if 75% or more of the copepods were alive at the end of the incubation period. In total, 24 successful incubations were performed in the CC, and 53 in the NPSG.

In the laboratory, samples were examined under an epifluorescence microscope (365 nm excitation, 450 nm emission) for evidence of plastic ingestion. Beads found in either the digestive tract (Fig 4.2a, 4.2b) or in fecal pellets (Fig 4.2c) were considered to be ingested. If multiple beads were present in either a copepod's body or in a fecal pellet, each bead was counted as a separate instance of ingestion. The rate of plastic ingestion was calculated as: ((No.plastic beads in copepod digestive tract+No.beads in fecal pellets))/(No.copepods*hours incubated). Fecal pellet production was calculated as: (No.fecal pellets)/(No.copepods*hours incubated).

Ingestion by barnacles

Floating debris items with attached gooseneck barnacles (*Lepas anatifera* and *Lepas pacifica*) were opportunistically collected during the 2009 Scripps

Environmental Accumulation of Plastic Expedition (SEAPLEX). If possible, the entire piece of debris with attached barnacles was preserved in 5% Formalin buffered with sodium borate. When the item was too large to be preserved (e.g., a fishing buoy), barnacles were removed and preserved separately. Due to the limitations of this method, a large number of the barnacles in this study (53 of 80 examined) came from a single buoy.

In the laboratory, barnacles were dissected and the contents of their stomach and intestinal tract examined under a dissecting microscope. Plastic particles found in the stomach or intestine were quantified, photographed digitally, and their size measured with the software package NIH ImageJ. Statistics and figures were generated with the R statistical environment, version R-2.13.1 (R Development Core Team 2011). The Nemenyi-Damico-Wolfe-Dunn post-hoc test was performed using the coin package (Hothorn et al. 2008).

Results

Zooplankton incubation experiments

Copepod ingestion of microplastic beads in either the California Current (CC) or North Pacific Subtropical Gyre (NPSG) was minimal (Fig 4.2d, 4.2e), with median values of 0.001 and 0 beads ingested copepod^{-1} h^{-1}, respectively. There was no significant difference among ingestion rates at different microplastic concentrations offered in the CC (Kruskal-Wallis p=0.329). In the NPSG there were significant differences among microplastic concentrations (Kruskal-Wallis p=0.001), but only the ingestion rate at the highest prey concentration differed from the other two (Nemenyi-

Damico-Wolfe-Dunn post-hoc p=0.006). There were no significant differences among fecal pellet production rates at difference microplastic concentrations in either the CC (Kruskal-Wallis p=0.134) or the NPSG (p=0.993).

At the low and medium microplastic concentrations, more beads were ingested in the CC than in the equivalent NPSG treatments (Mann-Whitney U, low p=0.005, medium p=0.001). At the high microplastic concentration, there was no significant difference in ingestion between the CC and NPSG (Mann-Whitney U p=0.106). There was no significant difference in fecal pellet production between the CC and NPSG in any of the treatments (Mann-Whitney U; low p=0.896, medium p=0.784, high p=0.273).

Ingestion by barnacles

Of the 63 *Lepas pacifica* and 17 *Lepas anatifera* examined, 24 *L. pacifica* and 2 *L. anatifera* contained plastic (a total of 26 of 80, or 32.5%). Twelve of the barnacles that ingested plastic had one plastic particle in their stomach or intestines, 5 individuals had two particles, and 9 individuals contained 3 or more particles, to a maximum of 6 (Fig 4.3a). The number of ingested particles was significantly related to capitulum length, with larger individuals ingesting more plastic (Fig 4.3b, Spearman's rank, p<0.001).

In total, 62 plastic particles were recovered from barnacle digestive tracts. Of these, 95% were degraded fragments and 5% were monofilament line. None of the pre-production pellets known as "nurdles" were found. The median surface area of ingested particles was 0.91 mm^2 (Equivalent Circular Diameter (ECD)=0.54 mm), smaller than the median surface area of 1.27 mm^2 (ECD=0.63 mm) for all particles collected in 2009 (Fig 4.3c, Kolmogorov-Smirnov test p=0.002). The smallest particle ingested by barnacles was 0.08 mm^2 (ECD=0.16 mm), and the largest 3.70 mm^2 (ECD=1.08 mm) No blockage of the stomach or intestine was observed, and particles did not accumulate in any area of the digestive tract. All particles were of a plausible size to pass through the anus.

Discussion

When exposed to ecologically realistic concentrations of microplastic, neustonic zooplankton in this study consumed relatively few plastic particles. While the quantity and size spectra of sub-333 µm microplastic in the surface waters of the NPSG have not yet been directly measured, the microplastic concentrations used in this study are plausible based on a meta-analysis of all available plastic size spectra data (Hidalgo-Ruz et al. 2012). Zooplankton have been shown to readily ingest microplastic under laboratory conditions (Burns 1968, Wilson 1973, Frost 1977), but those studies used substantial higher microplastic concentrations of approximately 70-100,000 beads L^{-1} to mimic phytoplankton concentrations (Huntley et al. 1983, Paffenhöfer and Van Sant 1985). The concentrations of microplastic used in this experiment (10-1,000 beads L^{-1}) were substantially lower, which may partially explain the lack of ingestion.

There is some evidence that copepod ingestion of plastic may be species-specific. For example, the marine copepod *Temora longicornis* was more likely to ingest plastic beads that *Pseudocalanus* spp., and both were more likely to ingest plastic than the freshwater copepod *Eudiaptomus gracilis* (DeMott 1988). In the present study, the CC copepods were primarily *Calanus pacificus* while the NPSG copepods were primarily Pontellidae and *Clausocalanus* spp. It is possible that difference in species composition explained why, at low and medium concentration of microplastic. CC copepods ingested microplastic at higher rates than those in the NPSG.

Evidence that the presence of non-edible particles reduces the rate of feeding on edible particles has been found in some studies (Huntley et al. 1983, Ayukai 1987), but not others (DeMott 1989), and found to be dependent on particle size (Huntley et al. 1983). Along with the lack of direct ingestion, the present study found no relationship between microplastic and fecal pellet production, which suggests that copepod feeding on phytoplankton was not affected by microplastic concentration, although the rate of fecal pellet production was low.

While many copepods are known to be selective feeders (Kleppel 1993), lepadid barnacles are quite non-selective. *Lepas anatifera* opportunistically ingests a wide variety of zooplankton and even fills its gut with sand when stranded on the beach (Howard and Scott 1959). *L. anatifera* can also readily ingest large prey items up to 5 mm in diameter, larger than the majority of microplastic debris (Patel 1959). Less is known about the feeding habits of *L. pacifica*, but it is presumed to have a similar feeding ecology as *L. anatifera* and other lepadid barnacles (Crisp and Southward 1961, Cheng and Lewin 1976). The relatively high percentage of barnacles that had ingested microplastic may therefore be explained by non-selective suspension feeding when exposed to the high concentrations of microplastic present in the NPSG.

Microplastic particles were also found in 9.2% of mesopelagic fishes collected on the same expedition as the barnacles (Davison and Asch 2011). It is likely that barnacles encounter microplastic more frequently than vertically migrating mesopelagic fishes, due to the barnacles' location at the air-sea interface. The objects to which the barnacles are attached may also shed microplastic particles, increasing the likelihood of ingestion by barnacles.

Assessing the ecological significance of plastic ingestion in pelagic invertebrates and fishes remains a challenge. Even in relatively well-studied species, it has been difficult to link plastic ingestion to mortality. For example, two studies of plastic ingestion by Laysan and black-footed albatross chicks did not find a linkage between cause of death and plastic ingestion (Sileo et al. 1990, Sievert and Sileo 1993), though a third study linked plastic ingestion with lower body weight in adult birds (Spear et al. 1995). Plastic ingestion may also lead to increased body loads of persistent organic pollutants in both vertebrates and invertebrates (Endo et al. 2005, Teuten et al. 2009, Yamashita et al. 2011), but it is not known whether this occurs in barnacles, or has population-level ramifications in any taxa. None of the plastic ingestion studies on other benthic invertebrates found acute negative effects from plastic ingestion, though these studies were all relatively short-term (Thompson et al. 2004, Browne et al. 2008, Graham and Thompson 2009). Likewise, the lepadid barnacles in this study did not show evidence of acute harm (e.g., intestinal blockage or ulceration), though negative long-term effects cannot be ruled out. Because *Lepas anatifera* appear to survive well in the laboratory (Patel 1959), more detailed toxicological studies may be possible.

If barnacles are an important prey item, it is possible that barnacle ingestion of plastic particles could transfer plastic or pollutants through the food web. Plastic particles found in fur seals (Eriksson and Burton 2003) and piscivorous fishes (Davison and Asch 2011) have been linked to consumption of contaminated prey. However, the only documented predator of rafting *Lepas* spp. is the nudibranch *Fiona pinnata,* (Bieri 1966), though it is probable that omnivorous rafting crabs also consume barnacles to some extent (Davenport 1992, Frick et al. 2011). Relatively low rates of predation on these barnacles may explain *Lepas'* place as one of the most abundant members of the North Pacific subtropical rafting community (Newman and Abbott 1980, Thiel and Gutow 2005). For example, one study found that *L. pacifica* was excluded from nearshore kelp forests by the fish *Oxyjulis californica*, but was able to inhabit floating kelp paddies in high densities when *O. californica* was absent (Bernstein and Jung 1979). Therefore, the likelihood of predators ingesting plastic by feeding on barnacles seems relatively low.

While plastic ingestion in taxa such as sea turtles (Bugoni et al. 2001) and cetaceans (Jacobsen et al. 2010) is clearly detrimental, the implications for invertebrates may be taxon-specific. Our results suggest that the plastic-associated rafting assemblages dominated by lepadid barnacles may be more significantly impacted by microplastic ingestion than the neustonic zooplankton. Since little is known about the trophic structure and connectivity of both the rafting and drifting components of the neuston, additional studies are necessary to detect the impacts of microplastic ingestion on the pelagic ecosystem.

Acknowledgements

Ship time and laboratory space for the zooplankton incubations were provided by Sea Education Association on cruises S230 and S236. Assistance from the captain, crews, and students of the R/V *New Horizon* and SSV *Robert C. Seamans*, as well as M.D. Ohman, E. Zettler, M. Engels, and L. Sala made this project possible. Funding for the SEAPLEX cruise was provided by University of California Ship Funds, Project Kaisei/Ocean Voyages Institute, AWIS-San Diego, and NSF IGERT Grant No. 0333444. I was supported by California Department of Boating and Waterways (Contract 05-106-115), NSF GK-12 Grant No. 0841407 and donations from Jim & Kris McMillan, Jeffrey & Marcy Krinsk, Lyn & Norman Lear, Ellis Wyer, and an anonymous donor. Laboratory supplies, support, and some analytical equipment were supplied by the SIO Pelagic Invertebrate Collection and the California Current Ecosystem LTER site supported by NSF.

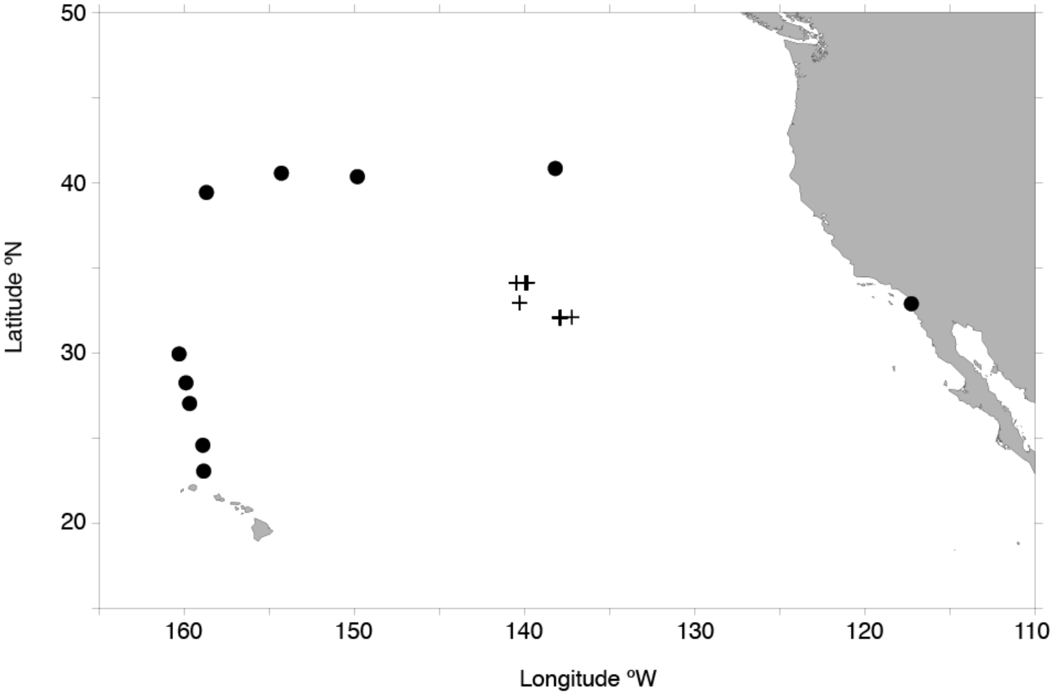


Figure 4.1. Map of the study area
Circles indicate locations of zooplankton incubation experiments and crosses indicate locations of barnacle collections.

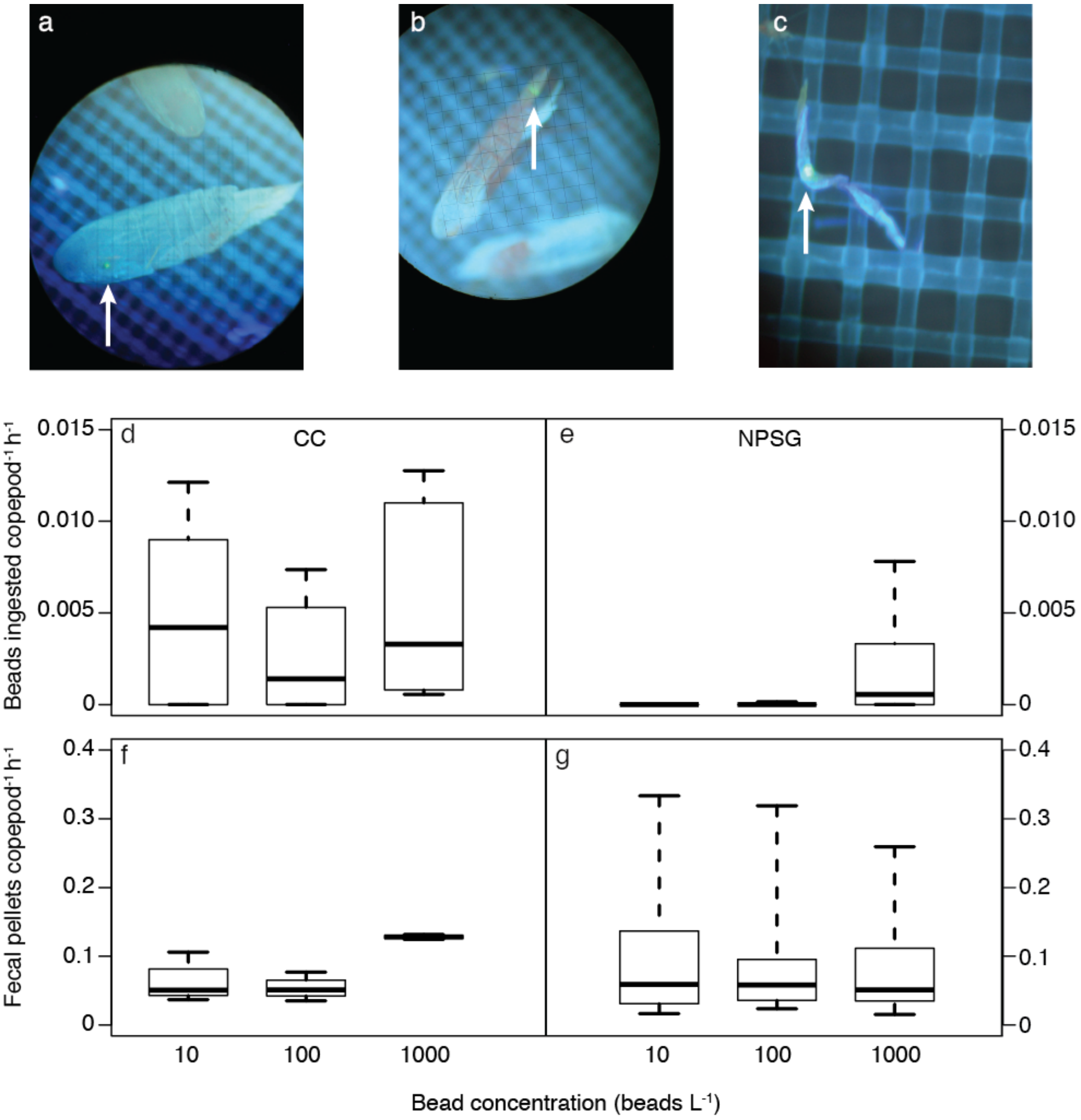


Figure 4.2. Copepod ingestion of microplastic particles
Microplastic particles are visible in (a) the foregut and (b) urosome of *Calanus pacificus* and inside a (c) fecal pellet. Rates of microplastic ingestion in the (d) California Current incubations and (e) the NPSG incubations are shown in relation to microplastic bead concentration, as are rates of fecal pellet production for the (f) California Current and (g) NPSG. Box plot whiskers are 95% confidence intervals. Sample sizes: California Current N=6, 13, 5; NPSG N=21, 20, 12.

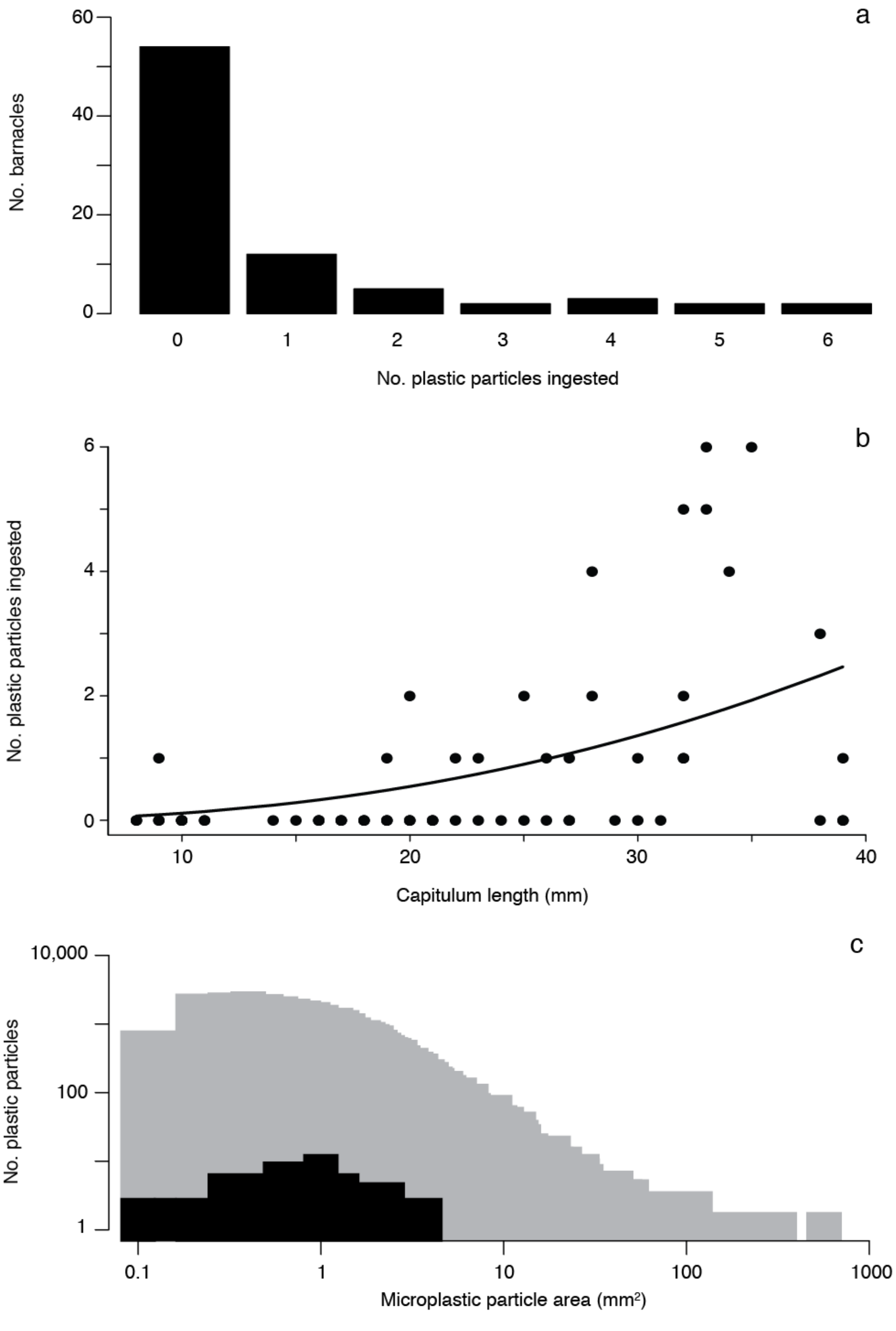


Figure 4.3. Barnacle ingestion of microplastic particles
(a) Frequency distribution of microplastic pellets ingested by individual lepadid barnacles (N=80). (b) Plastic particles ingested vs. capitulum length for each individual barnacle, fitted with an exponential curve. (N=64). (c) Size–frequency distributions for all microplastic particles collected in 2009 (grey; N=30,518) and particles ingested by barnacles (black; N=58). Note: 62 microplastic particles were recovered from barnacles, but 4 were lost before they could be photographed for this analysis.

References

Allsopp, M., A. Walters, D. Santillo, and P. Johnston. 2006. Plastic debris in the world's oceans. Page 44. Greenpeace.

Avery-Gomm, S., P. D. O'Hara, L. Kleine, V. Bowes, L. K. Wilson, and K. L. Barry. 2012. Northern fulmars as biological monitors of trends of plastic pollution in the eastern North Pacific. Marine Pollution Bulletin 64:1776–1781. doi: 10.1016/j.marpolbul.2012.04.017.

Ayukai, T. 1987. Discriminate feeding of the calanoid copepod Acartia clausi in mixtures of phytoplankton and inert particles. Marine Biology 94:579–587. doi: 10.1007/BF00431404.

Azzarello, M. Y., and E. S. Van Vleet. 1987. Marine birds and plastic pollution. Marine Ecology Progress Series 37:295–303. doi: 10.3354/meps037295.

Bernstein, B., and N. Jung. 1979. Selective pressures and coevolution in a kelp canopy community in southern California. Ecological Monographs 49:335–355. doi: 10.2307/1942488.

Bieri, R. 1966. Feeding preferences and rates of the snail, Ianthina prolongata, the barnacle, Lepas anserifera, the nudibranchs, Glaucus atlanticus and Fiona pinnata, and the food web in the marine neuston. Publications of the Seto Marine Biological Laboratory 14:161–170.

Bjorndal, K. A., A. B. Bolten, and C. J. Lagueux. 1994. Ingestion of marine debris by juvenile sea turtles in coastal Florida habitats. Marine Pollution Bulletin 28:154–158. doi: 10.1016/0025-326X(94)90391-3.

Boerger, C. M., G. L. Lattin, S. L. Moore, and C. J. Moore. 2010. Plastic ingestion by planktivorous fishes in the North Pacific Central Gyre. Marine Pollution Bulletin 60:2275–2278. doi: 10.1016/j.marpolbul.2010.08.007.

Browne, M. A., A. Dissanayake, T. S. Galloway, D. M. Lowe, and R. C. Thompson. 2008. Ingested microscopic plastic translocates to the circulatory system of the mussel, Mytilus edulis (L). Environmental Science & Technology 42:5026–31. doi: 10.1021/es800249a.

Bugoni, L., L. Krause, and M. V. Petry. 2001. Marine debris and human impacts on sea turtles in southern Brazil. Marine Pollution Bulletin 42:1330–1334. doi: 10.1016/S0025-326X(01)00147-3.

Burns, C. W. 1968. The relationship between body size of filter-feeding Cladocera and the maximum size of particle ingested. Limnology and Oceanography 13:675–678.

Carpenter, E. J., and K. L. Smith. 1972. Plastics on the Sargasso Sea surface. Science 175:1240. doi: 10.1126/science.175.4027.1240.

Cheng, L. 1975. Marine pleuston-animals at the sea-air interface. Oceanography and Marine Biology: An Annual Review 13:181–212.

Cheng, L., and R. A. Lewin. 1976. Goose barnacles (Cirripedia: Thoracica) on flotsam beached at La Jolla, California. Fishery Bulletin 74.

Crisp, D. J., and A. J. Southward. 1961. Different types of cirral activity of barnacles. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences 243:271–307.

Davenport, J. 1992. Observations on the ecology, behaviour, swimming mechanism and energetics of the neustonic grapsid crab, Planes minutus. Journal of the Marine Biological Association of the United Kingdom 72:611–620. doi: 10.1017/S0025315400059385.

Davison, P., and R. G. Asch. 2011. Plastic ingestion by mesopelagic fishes in the North Pacific Subtropical Gyre. Marine Ecology Progress Series 432:173–180. doi: 10.3354/meps09142.

Day, R. H., and D. G. Shaw. 1987. Patterns in the abundance of pelagic plastic and tar in the north Pacific Ocean, 1976-1985. Marine Pollution Bulletin 18:311–316. doi: 10.1016/S0025-326X(87)80017-6.

DeMott, W. R. 1988. Discrimination between algae and artificial particles by freshwater and marine copepods. Limnology and Oceanography 33:397–408.

DeMott, W. R. 1989. Optimal foraging theory as a predictor of chemically mediated food selection by suspension-feeding copepods. Limnology and Oceanography 34:140–154.

Derraik, J. G. B. 2002. The pollution of the marine environment by plastic debris: a review. Marine Pollution Bulletin 44:842–852. doi: 10.1016/S0025-326X(02)00220-5.

Endo, S., R. Takizawa, K. Okuda, H. Takada, K. Chiba, H. Kanehiro, H. Ogi, R. Yamashita, and T. Date. 2005. Concentration of polychlorinated biphenyls (PCBs) in beached resin pellets: Variability among individual particles and regional differences. Marine Pollution Bulletin 50:1103–1114.

Eriksson, C., and H. Burton. 2003. Origins and biological accumulation of small plastic particles in fur seals from Macquarie Island. AMBIO: A Journal of the Human Environment 32:380–384. doi: 10.1579/0044-7447-32.6.380.

Frick, M. G., K. Kopitsky, A. B. Bolten, K. A. Bjorndal, and H. R. Martins. 2011. Sympatry in grapsoid crabs (genera Planes and Plagusia) from olive ridley sea turtles (Lepidochelys olivacea), with descriptions of crab diets and masticatory structures. Marine Biology 158:1699–1708. doi: 10.1007/s00227-011-1684-9.

Frost, B. W. 1977. Feeding behavior of Calanus pacificus in mixtures of food particles. Limnology and Oceanography 22:472–491.

Fry, D. M., S. I. Fefer, and L. Sileo. 1987. Ingestion of plastic debris by Laysan Albatrosses and Wedge-tailed Shearwaters in the Hawaiian Islands. Marine Pollution Bulletin 18:339–343. doi: 10.1016/S0025-326X(87)80022-X.

Goldstein, M. C., M. Rosenberg, and L. Cheng. 2012a. Increased oceanic microplastic debris enhances oviposition in an endemic pelagic insect. Biology Letters 8:817–820. doi: 10.1098/rsbl.2012.0298.

Goldstein, M. C., A. J. Titmus, and M. Ford. 2012b. Scales of spatial heterogeneity of plastic marine debris in the northeast Pacific Ocean PLOS ONE, submitted.

Graham, E. R., and J. T. Thompson. 2009. Deposit- and suspension-feeding sea cucumbers (Echinodermata) ingest plastic fragments. Journal of Experimental Marine Biology and Ecology 368:22–29. doi: 10.1016/j.jembe.2008.09.007.

Hidalgo-Ruz, V., L. Gutow, R. C. Thompson, and M. Thiel. 2012. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environmental Science & Technology 46:3060–3075. doi: 10.1021/es2031505.

Hothorn, T., K. Hornik, M. A. van de Wiel, and A. Zeileis. 2008. Implementing a class of permutation tests: the coin package. Journal of Statistical Software 28:1–23.

Howard, G., and H. Scott. 1959. Predaceous feeding in two common gooseneck barnacles. Science 129:717–718. doi: 10.1126/science.129.3350.717.

Huntley, M. E., K.-G. Barthel, and J. L. Star. 1983. Particle rejection by Calanus pacificus: discrimination between similarly sized particles. Marine Biology 74:151–160. doi: 10.1007/BF00413918.

Jacobsen, J. K., L. Massey, and F. Gulland. 2010. Fatal ingestion of floating net debris by two sperm whales (Physeter macrocephalus). Marine Pollution Bulletin 60:765–767. doi: 10.1016/j.marpolbul.2010.03.008.

Kleppel, G. S. 1993. On the diets of calanoid copepods. Marine Ecology Progress Series 99:183–195.

Kremer, P., and L. P. Madin. 1992. Particle retention efficiency of salps. Journal of Plankton Research 14:1009–1015. doi: 10.1093/plankt/14.7.1009.

Kukulka, T., G. Proskurowski, S. Morét-Ferguson, D. W. Meyer, and K. L. Law. 2012. The effect of wind mixing on the vertical distribution of buoyant plastic debris. Geophysical Research Letters 39:6 pp. doi: 201210.1029/2012GL051116.

Laist, D. 1997. Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. Pages 99–140 *in* J. Coe and D. Rogers, editors. Marine debris: sources, impact and solutions. Springer, New York.

Law, K. L., S. Moret-Ferguson, N. A. Maximenko, G. Proskurowski, E. E. Peacock, J. Hafner, and C. M. Reddy. 2010. Plastic accumulation in the North Atlantic Subtropical Gyre. Science 329:1185–1188. doi: 10.1126/science.1192321.

Moore, C. J., S. L. Moore, M. K. Leecaster, and S. B. Weisberg. 2001. A comparison of plastic and plankton in the North Pacific central gyre. Marine Pollution Bulletin 42:1297–1300. doi: 10.1016/S0025-326X(01)00114-X.

Murray, F., and P. R. Cowie. 2011. Plastic contamination in the decapod crustacean Nephrops norvegicus (Linnaeus, 1758). Marine Pollution Bulletin 62:1207–1217. doi: 10.1016/j.marpolbul.2011.03.032.

Newman, W. A., and D. P. Abbott. 1980. Cirripedia: The Barnacles. Pages 504–535 *in* R. H. Morris, D. P. Abbott, and E. C. Haderlie, editors. Intertidal Invertebrates of California. Stanford University Press, Stanford.

Paffenhofer, G.-A., and K. B. Van Sant. 1985. The feeding response of a marine planktonic copepod to quantity and quality of particles. Marine Ecology Progress Series 27:55–65.

Patel, B. 1959. The influence of temperature on the reproduction and moulting of Lepas anatifera L. under laboratory conditions. Journal of the Marine Biological Association of the United Kingdom 38:589–597. doi: 10.1017/S0025315400007013.

Possatto, F. E., M. Barletta, M. F. Costa, J. A. Ivar do Sul, and D. V. Dantas. 2011. Plastic debris ingestion by marine catfish: An unexpected fisheries impact. Marine Pollution Bulletin 62:1098–1102. doi: 10.1016/j.marpolbul.2011.01.036.

R Development Core Team. 2011. R: A language and environment for statistical computing. Vienna, Austria. Retrieved from http://www.r-project.org.

Rios, L., P. Jones, C. Moore, and U. Narayan. 2010. Quantitation of persistent organic pollutants adsorbed on plastic debris from the Northern Pacific Gyre's "eastern garbage patch". Journal of Environmental Monitoring 12:2226–2236. doi: 10.1039/c0em00239a.

Sievert, P. R., and L. Sileo. 1993. The effects of ingested plastic on growth and survival of albatross chicks. *in* K. Vermeer, K. T. Briggs, K. H. Morgan., and D. Siegel-Causey, editors. The status, ecology, and conservation of marine birds of the North Pacific. Canadian Wildlife Service Special Publications, Ottawa.

Sileo, L., P. Sievert, and M. Samuel. 1990. Causes of mortality of albatross chicks at Midway Atoll. Journal of Wildlife Diseases 26:329–338.

Spear, L. B., D. G. Ainley, and C. A. Ribic. 1995. Incidence of plastic in seabirds from the tropical pacific, 1984-1991: Relation with distribution of species, sex, age, season, year and body weight. Marine Environmental Research 40:123–146. doi: 10.1016/0141-1136(94)00140-K.

Teuten, E. L., J. M. Saquing, D. R. U. Knappe, M. A. Barlaz, S. Jonsson, A. Bjorn, S. J. Rowland, R. C. Thompson, T. S. Galloway, R. Yamashita, D. Ochi, Y. Watanuki, C. Moore, V. Pham Hung, T. S. Tana, M. Prudente, R. Boonyatumanond, M. P. Zakaria, K. Akkhavong, Y. Ogata, H. Hirai, S. Iwasa, K. Mizukawa, Y. Hagino, A. Imamura, M. Saha, and H. Takada. 2009. Transport and release of chemicals from plastics to the environment and to wildlife. Philosophical Transactions of the Royal Society of London B 364:2027–2045. doi: 10.1098/rstb.2008.0284.

Thiel, M., and L. Gutow. 2005. The ecology of rafting in the marine environment II: The rafting organisms and community. Oceanography and Marine Biology: An Annual Review 43:279–418.

Thompson, R. C., Y. Olsen, R. P. Mitchell, A. Davis, S. J. Rowland, A. W. G. John, D. McGonigle, and A. E. Russell. 2004. Lost at sea: Where is all the plastic? Science 304:838. doi: 10.1126/science.1094559.

Wilson, D. S. 1973. Food size selection among copepods. Ecology 54:909–914.

Wong, C. S., D. R. Green, and W. J. Cretney. 1974. Quantitative tar and plastic waste distributions in Pacific Ocean. Nature 247:30–32. doi: doi:10.1038/247030a0.

Yamashita, R., H. Takada, M. Fukuwaka, and Y. Watanuki. 2011. Physical and chemical effects of ingested plastic debris on short-tailed shearwaters, Puffinus tenuirostris, in the North Pacific Ocean. Marine Pollution Bulletin 62:2845–2849. doi: 10.1016/j.marpolbul.2011.10.008.

CHAPTER 5: Increased oceanic microplastic debris enhances oviposition in an endemic pelagic insect

biology
letters
Marine biology

Biol. Lett. (2012) **8**, 817–820
doi:10.1098/rsbl.2012.0298
Published online 9 May 2012

Increased oceanic microplastic debris enhances oviposition in an endemic pelagic insect

Miriam C. Goldstein[1,*], Marci Rosenberg[1,2] and Lanna Cheng[1]

[1] *Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA 92093, USA*
[2] *University of California Los Angeles, Los Angeles, CA 90095, USA*
**Author for correspondence (mgoldstein@ucsd.edu).*

Plastic pollution in the form of small particles (diameter less than 5 mm)—termed 'microplastic'—has been observed in many parts of the world ocean. They are known to interact with biota on the individual level, e.g. through ingestion, but their population-level impacts are largely unknown. One potential mechanism for microplastic-induced alteration of pelagic ecosystems is through the introduction of hard-substrate habitat to ecosystems where it is naturally rare. Here, we show that microplastic concentrations in the North Pacific Subtropical Gyre (NPSG) have increased by two orders of magnitude in the past four decades, and that this increase has released the pelagic insect *Halobates sericeus* from substrate limitation for oviposition. High concentrations of microplastic in the NPSG resulted in a positive correlation between *H. sericeus* and microplastic, and an overall increase in *H. sericeus* egg densities. Predation on *H. sericeus* eggs and recent hatchlings may facilitate the transfer of energy between pelagic- and substrate-associated assemblages. The dynamics of hard-substrate-associated organisms may be important to understanding the ecological impacts of oceanic microplastic pollution.

Keywords: microplastic; marine debris; North Pacific Subtropical Gyre; *Halobates sericeus*; neuston

1. INTRODUCTION

Plastic accumulation in the North Pacific Subtropical Gyre (NPSG)—colloquially known as the 'Great Pacific Garbage Patch'—has been a matter of public concern [1]. Before the advent of plastic marine debris, hard-substrate habitat in the NPSG was limited to relatively rare materials such as floating wood, pumice and seashells [2]. Despite this limitation, the NPSG houses a native substrate-associated rafting community that includes attached macroalgae, sessile as well as motile invertebrates and fishes [3]. The pelagic insect *Halobates sericeus* (Heteroptera: Gerridae), widespread across the eastern NPSG, belongs to both the surface-associated pelagic community (the 'neuston') and to the substrate-associated rafting community. *Halobates sericeus* moves freely over the air–sea interface where it preys on zooplankton, and is preyed upon by seabirds, marine turtles and surface-feeding fishes [4,5]. However, it requires hard substrates upon which to lay eggs, and therefore its reproduction is limited by the availability of floating materials [6].

Subtropical gyres are areas of convergence that accumulate particularly high concentrations of plastic marine debris [7–12]. Of this debris, the vast numerical majority is small fragments less than 5 mm in diameter, termed 'microplastic' [10–12]. Known environmental impacts of microplastic include ingestion by fishes and invertebrates [13–16], transport of organic pollutants [17] and alien species introduction [18]. To our knowledge, there have been no studies examining the effects of oceanic plastic debris on pelagic invertebrate communities. Because invertebrates are a critical link between primary producers and nekton, plastic-induced changes in their population structure could have ecosystem-wide consequences.

The goal of this study was to investigate the impact of microplastic debris as a novel habitat in the NPSG. To do this, we (i) quantified the increase in North Pacific microplastic over the past four decades; and (ii) correlated the increase in microplastic between 1972–1973 and 2009–2010 to changes in *H. sericeus* abundance.

2. MATERIAL AND METHODS

We combined data from all available georeferenced peer-reviewed literature [7–11] and other publicly available sources [19] to compare changes in microplastic abundance between 1972–1987 and 1999–2010 (electronic supplementary material, table S1). For *H. sericeus*, we used surface samples collected by neuston nets at sea between 1972–1973 and 2009–2010 (complete methods in the electronic supplementary material).

Samples were sorted under a dissecting microscope. *Halobates sericeus* was enumerated and classified by eye, whereas microplastic particles were enumerated and measured using the ZOOSCAN optical analysis system [10]. To determine the size range of particles used by *H. sericeus* for oviposition, the two-dimensional surface area and maximum diameter of a subset of plastic particles with attached eggs ($n = 207$) were measured using IMAGEJ (NIH). Dry mass of zooplankton and *H. sericeus* eggs were obtained from preserved samples.

We computed statistics using non-parametric methods in the R statistical environment (v. 2.13.1). Maps were created in SURFER v. 8 (Golden Software), and interpolated using point kriging. New data from this study are deposited with the California Current Ecosystem LTER DataZoo (http://oceaninformatics.ucsd.edu/datazoo/data/ccelter/datasets?action=group&id=1).

3. RESULTS

Microplastic debris in the North Pacific increased by two orders of magnitude between 1972–1987 and 1999–2010 in both numerical (NC) and mass concentrations (MC; figure 1 and electronic supplementary material, table S2). In 1972–1987, no microplastic was found in more than half of the samples (median NC = 0 particles m^{-3}, MC = 0 mg m ^{3}). By 1999–2010, median NC had increased significantly to 0.116 particles m ^{3} and MC to 0.086 mg m ^{3} (all following are two-tailed Mann–Whitney *U*-tests, NC = $p < 0.0001$; MC = $p < 0.0001$). This increase was driven primarily by an increase in microplastic abundance in the NPSG (electronic supplementary material, table S2; NC: $p < 0.0001$; MC: $p < 0.0001$). Although a significant increase in NC was also found off Alaska (electronic supplementary material, table S2; $p = 0.0197$), MC remained unchanged ($p = 0.3711$). There was no significant change in the California Current [10] or the Eastern Tropical Pacific (electronic supplementary

Electronic supplementary material is available at http://dx.doi.org/10.1098/rsbl.2012.0298 or via http://rsbl.royalsocietypublishing.org.

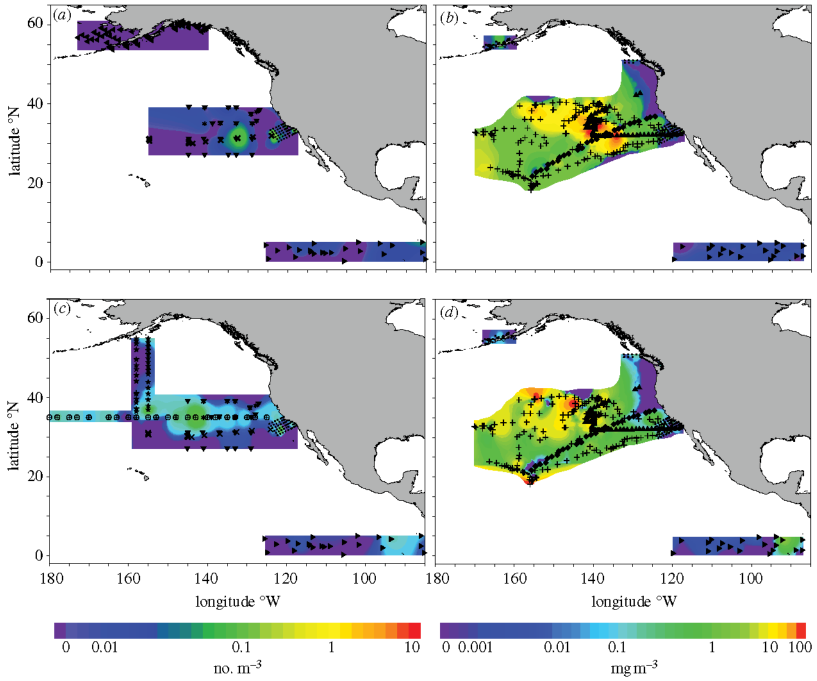


Figure 1. Microplastic concentrations in 1972–1987 and 1999–2010. Numerical concentration (no. m^{-3}) for (*a*) 1972–1987 and (*b*) 1999–2010; microplastic mass concentration (mg m^{-3}) for (*c*) 1972–1987 and (*d*) 1999–2010. New data from this study include 7205 (asterisks), 7210 (inverted triangles), Southtow 13 (cross symbols), STAR (right-facing triangles), SEAPLEX (triangles) and EX1006 (diamonds). Published data are Wong *et al.* [7] (crossed circles), Shaw [8] (stars), Day & Shaw [9] (left-facing triangles), Gilfillan *et al.* [10] (filled circles) and Doyle *et al.* [11] (filled circles). Gilfillan *et al.* [10] and Doyle *et al.* [11] have overlapping stations. Non-peer-reviewed publicly available data from Algalita Marine Research Foundation [19] (plus symbols).

material, table S2; NC: $p = 0.3332$; MC: $p = 0.2528$). These results were confirmed when we conducted additional subsampling as controls for regional and seasonal variation (see electronic supplementary material).

We found no association between microplastic concentration and the abundance of *H. sericeus* adults/juveniles in 1972–1973 (figure 2*a*), but a positive association in 2009–2010 (figure 2*b*). Similarly, there was no association between microplastic concentration and the abundance of *H. sericeus* eggs deposited on microplastic in 1972–1973 (figure 2*c*), but a positive association in 2009–2010 (figure 2*d*). We also found a significant increase in the median abundance of *H. sericeus* adults/juveniles and eggs (two-tailed Mann–Whitney *U*-test, adults/juveniles, $p = 0.0024$, eggs $p < 0.0001$). When seasonal variation in *H. sericeus* abundance was controlled by restricting the comparison to October 1972 and October 2010, egg abundance increased with plastic particle abundance (one-tailed Mann–Whitney *U*-test, $p = 0.0497$), but not adult/juvenile abundance ($p = 0.8680$).

Halobates sericeus eggs measured 0.8–1.2 mm in length and were found on microplastic particles ranging from 0.002 to 0.054 cm^2 ($M = 0.015$), a size class that includes 81.2 per cent of all particles collected in 2009–2010 (figure 2*e*,*f*). We estimate that the biomass of one to three eggs is equivalent to 9.2–27.6% of the daytime zooplankton biomass over 1 m^2 of the top 20 cm of surface water.

4. DISCUSSION

Our study associates the dramatic increase in microplastic abundance in the past 40 years with oviposition of *H. sericeus*, an abundant and conspicuous member of the NPSG pelagic community. Intra- and inter-annual samples from the NPSG in the intervening decades are not available, so we cannot rule out the possibility that there might be a more variable temporal pattern. However, the long-term trend supports a significant increase in microplastic concentration.

The abundance of both microplastic and *H. sericeus* are spatially and temporally heterogeneous within the NPSG, but *H. sericeus* is highly mobile and can skate at speeds up to 0.8–1.3 m s^{1} [4]. If *H. sericeus*

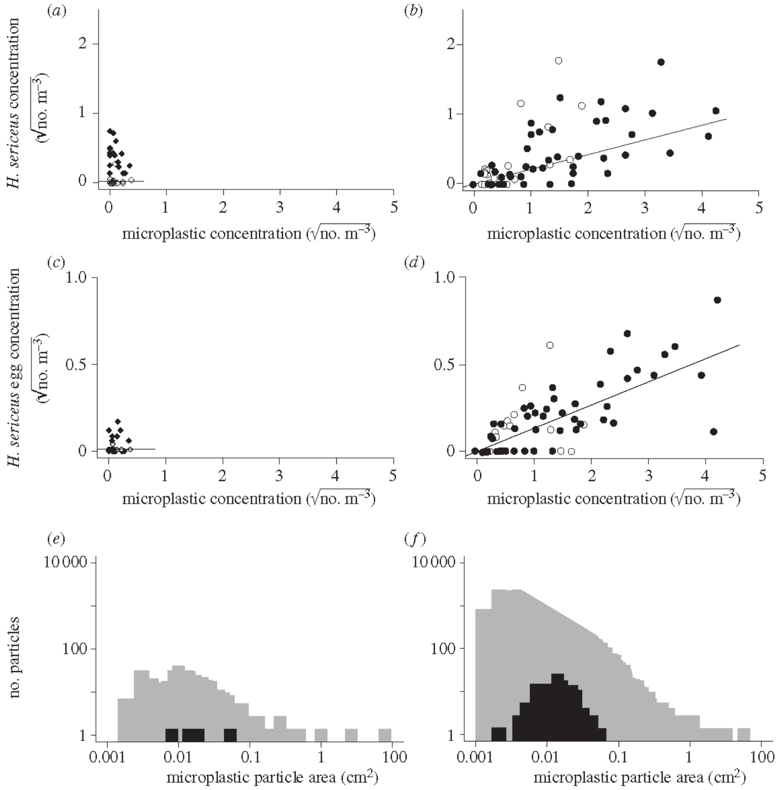


Figure 2. *Halobates sericeus* adult and juvenile numerical concentration (NC) versus microplastic NC in 1972–1973 (*a*: Spearman rank correlation, $p = 0.3644$; $r^2 = 0.019$) and 2009–2010 (*b*: Spearman rank correlation, $p < 0.0001$; $r^2 = 0.404$); *H. sericeus* egg NC versus microplastic NC in 1972–1973 (*c*: Spearman rank correlation $p = 0.0614$; $r^2 = 0.079$) and 2009–2010 (*d*: Spearman rank correlation, $p < 0.0001$; $r^2 = 0.512$). Also shown are size–frequency histograms for all microplastic particle areas (grey) and particles with attached eggs (black) in (*e*) 1972–1973 and (*f*) 2009–2010. Symbols (*a–d*) represent dates of data collection: spring 1972 (grey diamonds), autumn 1972 (filled diamonds), winter 1973 (open diamonds), summer 2009 (filled circles) and autumn 2010 (open circles). Only particles in the size range used by *H. sericeus* were used to calculate microplastic NC (*a–d*). Eggs in the samples for (*e*) were dislodged from their original substrate (63%) are excluded from this figure.

acted as a passive particle on the ocean surface, then a positive correlation between it and plastic abundance would be expected in all sampling periods. We found no such correlation for either adults/juveniles or eggs in 1972–1973, but a significant correlation for both adults/juveniles and eggs in 2009–2010 (figure 2). We interpret this to mean that microplastic increase has released this pelagic insect from substrate limitation for oviposition.

We estimated the increase in hard substrate in the top 20 cm of the NPSG (4×10^6 km^3; [20]). Microplastic particles in the size range used by *H. sericeus* increased from a median NC of 0.002 particles m^{-3} in 1972–1973 to 1.194 in 2009–2010, with a decrease in median surface area from 0.016 cm^2 to 0.015 cm^2. It should be noted that these microplastic NC are higher than those previously reported [2,10–12], potentially due to targeted sampling of high-plastic areas in our study. We caution that this is a rough approximation, but nonetheless suggests a substantial expansion of hard substrate available to *H. sericeus* and other substrate-associated organisms.

Predation on eggs and recent hatchlings may limit *H. sericeus* populations and transfer energy between pelagic and substrate-associated communities. For example, the epipelagic crab *Planes minutus* is known to prey on both *Halobates* individuals and eggs in the Atlantic Ocean [4]. Because eggs are equivalent to a substantial percentage (9.2–27.6%) of daytime NPSG biomass, they may be an efficient target for predators such as epipelagic crabs and omnivorous fishes, both of which were observed to be abundant during 2009–2010 sampling. *Halobates sericeus* is capable of oviposition on large items [6], but no eggs were found on large items in 2009–2010, suggesting that eggs may be removed from microplastic particles by predators.

The novel ecological interactions caused by the introduction of plastic particles to oceanic ecosystems, termed the 'plastisphere' [21], may transfer energy between pelagic and substrate-associated assemblages [3]. If microplastic densities continue to increase, then substrate-associated biota such as *H. sericeus* may be expected to increase as well, potentially at the expense of prey such as zooplankton or fish eggs [3,4]. Future work should incorporate the dynamics of substrate-associated assemblages with ongoing work in toxicology [17], microbial ecology [21] and faunal interactions [13–16] to provide a better understanding of the impact of microplastic pollution on pelagic marine ecosystems.

Funding for SEAPLEX was provided by University of California Ship Funds, Project Kaisei/Ocean Voyages Institute, AWIS-San Diego, and NSF IGERT (grant no. 0333444). EX1006 samples courtesy of the NOAA Okeanos Explorer Program, 2010 Always Exploring expedition, made possible by M. Ford. M.C.G. was supported by donations from Jim & Kris McMillan, Jeffrey & Marcy Krinsk, Lyn & Norman Lear, Ellis Wyer and an anonymous donor. Assistance from the crews of the R/V *New Horizon* and R/V *Okeanos Explorer*, L. Gilfillan, A. Townsend, L. Sala, the SIO Pelagic Invertebrate Collection, the CCE LTER site supported by NSF and many laboratory volunteers made this project possible. We thank Algalita Marine Research Foundation for their publicly available data. Conversations with M.D. Ohman, J. Drew, and J.E. Byrnes and comments from M. Thiel and an anonymous reviewer greatly improved this manuscript.

1 Kaiser, J. 2010 The dirt on ocean garbage patches. *Science* **328**, 1506. (doi:10.1126/science.328.5985.1506)

2 Thiel, M. & Gutow, L. 2005 The ecology of rafting in the marine environment. I. The floating substrata. *Oceanogr. Mar. Biol. Annu. Rev.* **42** 181–263. (doi:10.1201/9780203507810.ch6)

3 Thiel, M. & Gutow,, L. 2005 The ecology of rafting in the marine environment. II. The rafting organisms and community. *Oceanogr. Mar. Biol. Annu. Rev.* **43**, 279–418. (doi:10.1201/9781420037449.ch7)

4 Andersen, N. N. & Cheng, L. 2004 The marine insect *Halobates* (Heteroptera: Gerridae): biology, adaptations, distribution and phylogeny. *Oceanogr. Mar. Biol. Annu. Rev.* **42**, 119–180. (doi:10.1201/9780203507810.ch5)

5 Cheng, L., Spear, L. & Ainley, D. G. 2010 Importance of marine insects (Heteroptera: Gerridae, *Halobates* spp.) as prey of eastern tropical Pacific seabirds. *Mar. Ornithol.* **38**, 91–95.

6 Cheng, L. & Pitman, R. L. 2002 Mass oviposition and egg development of the ocean-skater *Halobates sobrinus* (Heteroptera: Gerridae). *Pac. Sci.* **56**, 441–447. (doi:10.1353/psc.2002.0033)

7 Wong, C. S., Green, D. R. & Cretney, W. J. 1974 Quantitative tar and plastic waste distributions in Pacific Ocean. *Nature* **247**, 30–32. (doi:10.1038/247030a0)

8 Shaw, D. G. 1977 Pelagic tar and plastic in the Gulf of Alaska and Bering Sea: 1975. *Sci. Total Environ.* **8**, 13–20. (doi:10.1016/0048-9697(77)90058-4)

9 Day, R. H. & Shaw, D. G. 1987 Patterns in the abundance of pelagic plastic and tar in the north Pacific Ocean, 1976–1985. *Mar. Pollut. Bull.* **18**, 311–316. (doi:10.1016/S0025-326X(87)80017-6)

10 Gilfillan, L. R., Ohman, M. D., Doyle, M. J. & Watson, W. 2009 Occurrence of plastic micro-debris in the southern California Current system. *Cal. Coop. Ocean. Fish.* **50**, 123–133.

11 Doyle, M. J., Watson, W., Bowlin, N. M. & Sheavly,, S. B. 2011 Plastic particles in coastal pelagic ecosystems of the Northeast Pacific ocean. *Mar. Environ. Res.* **71**, 41–52. (doi:10.1016/j.marenvres.2010.10.001)

12 Hidalgo-Ruz, V., Gutow, L., Thompson, R. C. & Thiel, M. 2012 Microplastics in the marine environment: a review of the methods used for identification and quantification. *Environ. Sci. Technol.* **46**, 3060–3075. (doi:10.1021/es2031505)

13 Boerger, C. M., Lattin, G. L., Moore, S. L. & Moore, C. J. 2010 Plastic ingestion by planktivorous fishes in the North Pacific Central Gyre. *Mar. Pollut. Bull.* **60**, 2275–2278. (doi:10.1016/j.marpolbul.2010.08.007)

14 Davison, P. & Asch, R. G. 2011 Plastic ingestion by mesopelagic fishes in the North Pacific Subtropical Gyre. *Mar. Ecol. Prog. Ser.* **432**, 173–180. (doi:10.3354/meps09142)

15 Thompson, R. C., Olsen, Y., Mitchell, R. P., Davis, A., Rowland, S. J., John, A. W. G., McGonigle, D. & Russell, A. E. 2004 Lost at sea: Where is all the plastic? *Science* **304**, 838. (doi:10.1126/science.1094559)

16 Browne, M. A., Dissanayake, A., Galloway, T. S., Lowe, D. M. & Thompson, R. C. 2008 Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus edulis* (L). *Environ. Sci. Technol.* **42**, 5026–5031. (doi:10.1021/es201811s)

17 Teuten, E. L. *et al.* 2009 Transport and release of chemicals from plastics to the environment and to wildlife. *Phil. Trans. R. Soc. B* **364**, 2027–2045. (doi:10.1098/rstb.2008.0284)

18 Barnes, D. K. A. 2002 Invasions by marine life on plastic debris. *Nature* **416**, 808–809. (doi:10.1038/416808a)

19 Algalita Marine Research Foundation. 2002–2011 Mapping plastic pollution: GIS Maps of plastic density in the North Pacific Subtropical Gyre (NPSG). See http://www.algalita.org/research/Maps_Home.html.

20 Karl, D. M. 1999 Minireviews: a sea of change: biogeochemical variability in the North Pacific Subtropical Gyre. *Ecosystems* **2**, 181–214. (doi:10.1007/s100219900068)

21 Zettler, E. R., Mincer, T., Proskurowski, G. & Amaral-Zettler, L. A. 2011 The 'plastisphere': a new and expanding habitat for marine protists. *J. Phycol.* **47**, S45.

Supplementary Material

Full Materials and Methods

Plastic numerical and mass concentration values included all available georeferenced data in the peer-reviewed literature as well as publicly available data from the Algalita Marine Research Foundation [Table S1]. Methods for the peer-reviewed data can be found in the publication in which they appeared. Because raw data from Algalita Marine Research Foundation were not made public, we used median values for each bin. When data were combined, we were able to compare changes in microplastic abundance between 1972-87 and 1999-2010.

Methods for new data, which includes samples from 1972-3 and 2009-10, are as follows. Samples from the early 1970s were collected on three cruises. Ten samples from 7205 (spring 1972) and 21 samples from 7210 (fall 1972) were collected using an ovoid 1-meter plankton net with 505 µm mesh towed for 20 minutes at the sea surface with a velocity of 0.7-1 m s^{-1} [S1]. A flowmeter was not used, but the deployers estimated the water flow through the net at 250-300 m^3. We used a value of 275 m^3 to calculate density from these tows. Fourteen samples from Southtow 13 (winter 1973) were collected using a rectangular neuston net (1.0 x 0.5 meters) with 505 µm mesh. These nets were towed at 2 m s^{-1} for varying amounts of time ranging from 20 minutes to 4 hours. Water flow through the net was calculated using the starting and ending coordinates. All samples were preserved in 1.8% formaldehyde buffered with sodium borate and archived in the Scripps Institution of Oceanography Pelagic Invertebrates Collection.

The 2009 samples (N=119 samples, 45 of which were also sampled for *Halobates*) were collected on the SEAPLEX cruise on the *R/V New Horizon* in August 2009. The 2010 samples (N=28) were collected on the EX1006 cruise on the R/V *Okeanos Explorer* in October 2010. Both sets of samples were collected using a standard manta net (0.86 x 0.2 m) with 333 µm mesh [S2], towed for 15 minutes at 0.7-1 m s^{-1}. Water through the net was measured with a General Oceanics analog flowmeter. The SEAPLEX samples were preserved in 1.8% formaldehyde buffered with sodium borate, and the EX1006 samples in 95% ethanol.

Each sample was sorted at 6-12x magnification under a Wild M-5 dissecting microscope, and plastic particles and *H. sericeus* removed for further analysis. Plastic particles were soaked in deionized water to remove salts, dried at 60°C, and stored in a desiccator. Dry mass was measured on an analytical balance. Particles were then digitally imaged with a Zooscan digital scanner [S3]. The total number of particles as well as two-dimensional surface area and maximum diameter of each particle were measured using NIH ImageJ-based tools in the Zooprocess software, calibrated against manual measurements [10, S3].

The diameter of plastic particles as measured by Zooscan was used to determine that there was no significant effect of the change from 505 µm plankton net mesh to 333 µm mesh. There was no significant difference in particle size spectra from fall 1972 to fall 2010 (Kolmogorov-Smirnov test, p=0.2228), and 98.5% of the particles caught in the 333 µm net would also have been caught in a 505 µm net.

H. sericeus samples were enumerated and classified into 5 categories: juvenile, adult male, adult female, newly molted, and molted exoskeletons. *H. sericeus* eggs, both those attached to plastic and those that had become detached during the collection process, were also enumerated. To determine the size range of particles utilized by *H. sericeus* for oviposition, the two-dimensional surface area and maximum diameter of a subset of plastic particles with attached eggs (N=207) were measured using NIH ImageJ, and compared to the size of all plastic particles collected in 2009-10 (N=32,090). Only plastic particles in the size range known to be utilized by *H. sericeus* were used to calculate plastic concentrations in Fig. 2 (N=26,045).

Dry mass of zooplankton was obtained from preserved manta tow samples (N=46, [S4]). After fixation in 1.8% formaldehyde for 24 months, samples were split in a Folsom splitter, filtered onto 202 µm Nitex mesh pads and rinsed with isotonic ammonium formate. Filters were dried for 24 hours at 60°C and placed in a dessicator until weighing. Filters were weighed to the nearest 0.0001 gram on the same analytical balance as the plastic samples. A 20% correction factor was applied in order to compensate for the biomass lost by preservation [S4, S5]. A similar method was used for dry mass of *H. sericeus* eggs (N=52), except that they were dried in pre-weighed aluminum crucibles and weighed on an electrobalance to the nearest microgram.

Maximum length of *H. sericeus* eggs ranges from 0.8-1.2 mm, and a single microplastic particle commonly has between 1 to 3 eggs attached. To compare the relative biomass of *H. sericeus* eggs and zooplankton, we divided the median egg dry mass (0.059 mg egg^{-1}) by 1 m^2 of the median daytime zooplankton dry mass (0.642 mg m^{-2}). Using this estimation, one egg was equivalent to 9.2% of the daytime zooplankton biomass in the top 20 cm of 1 m^2 of surface water, and three eggs (0.059 mg egg^{-1} x 3) equivalent to 27.6% of the median daytime zooplankton biomass. Daytime values were used because the conspicuous size and color of *H. sericeus* eggs make them likely prey for diurnal visual predators such as omnivorous fishes or seabirds.

We computed all statistics using the R statistical environment (version R-2.13.1) [S6]. Because the data did not meet parametric assumptions of normality, we used nonparametric methods with alpha values of 0.05. We used the Mann-Whitney test for abundance comparisons and the Spearman rank correlation to examine the relationship between *H. sericeus* and microplastic. R^2 values were calculated from Spearman's rho. Lines were fit to correlations using the Theil-Sen single median method as implemented in the R MBLM package [S7]. Maps were created in Surfer 8 (Golden Software) [S8] and interpolated using point kriging. Figures were created in R and formatted in Adobe Illustrator CS5.1. New data from this study are deposited with the California Current Ecosystem LTER DataZoo (http://oceaninformatics.ucsd.edu/datazoo/data/ccelter/datasets?action=group&id=1).

Control for regional and seasonal variation in microplastic abundance

In order to avoid effects of regional and seasonal variations in oceanic conditions on data analyses, we chose an area in the North Pacific Subtropical Gyre (NPSG) between Hawaii and California where comparable samples were available for the present study. A subset of 41 samples, 21 collected in October 1972, and 20 in October 2010 were analyzed. We found an increase of two orders of magnitude in microplastic, with median numerical concentration (NC) increasing from 0.003 to 0.270 particles m^{-3} (two-tailed Mann-Whitney test, $p<0.0001$) and mass concentration (MC) increasing from 0.004 to 1.158 mg m^{-3} (two-tailed Mann-Whitney test, $p<0.0001$).

Supplementary Tables

Table S1. Data sources for microplastic numerical and mass concentrations. The season/year, region, sample size, and data type are given for each data source. Samples used for the *H. sericeus* analyses are designated with an "x." Regions are the North Pacific Subtropical Gyre (NPSG), Alaska (AK), the California Current (CA), and the Eastern Tropical Pacific (ETP). Data types are numerical concentration (C), and mass concentration (M). Data sources are given as cruise names for new data or citations for published or public data.

season/year	**region**	**N**	**data type**	**source**	***H. sericeus* analysis**
Spring 1972	NPSG	10	C, M	7205 (new data)	x
Fall 1972	NPSG	21	C, M	7210 (new data)	x
Fall 1972	NPSG	31	M	Wong et al. 1974 [7]	
Winter 1973	NPSG	14	C, M	Southtow 13 (new data)	x
October 1974 & 1975	AK	71	C	Shaw 1977 [8]	
June-August 1976 & 1985	AK, NPSG	31	M	Day & Shaw 1987 [9]	
Winter 1984	CA	61	C, M	Gilfillan et al. 2009 [10]	
Fall 1987	ETP	23	C, M	STAR 8710 (new data)	
Season varied, years 1999, 2000, 2002, 2005-2008	CA, NPSG	178	C, M	Algalita Marine Research Foundation [19]	
Fall 1999	ETP	5	C, M	STAR 9910 (new data)	
Fall 2000	ETP	6	C, M	STAR 0010 (new data)	
Throughout 2006	AK, CA	234	C, M	Doyle et al. 2011 [11]	
Fall 2006	ETP	9	C, M	STAR 0610 (new data)	
Winter 2007	CA	66	C, M	Gilfillan et al. 2009 [10]	
Summer 2009	CA, NPSG	119	C, M	SEAPLEX (new data)	x
Fall 2010	CA, NPSG	28	C, M	EX1006 (new data)	x

Table S2. Microplastic particle and mass concentrations in 1972-87 and 1999-2010. Median, 5th to 95th percentiles of the data, and maximum values are given for each region. Regions are the North Pacific Subtropical Gyre (NPSG), Alaska (AK), the California Current (CA), and the Eastern Tropical Pacific (ETP).

particle concentration 1972-1987					
	median (no. m^{-3})	**5th to 95th percentile (no. m^{-3})**	**maximum (no. m^{-3})**	**N**	**data source**
all data	0.000	0.000-0.117	0.822	200	-
NPSG	0.003	0.000-0.071	0.221	45	this study
AK	0.000	0.000-0.010	0.010	71	[8]
CA	0.012	0.000-0.471	0.822	61	[10]
ETP	0.000	0.000-0.043	0.087	23	this study
particle concentration 1999-2010					
all data	0.116	0.000-4.696	32.760	645	-
NPSG	0.425	0.092-8.649	32.760	301	[19], this study
AK	0.000	0.000-0.140	0.406	22	[11]
CA	0.010	0.000-0.228	3.141	302	[10,11,19], this study
ETP	0.012	0.000-0.034	0.044	20	this study
mass concentration 1972-1987					
	median (mg m^{-3})	**5th to 95th percentile (mg m^{-3})**	**maximum (mg m^{-3})**	**N**	**data source**
all data	0.000	0.000-0.675	5.337	191	-
NPSG	0.003	0.000-0.705	3.500	87	[7,9], this study
AK	0.000	0.000-0.078	0.600	20	[9]
CA	0.003	0.000-1.001	5.337	61	[10]
ETP	0.000	0.000-0.089	0.401	23	this study
mass concentration 1999-2010					
all data	0.086	0.000-25.000	250.000	645	-
NPSG	3.000	0.000-25.000	250.000	301	[19], this study
AK	0.000	0.000-0.268	0.406	22	[11]
CA	0.001	0.000-0.713	3.000	302	[10,11,19], this study
ETP	0.003	0.000-0.385	6.581	20	this study

Supplementary References

S1. Ahlstrom, E.H. & Stevens, E. 1976 Report of neuston (surface) collections made on an extended CalCOFI cruise during May 1972. *Cal. Coop. Ocean. Fish.* **18**, 167-180.

S2. Brown, D.M. & Cheng, L. 1981 New net for sampling the ocean surface. *Mar. Ecol-Prog. Ser.* **5**, 225-227. (doi:10.3354/meps005225)

S3. Gorsky, G., Ohman, M. D., Picheral, M., Gasparini, S., Stemmann, L., Romagnan, J.-B., Cawood, A., Pesant, S., Garcia-Comas, C. & Prejger F. 2010 Digital zooplankton image analysis using the ZooScan integrated system. *J. Plankton Res.* **32**, 285-303. (doi:10.1093/plankt/fbp124)

S4. Omori, M. & Ikeda T. 1984 *Methods in Marine Zooplankton Ecology*, pp 88-89. New York: Wiley-Interscience.

S5. Omori, M. 1978 Some factors affecting on dry weight, organic weight and concentrations of carbon and nitrogen in freshly prepared and in preserved zooplankton. *Int. Rev. Gesamten Hydrobiol. Hydrogr.* **63**, 261-269. (doi:10.1002/iroh.19780630211)

S6. R Development Core Team. 2011 R: A language and environment for statistical computing. R Foundation for Statistical Computing, ISBN 3-900051-07-0. http://www.r-project.org.

S7. Komsta L. 2007 Median-Based Linear Models. R package version 0.11. http://cran.r-project.org/package=mblm.

S8. Golden Software, Inc. 2002 Surfer, Release 8. Golden, CO.

Chapter 5, in full, is a reprint of the material as it appears in *Biology Letters* 8(5): 817-820, Goldstein, M.C.; Rosenberg M.; Cheng, L., 2012. The dissertation author was the primary investigator and author of this paper.

CHAPTER 6: Relationship of diversity and habitat area in North Pacific plastic-associated rafting communities

Abstract

Ocean plastic debris has increased worldwide, leading to a rise in plastic-associated rafting assemblages. Plastic debris augments natural floating hard-substrate habitat (e.g., algal rafts) in the open ocean, allowing “islands” of substrate-dependent organisms to persist in an otherwise unsuitable habitat. Plastic debris also enhances the dispersal potential of substrate-dependent biota, including potentially invasive species. Here, we ask: a) are potentially invasive or harmful taxa associated with the rafting community assemblages in the NPSG; and b) does the number of taxa associated with North Pacific Subtropical Gyre (NPSG) plastic debris vary with surface area of available substrate? To this end, we examined a total of 242 debris objects collected in the eastern Pacific in 2009 and 2011 and the western Pacific in 2012. We identified 96 rafting taxa from 11 phyla. In concordance with classic species-area curves, the number of rafting taxa was positively correlated with the size of the raft, though substrate type (e.g., rope clump, foam) was also important. We identified several potentially invasive plastic-associated rafting taxa, including the coral pathogen *Halofolliculina* spp. and the majid crab *Herbstia* spp. Top-down effects of rafting assemblages may not be significant – we estimated lepadid barnacle predation on neustonic zooplankton to be less than 1% of daytime surface biomass of zooplankton. Our findings suggest that diversity patterns on plastic debris are compatible with the concept of island

biogeography, and that targeting larger debris items for removal may be a viable strategy for invasive species control.

Introduction

Naturally occurring floating objects in the pelagic environment have long played host to a suite of specialized species (M. Thiel and L. Gutow 2005a). These substrates, such as drift algae, pumice, and wood, provide transport and habitat for benthic organisms (M. Thiel and L. Gutow 2005b). In recent decades, natural rafts have been augmented by anthropogenic plastic debris, which was first detected in the open ocean in the early 1970s (Carpenter and Smith 1972, Venrick et al. 1973, Wong et al. 1974). Rafting on plastic debris has now been observed all over the world (M. Thiel and L. Gutow 2005b, Goldstein et al. 2012), and increases with supply of plastic debris (Winston 1982). Although rafting is usually rare in the Southern Ocean due to low temperatures and large waves, rafting on plastic debris has even been observed there (Barnes and Fraser 2003).

The composition of the rafting assemblage depends on the type of object and its stability. In general, artificial substrates do not host the same communities as natural substrates (Tyrrell and Byers 2007, Pister 2009). In the case of rafting objects, biotic rafts (e.g., wood, drifting kelp) do not drift for as long as abiotic rafts (e.g., plastic, tar), but do provide a food source for rafting organisms, and may therefore may be more successful at transporting a variety of species (Donlan and Nelson 2003, M. Thiel and L. Gutow 2005a). The stability of the rafting object may also affect the diversity of the attached assemblage – pieces with fewer changes of orientation have greater species richness and cover than less stable pieces (Bravo et al. 2011). Fouling also increases the density of the raft, which may cause sinking in the water column and a subsequent rise to the surface if fouling organisms die or are removed by predators (Ye and Andrady 1991, Moret-Ferguson et al. 2010).

Diversity patterns in open-ocean rafting assemblages, particularly plastic-associated assemblages, are largely unexplored. In many ecosystems, diversity is predicted by the species-area curve, in which the number of species increases as a function of available surface area, though the shape of this curve has been a matter of some debate (He and Legendre 1996). Species-area curves can be explained by the concept of island biogeography, which predicts that species diversity is a balance between arrival of species through migration and the loss through extinction, both processes that vary with available habitat area (MacArthur and Wilson 1963). While species-area curves are one of the most widely observed patterns in ecology, there are exceptions, such as the "small-island effect," in which the areas of the ecosystems observed are all too small for a diversity pattern to be detected (Lomolino 2000). It is unknown whether plastic-associated rafting assemblages follow the species-area pattern, particularly since artificial substrates strongly select for particular life history traits such as suspension feeding (Thiel and Haye 2006).

The unusual properties of plastic make it a vector for the transport of nonindigenous species. For example, a piece of flotsam with traces of tropical biota, including self-fertilizing corals, was recently discovered in the Netherlands (Hoeksema et al. 2012), and Southern Ocean bryozoans in reproductive condition were found on a beached packing band in Antarctica (Barnes and Fraser 2003). Due to the slow velocity of debris drift, rafted invertebrates are thought to be more viable than those transported by other methods such as ballast water or ship hull fouling (Barnes 2002, Lewis et al. 2005). Benthic organisms such as bryozoans, barnacles, and hydroids are commonly found on plastic debris, and at least one new species introduction has resulted from rafting on plastic debris (Aliani and Molcard 2003, Barnes and Milner 2005). The particular vulnerability of island ecosystems to invasions and the large amount of plastic debris collecting on the mid-Pacific islands makes lateral transport of fouling species a matter of particular concern in the North Pacific (McDermid and McMullen 2004). Recently, a non-native hydroid and two ascidians were recorded from debris at French Frigate Shoals (Godwin et al. 2008). However, most studies have examined beached material, not *in situ* debris (Winston et al. 1997, Barnes 2002, Barnes and Fraser 2003, Barnes and Milner 2005, Hoeksema et al. 2012).

In this study, we asked: a) are potentially invasive or harmful taxa associated with the rafting community assemblages in the NPSG; and b) does the number of taxa associated with North Pacific Subtropical Gyre (NPSG) plastic debris vary with surface area of available substrate?

Methods

Samples were collected on three cruises, the 2009 Scripps Environmental Accumulation of Plastics Expedition (SEAPLEX), the 2010 Algalita Eastern North Pacific Gyre Expedition and the 2012 Western North Pacific Japanese Tsunami Debris Field Expedition (Fig 6.1a-d).

For the 2009 samples, floating debris items were opportunistically collected by dip net. A subset of plastics collected using a standard manta net (0.86 x 0.2 m) with 333 μm mesh (Brown and Cheng 1981), towed for 15 minutes at 0.7-1 m s^{-1} were also included in this study. If possible, the entire piece of debris with attached fauna was preserved in either 5% Formalin buffered with sodium borate or 95% ethanol. An attempt was made to preserve portions of most samples in both preservatives to allow for both morphological and molecular studies. When the item was too large to be preserved, the item was either subsampled (e.g., portions of a tarp were cut and preserved) or the fauna were removed and preserved separately (e.g., in the case of a large fishing buoy).

On the 2011 and 2012 expeditions, debris items were collected by dipnet during timed debris observation periods or opportunistically during other daylight sightings. Debris items were inspected for attached organisms immediately, and then taken to shipboard laboratory for microscope inspection, photography, and preservation. If possible, the entire piece of debris with attached fauna was preserved in 5% Formalin. Where not possible, organisms were removed and preserved separately. Three floating masses of nets, rope, and entangled debris were sampled differently. In 2011, the net mass was examined by divers in the water, who noted associated fishes, collected fouling organisms opportunistically, and subsampled the materials for inspection on board. In 2012 both net masses were inspected in the water first, and then hauled on board and dissected on deck for a more thorough collection of fouling organisms.

In the laboratory, objects were examined for rafting fauna under a Wild M-5 dissecting microscope. The preservative was also filtered through 150 μm Nitex mesh to retain non-attached biota. The object was photographed digitally and its size measured with the software package NIH ImageJ. During the 2011 and 2012 expeditions, organisms and small debris were inspected and photographed on board using a Dino-Lite Premiere Digital Microscope. Object dimensions were measured manually using a ruler. Later identification of preserved specimens on shore was made using dissection or compound microscopes. All fauna were identified to the lowest possible taxonomic level. When objects with different taxonomic resolutions were compared, taxa were collated to comparable levels. For example, *Lepas pacifica, Lepas anatifera*, and *Lepas* spp. were counted as one taxon. A complete list of debris locations and associated taxa is given in Table S6.1.

To understand one of the potential top-down impacts of plastic-associated rafting assemblages, we estimated the degree of gooseneck barnacle (*Lepas* spp.) predation on neustonic zooplankton. We chose *Lepas* because they are a zooplankton predator that can comprise up to 80-100% of the total rafting biomass (Tsikhon-Lukanina et al. 2001). Because of the relatively sparse occurrence of the larger plastic debris items, we express the predator ingestion on a scale of km^2 rather than m^2, though this obscures zooplankton spatial heterogeneity.

Overall debris abundance was taken from quantitative visual surveys from the eastern Pacific in 2009, and given as approximately 40 medium objects km^{-2} and 16 large objects km^{-2} (Titmus and Hyrenbach 2011). Barnacle abundance was obtained from 10 objects collected in 2012 from the western Pacific. Based on these counts, we estimated that an average medium-sized object (surface area approximately 0.5 m^2) hosted 100 barnacles, and a large object (surface area >5 m^2) hosted 1,000 barnacles, giving a barnacle density of 20,000 barnacles km^{-2}. *Lepas* barnacle growth has been measured at approximately 0.3 mm capitulum length day^{-1} (Evans 1958, Hobday 2000, Tsikhon-Lukanina et al. 2001, M. Thiel and L. Gutow 2005b). We converted *Lepas* growth into wet mass (Goldberg 1985), ash-free dry weight (Ricciardi and Bourget 1998), and carbon mass (conversion of 0.35; Postel et al. 2000). Assimilation efficiency was estimated to be 0.68 (Ritz and Crisp 1970).

Statistics and figures were generated with the R statistical environment, version R-2.13.1 (R Development Core Team 2011). The Nemenyi-Damico-Wolfe-Dunn post-hoc test was performed using the coin package (Hothorn et al. 2008).

Results

We examined a total of 242 debris objects and identified 96 associated rafting taxa (Table 6.1). The debris was comprised of 66% small plastic fragments (<2 cm in diameter), 21% hard objects, 7% rope clumps, 3% flexible substrates (e.g., tarps), and 3% expanded foam (e.g., "Styrofoam"). Debris substrate area ranged from 2.54×10^{-7} m^2 to 15 m^2, with a median of 1.18×10^{-4} m^2. There were no statistical differences between cruise years/locations (Chi-square $p>0.5$) for the following analyses, so data from all cruises were combined. Representatives of 11 phyla were found, with the most abundant phylum being the Arthropoda, followed by Cnidaria and Mollusca (Fig 6.2a). The plurality of these taxa were suspension feeders, though omnivores, grazers, and predators were also well represented (Fig 6.2b). Slightly more taxa were unattached than were sessile (Fig 6.2c). Of all identified taxa, 27 had not been previously found to occur in rafting assemblages (Fig 6.2d).

We found a significant positive relationship between the size of the debris object and the number of taxa found on that object (Fig 6.3a, Kendall's tau $p<0.001$). This relationship is expressed as log-transformed data in Figure 6.3b, and remained significant when the four largest items were removed. The eight most abundant phyla also exhibited significant positive relationships between object size and number of taxa (Fig 6.4, Kendall's tau $p<0.01$). When the four largest items were excluded from each comparison, these relationships remained significant, with the exception of Porifera ($p=0.121$).

Debris type had a significant effect on the number of taxa inhabiting it (Kruskal-Wallis $p<0.001$). The median number of taxa was highest on hard plastic objects such as fragments and bottles (Fig 6.5, Nemenyi-Damico-Wolfe-Dunn post-hoc test $p<0.001$). The overall highest number of taxa was found on rope clumps, though the median number of taxa was lower than on hard objects ($p<0.001$). There was no significant difference between rope clumps and flexible substrates (e.g., tarps; $p=0.085$) or between flexible and foam substrates (e.g., fishing floats; $p=0.982$). Small plastic particles less than 2 cm in diameter, of which 98% were hard fragments, had the lowest number of taxa ($p<0.001$).

Assuming a daily growth of 0.3 mm capitulum length day^{-1}, the carbon required per barnacle is 5 μg day^{-1}. Therefore, given an assimilation efficiency of 0.68 (Ritz and Crisp 1970), the total carbon required for barnacle growth is 147 mg km^{-2} . Median daytime zooplankton biomass in 2009 was 642,000 mg km^{-2} (Goldstein et al. 2012), which converts to 256,800 mg carbon km^{-2} (Postel et al. 2000). *Lepas* is therefore estimated to ingest 0.06% of daytime zooplankton carbon biomass.

Discussion

We found a diverse and widespread rafting assemblage inhabiting North Pacific plastic debris. The majority of taxa were known members of the rafting assemblage such as *Lepas* spp. barnacles and membraniporid bryozoans, but we documented 27 taxa that had not been previously found in rafting assemblages. Many of the previously undocumented taxa were from groups that are known to be prolific and successful rafters, such as the bryozoans, sponges, and peracarid crustaceans (Barnes 2002, Thiel and Gutow 2005b). We were surprised to find a small number of boring organisms rafting on pelagic plastic debris composed of foamed polystyrene. These included the bivalve *Zirfaea*, the shipworm *Teredo*, and a sphaeromatid isopod. While boring organisms are known to colonize rafts of biotic origin, such as wood and algae, they are relatively rare on plastic debris (Thiel and Gutow 2005b, Thiel and Haye 2006), although sphaeromatid isopods are known to burrow in polystyrene floats in coastal ecosystems (Davidson 2012).

We documented several taxa of potential concern. The folliculinid ciliates (*Halofolliculina* spp.) found on western Pacific plastic debris are pathogens that causes skeletal eroding band (SEB) disease in corals (Rodriguez et al. 2009). Though originally thought to be limited to the Indian Ocean and South Pacific, SEB disease was discovered in Caribbean corals in 2004 (Croquer et al. 2006) and in Hawaiian corals in 2010 (Palmer and Gates 2010). The mechanism behind the spread of SEB are not known (Croquer et al. 2006), but since the Hawaiian Islands are highly impacted by plastic debris (Dameron et al. 2007), it is possible that debris facilitated the dispersal of *Halofolliculina* to this area. Plastic debris has the potential to disperse non-ciliate pathogens, such as viruses, but the role of debris as a disease vector has been little studied (Pham et al. 2012).

Other taxa of concern are the crab *Herbstia* spp, also found in the western Pacific. This genus is not native to the western Pacific, but is found in the Atlantic, Caribbean, and eastern Pacific (World Register of Marine Species 2012). Two Atlantic species, *Herbstia nitida* and *Herbstia condyliata*, are considered are invasive species in the Mediterranean (Corsini and Kondilatos 2006, Denitto et al. 2010). While the origin of this *Herbstia* specimen is unknown, it was out of its native range in the western Pacific.

Many of the rafting taxa found are known invaders, but could have come either from their native range or from an already invaded area. These include the acorn barnacle *Megabalanus rosa,* native to Japan but an invasive species in Australia (Jones et al. 1990), as well as the bryozoans *Bugula* and *Victorella,* mussel *Mytilus galloprovincialis*, and acorn barnacle *Amphibalanus amphitrite*, which are invasive to the eastern Pacific (Fofonoff et al. 2012). Because most of the fauna present were either known members of the north Pacific rafting assemblage or widely distributed taxa, the source of the debris objects could not be determined from the associated assemblage.

We found a greater number of taxa on larger debris items than on smaller items. A positive relationship between object size and taxa number has also been observed in algal rafts (Ingólfsson 1995, Hobday 2000) and fisheries aggregation devices (Nelson 2003). This relationship may be driven by both physical and biological factors. Physically, larger objects are more likely to remain buoyant, even after developing a substantial rafting assemblage (M. Thiel and L. Gutow 2005a). Smaller objects with a substantial rafting assemblage may have become negatively buoyant, and were therefore not sampled by this study or by other studies focusing on material at the sea surface.

Biological interactions, as predicted by island biogeography, may also be an important driver of the positive species-area relationship on pelagic plastic debris. As on islands, the rate of migration to large pieces of plastic debris may exceed the rate of extinction (Simberloff 1976). Higher rates of migration to larger objects could be driven by larval settlement. For example, due to their greater surface area, larger objects will develop a more extensive biofilm than smaller objects, which is an important cue for larval settlement (Rodriguez et al. 1993). Larger objects are also easier to detect visually, which may attract epipelagic fishes. Extinction rates on larger items may be lower than extinction rates on smaller items due to their hydrodynamic stability, since stable spatial orientation is an important driver of diversity (Bravo et al. 2011). Large items without spatial stability may contain low diversity, such as a meter-long cylindrical polystyrene buoy that "rolled" along the sea surface (*H.S.C pers. obs.*). Spatial complexity may also be important. For example, the forward half of a small fishing boat floating upright in the western Pacific had more than 50 associated fishes, but very little attached biota (Fig S6.1, M.E. *pers. obs.*). Lastly, successional stage may influence diversity. A study in the western Pacific found that diversity was highest during early stages of succession, and then reduced by *Lepas* dominance (Tsikhon-Lukanina et al. 2001). The authors suggest that diversity may increase once more at later successional stages, which they define as being dominated by bivalves. However, floating debris in their study never reached this stage, perhaps due to lack of physical stability or limited larval supply.

We noted a shallow parabolic shape in both our overall taxa-area semi-log curve and for some of the phylum-specific curves, such as Arthropoda and Bryozoa. The parabola suggests higher numbers of taxa on medium-sized objects compared to slightly larger objects. This shape could be an artifact of different sampling methodologies for medium and large objects – medium objects were preserved without subsampling, while large objects had to be subsampled at sea, potentially causing inconspicuous taxa to be undersampled. To address the sampling issue, future studies should consider subsampling larger items with nonselective methodology such as suction. However, it is also possible that there is a threshold debris size beyond which fish and decapod predators suppress prey taxa diversity through direct predation and/or nonconsumptive predator effects (Matassa and Trussell 2011). Some epipelagic fishes preferentially associate with fouled rafting objects as opposed to unfouled rafting objects, suggesting an association between rafting invertebrates and these fishes (Nelson 2003, M. Thiel and L. Gutow 2005b). Additionally, the sea skater *Halobates sericeus* is capable of laying its eggs on large items (Cheng and Pitman 2002), but its eggs were found only on small fragments with few associated predators (Goldstein et al. 2012).

Most fishes observed in this study were associated with the three net and rope masses, with the exception of one juvenile triggerfish (*Canthidermis maculata*) on a bleach bottle and a school of sergeant majors (*Abudefduf* spp.) inside a plastic crate. The net-associated fishes exhibited all three types of behavior identified by Hirosaki (1960) for macroalgae-associated fishes: staying almost exclusively within the net mass, such as the Sargassum frogfish (*Histrio histrio*); remaining underneath or around the mass in close association, such as the sergeants; and swimming around the mass without close association, such as the mahi mahi (*Coryphaena hippurus*). The conspicuously low abundance or absence of some species such as *Lepas* spp. on net masses compared to isolated rope fragments may be partially attributed to these net-mass associated fishes. We also observed fish entangled in net masses that were still alive, recently dead, and partially decomposed.

We estimated that the percentage of resources consumed by plastic-rafting gooseneck barnacles in accumulation zones was much less than 1% of daytime neustonic zooplankton biomass. Though widespread oceanic plastic pollution has led to a substantial increase in pelagic hard substrate (Barnes 2002, M. Thiel and L. Gutow 2005a, Goldstein et al. 2012), *Lepas* barnacles do not yet appear to be exerting strong top-down pressure on the neustonic zooplankton community. However, this is a broad estimate based on a series of general assumptions. Assessing the true top-down impact of *Lepas* and other abundant rafting suspension feeders will require direct measurements in an oligotrophic context.

Plastic-associated rafting organisms may also be impacting the pelagic ecosystem by reworking the particle size spectrum through ingestion and egestion (Mook 1981). Suspension-feeding rafting organisms prey on a variety of particle sizes, from 3-5 µm for *Mytilus* mussels (Lesser et al. 1992), 10-20 µm for bryozoans (Pratt 2008), 20-125 µm for caprellid amphipods (Caine 1977), and 0.5 to more than 1 mm for lepadid barnacles and hydroids (Evans 1958, Boero et al. 2007). This size range encompasses much of the non-microbial particle size spectrum of the oligotrophic

North Pacific (Sheldon et al. 1972). Since particle size determines whether energy flows into the microbial loop or into the metazoan food web, large-scale alterations in particle size could substantially influence the species composition of the North Pacific Subtropical Gyre (Karl et al. 2001). Future research should also consider phytoplankton and microbial interactions with pelagic plastic debris (Maso et al. 2003, Zettler et al. 2011).

Though the majority of plastic debris in the North Pacific is in the form of small fragments (Hidalgo-Ruz et al. 2012), these particles carry few taxa, most of which are known subtropical rafters such as *Jelleyella* or *Membranipora* bryozoans. We found the majority of potentially harmful taxa, such as the majid crab *Herbstia*, on large items such as net balls, though the coral pathogen *Halofolliculina* spp. was found on medium-sized plastic fragments (0.03-0.1 m^2). Selective removal of medium to large plastic debris objects may provide a degree of protection to coastal habitats where invasion is of concern.

The ecological role of plastic-associated rafting assemblages on the open ocean remains unclear. While the most abundant large-bodied plastic rafting organisms, the lepadid barnacles, may not be sufficiently abundant to consume a significant portion of neustonic zooplankton biomass, durable plastic “islands” are hosts to a diversity of coastal organisms in the pelagic environment. Whether or not the plastic rafts introduce new species to distant coastal regions, the consequences of these “misplaced” organisms to open-ocean ecosystems, especially in debris-accumulation zones, merits further study.

Acknowledgements

Funding for the 2009 SEAPLEX cruise was provided by University of California Ship Funds, Project Kaisei/Ocean Voyages Institute, AWIS-San Diego, and NSF IGERT Grant No. 0333444. The 2011 and 2012 expeditions were made possible through collaboration between the 5 Gyres Institute, Algalita Marine Research Institute, and the University of Hawaii. The *Sea Dragon* was made available by Pangaea Explorations. M.C.G. was supported by NSF GK-12 Grant No. 0841407 and donations from Jim & Kris McMillan, Jeffrey & Marcy Krinsk, Lyn & Norman Lear, Ellis Wyer, and the Petersen Charitable Foundation. Funding for H.S. Carson was provided by the Will J. Reid Foundation. Laboratory supplies, support, and some analytical equipment for the 2009 samples were supplied by the SIO Pelagic Invertebrate Collection and the California Current Ecosystem LTER site supported by NSF. Many thanks to the captain and crew of the R/V *New Horizon* and *Sea Dragon* for their assistance in debris collection and many other logistics. We are grateful to H. Cha, M. DeMaintenon, M. Forrest, E. Moore, L. Sala, A. Townsend, and J. Winston for their assistance with taxonomy, and to S. Strutt for her work in the laboratory.

Chapter 6 is being prepared for submission to *Marine Ecology Progress Series* and is presented as part of this dissertation with the acknowledgement of the study co-authors Henry S. Carson and Marcus Eriksen. The dissertation author was the primary investigator and is the primary author of this material.

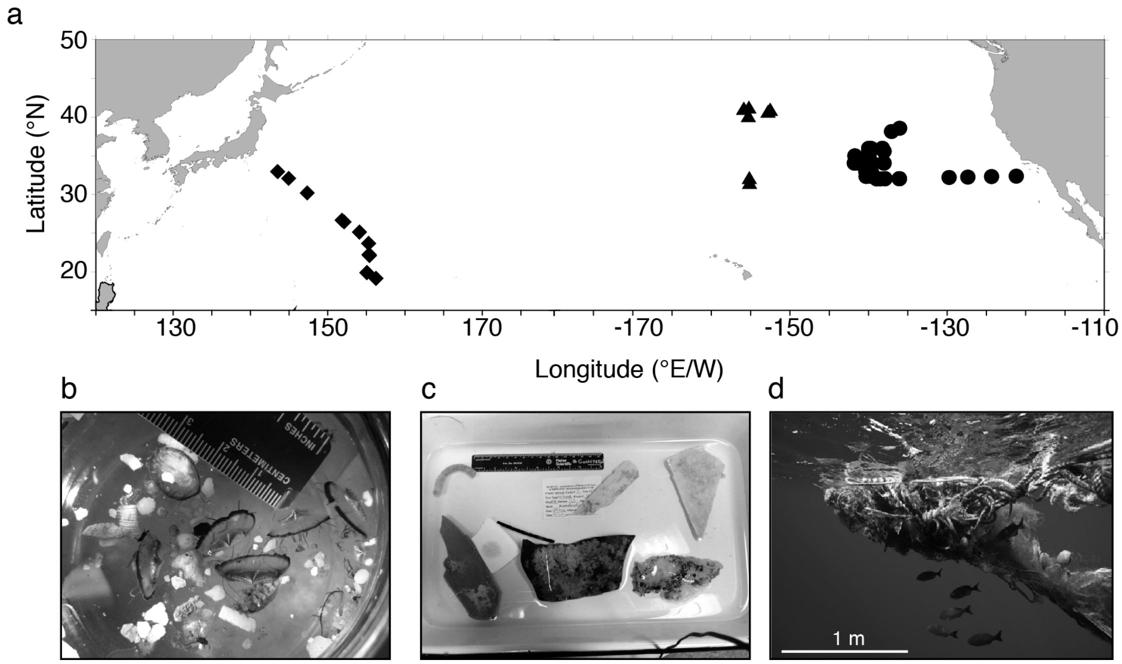


Figure 6.1. Map of sampling locations and photos of representative plastic debris a) Locations of debris collection in 2009 (circles), 2011 (triangles), and 2012 (diamonds). b) Small plastic particles intermixed with the chondrophore *Velella velella*. c) Medium plastic fragments. d) A large tangle of intermixed fishing-related nets, ropes and buoys along with other hard plastic debris ("rope clump").

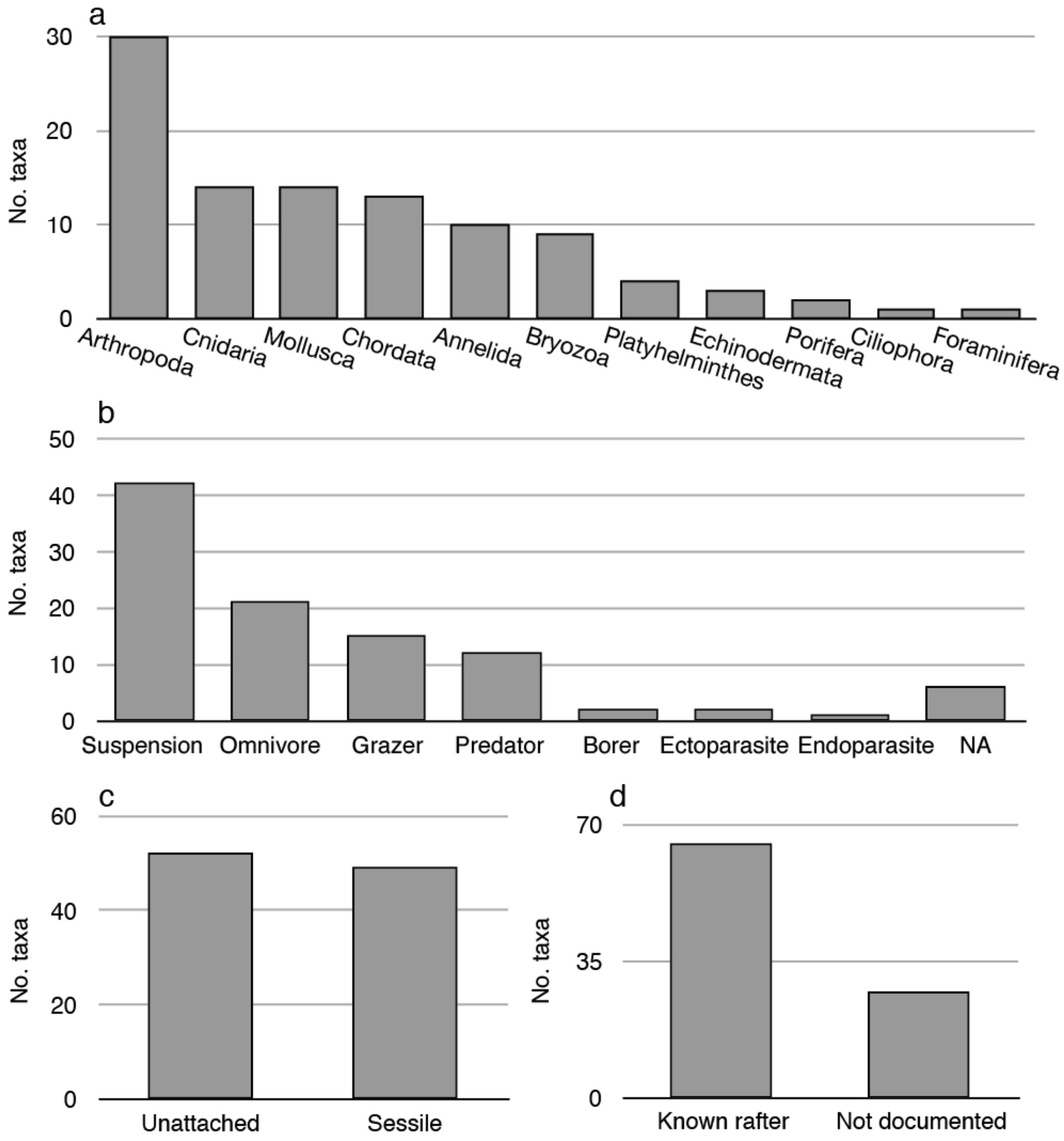


Figure 6.2. Characteristics of rafting taxa

a) Phyla found on or around floating plastic debris. b) Feeding types of rafting taxa. NA denotes eggs. c) Unattached taxa vs. sessile taxa. Fishes are excluded. d) Taxa that have previously been documented to occur in rafting communities vs. taxa that have not been documented. There was no statistical difference between cruise years/locations (chi-square $p>0.5$) for these analyses, so data from all cruises were combined in this figure. N=96 taxa.

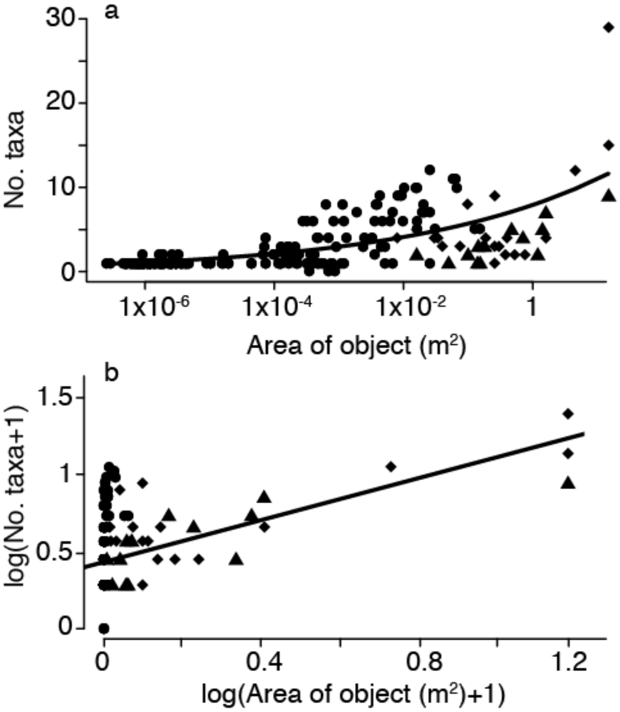


Figure 6.3. Number of taxa vs. surface area (m^2) of debris object
a) Semilog plot. Solid line is an exponential non-linear least squares regression. Kendall's tau=0.555, $p<0.001$. b) Log-log plot. Solid line is a linear regression ($F=48.69$, $p<0.001$, $R^2=0.169$). Symbols in both plots correspond to year and location of collection: eastern Pacific 2009 is shown in circles, eastern Pacific 2011 in triangles, and western Pacific 2012 in diamonds. Note that many of the symbols denoting small plastic objects overlap, making the sample size hard to discern visually. N=242 debris objects.

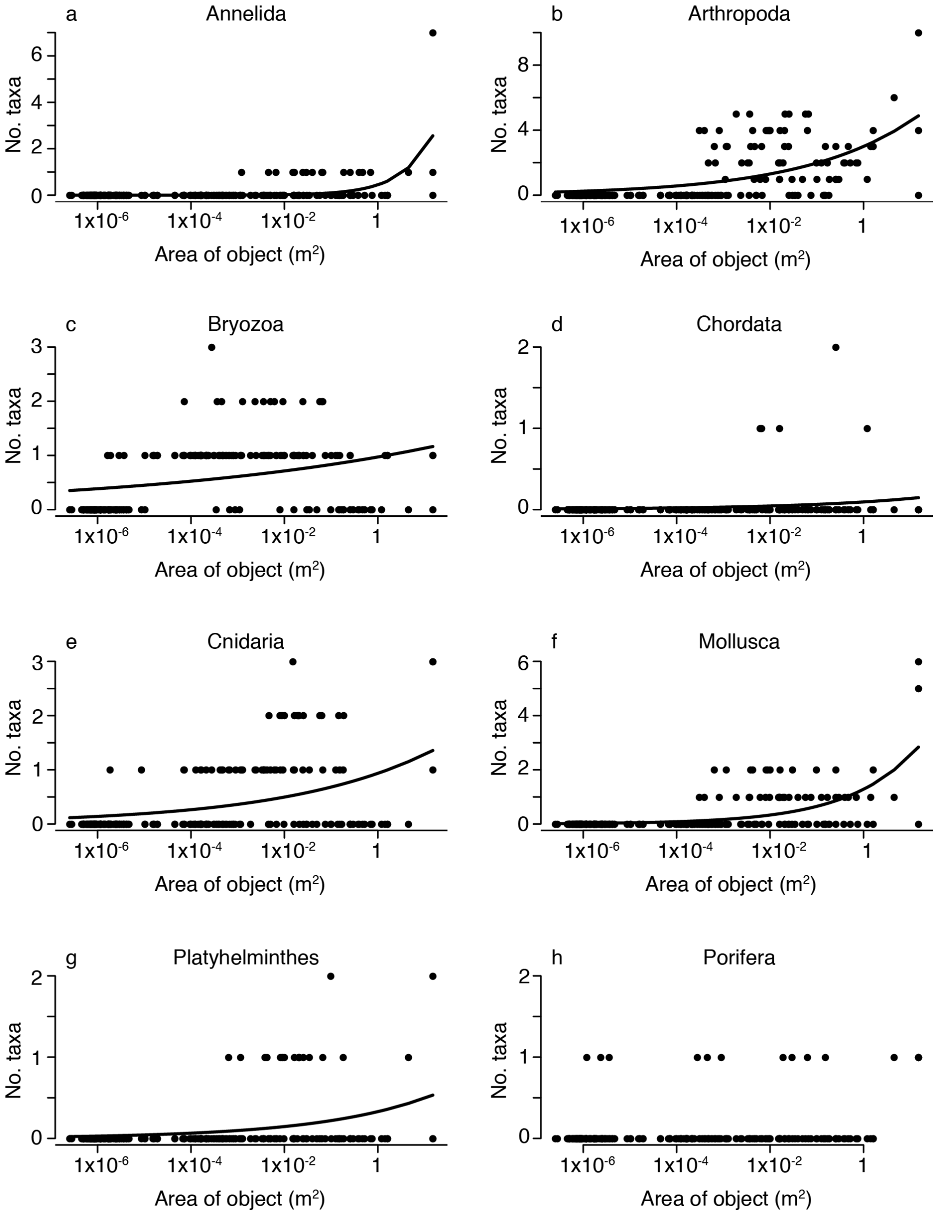


Figure 6.4. Semilog plots of taxa vs. surface area (m^2) of debris object, by phylum Solid line is an exponential non-linear least squares regression. All following statistics are for Kendall's tau. a) Annelida, tau=0.304, $p<0.001$. b) Arthropoda, tau=0.526, $p<0.001$. c) Bryozoa, tau=0.447, $p<0.001$. d) Chordata, tau=0.142, $p=0.007$. e) Cnidaria, tau=0.394, $p<0.001$. f) Mollusca, 0.417, $p<0.001$. g) Platyhelminthes, tau=0.267, $p<0.001$. h) Porifera, tau=0.163, $p=0.002$. If the 4 largest objects are excluded, all relationships remain significant with the exception of Porifera (tau=0.082, $p=0.121$). N=242 debris objects.

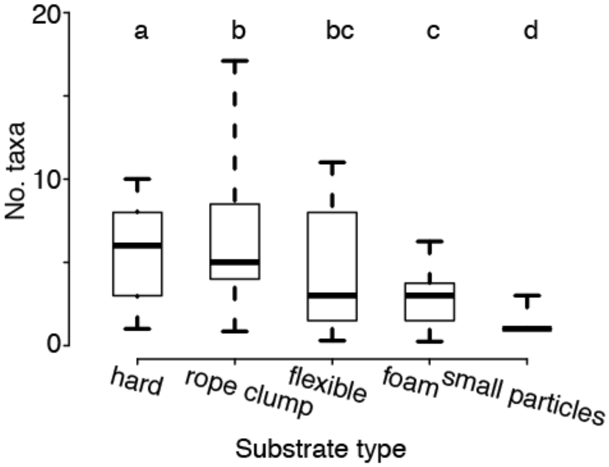


Figure 6.5. Number of taxa by debris substrate type
Letters above boxplots indicate groups that are significantly different (Nemenyi-Damico-Wolfe-Dunn post-hoc test $p<0.05$). Box center is the median, edges are 25% and 75% quartiles, and whiskers are 95% confidence intervals.

Table 6.1. Rafting taxa

Years observed are a=Eastern Pacific 2009; b=Eastern Pacific 2011; c=Western Pacific 2012. Previously documented as rafting are N=Not listed as rafting in the scientific literature, 1=listed in Thiel & Gutow 2005b, 2=Lovely 2005, 3=Carter et al. 2010, 4=Matthews 1963, 5=Riemann-Zürneck 1998, 6=Emerson and Chaney 1995.

Phylum	**Class**	**Order**	**Finest taxon Ided**	**Year observed**	**Previously documented as rafting**
Annelida	Polychaeta	Aciculata	*Eunice* spp.	c	1
Annelida	Polychaeta	Amphinomida	*Amphinome rostrata*	c	1
Annelida	Polychaeta	Amphinomida	*Hipponoe gaudichaudi*	a,b	1
Annelida	Polychaeta	Phyllodcida	*Halosydna* spp.	b	N
Annelida	Polychaeta	Phyllodocida	Nereididae	c	1
Annelida	Polychaeta	Phyllodocida	*Nereis* spp.	c	1
Annelida	Polychaeta	Phyllodocida	Phyllodocidae	c	1
Annelida	Polychaeta	Sabellida	*Salmacina* spp.	c	N
Annelida	Polychaeta	Sabellida	Subfamily Serpulinae	c	1
Annelida	Polychaeta	Sabellida	Subfamily Spirorbinae	a,c	1
Arthropoda	Malacostraca	Amphipoda	*Caprella* spp.	a,c	1
Arthropoda	Malacostraca	Amphipoda	*Elasmopus* spp.	a	1
Arthropoda	Malacostraca	Amphipoda	Hyalidae	a	1
Arthropoda	Malacostraca	Amphipoda	Isaeidae	b	N
Arthropoda	Malacostraca	Amphipoda	Pleustidae	c	N
Arthropoda	Malacostraca	Amphipoda	Sphaeromatidae	a	1
Arthropoda	Malacostraca	Amphipoda	Stenothoidae	a	1
Arthropoda	Malacostraca	Amphipoda	Suborder Gammaridea	c	1
Arthropoda	Malacostraca	Decapoda	*Chorilia* spp.	c	N
Arthropoda	Malacostraca	Decapoda	*Herbstia* spp.	c	N
Arthropoda	Malacostraca	Decapoda	Megalopae	b	1
Arthropoda	Malacostraca	Decapoda	*Palaemon affinis*	c	1
Arthropoda	Malacostraca	Decapoda	*Pilumnus* spp.	c	N
Arthropoda	Malacostraca	Decapoda	*Plagusia* spp.	c	1
Arthropoda	Malacostraca	Decapoda	*Plagusia squamosa*	a	1
Arthropoda	Malacostraca	Decapoda	*Planes cyaneus*	a,c	1
Arthropoda	Malacostraca	Decapoda	*Planes minutus*	a	1
Arthropoda	Malacostraca	Decapoda	*Planes* spp.	b,c	1
Arthropoda	Malacostraca	Isopoda	Cirolandiae	a	1
Arthropoda	Malacostraca	Isopoda	*Idotea* spp.	a,b,c	1
Arthropoda	Maxillopoda	Harpacticoida	Harpacticoida	a	1
Arthropoda	Maxillopoda	Kentrogonida	*Heterosaccus* spp.	c	N
Arthropoda	Maxillopoda	Lepadiformes	Barnacle cyprids	a	1
Arthropoda	Maxillopoda	Lepadiformes	*Lepas anitifera*	a,c	1
Arthropoda	Maxillopoda	Lepadiformes	*Lepas pacifica*	a	1
Arthropoda	Maxillopoda	Lepadiformes	*Lepas* spp.	a,b,c	1
Arthropoda	Maxillopoda	Sessilia	*(Amphi)balanus amphitrite*	b	1
Arthropoda	Maxillopoda	Sessilia	*Chthamalus* spp.	c	N
Arthropoda	Maxillopoda	Sessilia	*Megabalanus rosa*	c	N

Table 6.1. Rafting taxa, continued.

Phylum	**Class**	**Order**	**Finest taxon Ided**	**Year observed**	**Previously documented as rafting**
Arthropoda	Pycnogonida	Pantopoda	*Phoxichilidium quadradentatum*	a	N, may encyst in hydroids[2]
Arthropoda	Pycnogonida	Unknown	Unknown	c	1
Bryozoa	Gymnolaemata	Cheilostomatida	*Bugula* spp.	a,b,c	1
Bryozoa	Gymnolaemata	Cheilostomatida	*Jellyella eburnea*	a	1
Bryozoa	Gymnolaemata	Cheilostomatida	*Jellyella tuberculata*	a	1
Bryozoa	Gymnolaemata	Cheilostomatida	*Jellyella*/*Membranipora*	b,c	1
Bryozoa	Gymnolaemata	Cheilostomatida	*Membranipora tenella*	a	1
Bryozoa	Gymnolaemata	Ctenostomatida	*Bowerbankia spp.*	a	1
Bryozoa	Gymnolaemata	Ctenostomatida	*Victorella* spp.	a	N, may disperse through fragmentation of substrate[3]
Bryozoa	Stenolaemata	Cyclostomatida	*Filicrisia* spp.	a	N
Bryozoa	Stenolaemata	Cyclostomatida	*Stomatopora* spp.	a	N
Bryozoa	Stenolaemata	Cyclostomatida	*Tubulipora spp.*	a	1
Chordata	Perciformes	Actinopterygii	*Abudefduf* spp.*(vaigiensis?)*	b,c	N/A
Chordata	Perciformes	Actinopterygii	*Canthidermis maculata*	c	N/A
Chordata	Perciformes	Actinopterygii	*Chirolophis* spp.	c	N/A
Chordata	Perciformes	Actinopterygii	*Coryphaena hippurus*	b	N/A
Chordata	Perciformes	Actinopterygii	*Elagatis bipinnulata*	b	N/A
Chordata	Perciformes	Actinopterygii	*Histrio histrio*	c	N/A
Chordata	Perciformes	Actinopterygii	*Kyphosus* spp. *(vaigiensis?)*	b,c	N/A
Chordata	Perciformes	Actinopterygii	*Meiacanthus* spp.	c	N/A
Chordata	Perciformes	Actinopterygii	*Seriola rivoliana*	c	N/A
Chordata	Unknown	Unknown	Beige fish eggs	c	1
Chordata	Unknown	Unknown	Blue fish eggs	c	1
Chordata	Unknown	Unknown	Fish eggs	a,b	1
Ciliophora	Heterotrichea	Heterotrichida	*Halofolliculina* spp.	c	N on plastic, documented on wood[4]
Cnidaria	Anthozoa	Actinaria	Actiniidae	b	1
Cnidaria	Anthozoa	Actinaria	*Anthopleura* spp.	a.b	N, may disperse through detachment[5]
Cnidaria	Anthozoa	Actinaria	*Calliactis sp.*	c	N
Cnidaria	Anthozoa	Actinaria	*Metridium* spp.	a	N, may disperse through detachment[5]
Cnidaria	Anthozoa	Actinaria	Hormathiidae	c	1
Cnidaria	Anthozoa	Scleractinia	stony coral	b	1

Table 6.1. Rafting taxa, continued.

Phylum	**Class**	**Order**	**Finest taxon Ided**	**Year observed**	**Previously documented as rafting**
Cnidaria	Hydrozoa	Leptothecata	*Clytia gregaria*	a	N, though 9 other *Clytia* species documented as rafting[1]
Cnidaria	Hydrozoa	Leptothecata	*Obelia spp.*	a	1
Cnidaria	Hydrozoa	Leptothecata	*Plumularia setacea*	a	1
Cnidaria	Hydrozoa	Unknown	hydroid	b,c	1
Echinodermata	Ophiurodea		*Ophiuroidea* spp. 1	c	
Echinodermata	Ophiurodea		*Ophiuroidea* spp. 2	c	
Echinodermata	Ophiurodea		*Ophiuroidea* spp. 3	c	
Foraminifera	Polythalamea	Rotallida	*Planulina ornata*	a	N
Mollusca	Bivalvia	Arcoida	Arcidae	c	N
Mollusca	Bivalvia	Myoida	*Teredo* spp.	c	1
Mollusca	Bivalvia	Myoida	*Zirfaea* spp. *(pilsbryi?)*	b	N
Mollusca	Bivalvia	Mytiloida	*Mytilus galloprovincialis*	a,c	1
Mollusca	Bivalvia	Ostreoida	*Crassostrea gigas*	b,c	1
Mollusca	Bivalvia	Pectinoida	*Chlamys* spp.	c	1
Mollusca	Bivalvia	Pteroida	*Pinctada* spp.	c	1
Mollusca	Bivalvia	Unknown	Lower valve of oyster	c	1
Mollusca	Gastropoda	Caenogastropoda	*Litiopa melanostoma*	c	1
Mollusca	Gastropoda	Littorinimorpha	*Erronea* spp.	c	N, may have widespread larval transport[6]
Mollusca	Gastropoda	Nudibranchia	*Fiona pinnata*	a,b,c	1
Mollusca	Gastropoda	Nudibranchia	*Fiona pinnata* eggs	a	1
Mollusca	Gastropoda	Pleurobranchomorpha	*Berthella* spp.	c	N
Mollusca	Gastropoda	Superfamily Pyramidelloidea	*Odostomia (Evalea) tenuisculpta*	a	N
Platyhelminthes	Rhabditophora	Polycladida	Rhabditophora	c	1
Platyhelminthes	Rhabditophora	Rhabdocoela	Rhabdocoela	c	1
Platyhelminthes	Turbellaria	Unknown	flatworm	a,b	1
Platyhelminthes	Turbellaria	Unknown	flatworm	b	1
Porifera	Calcarea	Leucosolenida	*Sycon* spp.	b,c	N
Porifera	Demospongiae	Halichondrida	*Halichondria panacea*	a	N

References

Aliani, S., and A. Molcard. 2003. Hitch-hiking on floating marine debris: macrobenthic species in the Western Mediterranean Sea. Hydrobiologia 503:59–67. doi: 10.1023/B:HYDR.0000008480.95045.26.

Barnes, D. K. A. 2002. Invasions by marine life on plastic debris. Nature 416:808–809. doi: 10.1038/416808a.

Barnes, D. K. A., and K. P. P. Fraser. 2003. Rafting by five phyla on man-made flotsam in the Southern Ocean. Marine Ecology Progress Series 262:289–291. doi: 10.3354/meps262289.

Barnes, D. K. A., and P. Milner. 2005. Drifting plastic and its consequences for sessile organism dispersal in the Atlantic Ocean. Marine Biology 146:815–825. doi: 10.1007/s00227-004-1474-8.

Boero, F., C. Bucci, A. M. R. Colucci, C. Gravili, and L. Stabili. 2007. Obelia (Cnidaria, Hydrozoa, Campanulariidae): a microphagous, filter-feeding medusa. Marine Ecology 28:178–183. doi: 10.1111/j.1439-0485.2007.00164.x.

Bravo, M., J. C. Astudillo, D. Lancellotti, G. LunaJorquera, N. Valdivia, and M. Thiel. 2011. Rafting on abiotic substrata: properties of floating items and their influence on community succession. Marine Ecology Progress Series 439:1–17. doi: 10.3354/meps09344.

Brown, D. M., and L. Cheng. 1981. New net for sampling the ocean surface. Marine Ecology Progress Series 5:225–227. doi: 10.3354/meps005225.

Caine, E. A. 1977. Feeding mechanisms and possible resource partitioning of the Caprellidae (Crustacea: Amphipoda) from Puget Sound, USA. Marine Biology 42:331–336. doi: 10.1007/BF00402195.

Carpenter, E. J., and K. L. Smith. 1972. Plastics on the Sargasso Sea surface. Science 175:1240. doi: 10.1126/science.175.4027.1240.

Carter, M. C., J. D. D. Bishop, N. J. Evans, and C. A. Wood. 2010. Environmental influences on the formation and germination of hibernacula in the brackish-water bryozoan Victorella pavida Saville Kent, 1870 (Ctenostomata: Victorellidae). Journal of Experimental Marine Biology and Ecology 383:89–95. doi: 10.1016/j.jembe.2009.11.012.

Cheng, L., and R. L. Pitman. 2002. Mass Oviposition and Egg Development of the Ocean-Skater Halobates sobrinus (Heteroptera: Gerridae). Pacific Science 56:441–447. doi: 10.1353/psc.2002.0033.

Corsini, M., and G. Kondilatos. 2006. On the occurrence of two brachyurans, Myra subgranulata and Herbstia condyliata, on Rhodes Island (SE Aegean Sea). Crustaceana 79:167–174.

Croquer, A., Bastidas, Carolina, and D. Lipscomb. 2006. Folliculinid ciliates: a new threat to Caribbean corals? Diseases of Aquatic Organisms 69:75–8. doi: 10.3354/dao069075.

Dameron, O. J., M. Parke, M. A. Albins, and R. Brainard. 2007. Marine debris accumulation in the Northwestern Hawaiian Islands: An examination of rates and processes. Marine Pollution Bulletin 54:423–433. doi: 10.1016/j.marpolbul.2006.11.019.

Davidson, T. M. 2012. Boring crustaceans damage polystyrene floats under docks polluting marine waters with microplastic. Marine Pollution Bulletin 64:1821–1828. doi: 10.1016/j.marpolbul.2012.06.005.

Denitto, F., M. Pastore, and G. Belmonte. 2010. Occurrence of the Guinean species Herbstia nitida Manning Holthuis, 1981 (Decapoda, Brachyura) in a Mediterranean submarine cave and a comparison with the congeneric H. condyliata (Fabricius, 1787). Crustaceana 83:1017–1024. doi: 10.1163/001121610X513685.

Donlan, C. J., and P. A. Nelson. 2003. Observations of invertebrate colonized flotsam in the eastern tropical Pacific, with a discussion of rafting. Bulletin of Marine Science 72:231–240.

Emerson, W., and H. Chaney. 1995. A zoogeographic review of the Cypraeidae (Mollusca, Gastropoda) occurring in the eastern Pacific Ocean. Veliger 38:8–21.

Evans, F. 1958. Growth and maturity of the barnacles Lepas hillii and Lepas anatifera. Nature 182:1245–1246. doi: 10.1038/1821245b0.

Fofonoff, P., G. Ruiz, B. Steves, and J. Carlton. 2012. National Exotic Marine and Estuarine Species Information System. Retrieved October 26, 2012, from http://invasions.si.edu/nemesis/.

Godwin, L. S., L. Harris, A. Charette, and R. Moffitt. 2008. The marine invertebrate species associated with the biofouling of derelict fishing gear in the Pāpahanaumokuākea–Marine National Monument: A focus on marine non-native species transport. Preliminary Report, Pacific Islands Fisheries Science Center, Coral Reef Ecosystem Division, Honolulu, Hawaii.

Goldberg, H. 1985. An investigation of the feasibility of gooseneck barnacle mariculture (Lepas anatifera). MSc, University of British Columbia, Vancouver, BC. Retrieved from https://circle.ubc.ca/handle/2429/24671.

Goldstein, M. C., M. Rosenberg, and L. Cheng. 2012. Increased oceanic microplastic debris enhances oviposition in an endemic pelagic insect. Biology Letters 8:817–820. doi: 10.1098/rsbl.2012.0298.

He, F., and P. Legendre. 1996. On species-area relations. The American Naturalist 148:719–737.

Hidalgo-Ruz, V., L. Gutow, R. C. Thompson, and M. Thiel. 2012. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environmental Science & Technology 46:3060–3075. doi: 10.1021/es2031505.

Hirosaki, Y. 1960. Observations and experiments on the behavior of fishes toward floating objects in aquarium. Journal of the Faculty of Science of the Hokkaido University 14:320–326.

Hobday, A. J. 2000. Persistence and transport of fauna on drifting kelp (Macrocystis pyrifera (L.) C. Agardh) rafts in the Southern California Bight. Journal of Experimental Marine Biology and Ecology 253:75–96. doi: 10.1016/S0022-0981(00)00250-1.

Hoeksema, B. W., P. J. Roos, and G. C. Cadee. 2012. Trans-Atlantic rafting by the brooding reef coral Favia fragum on man-made flotsam. Marine Ecology Progress Series 445:209–218. doi: 10.3354/meps09460.

Hothorn, T., K. Hornik, M. A. van de Wiel, and A. Zeileis. 2008. Implementing a class of permutation tests: the coin package. Journal of Statistical Software 28:1–23.

Ingólfsson, A. 1995. Floating clumps of seaweed around Iceland: natural microcosms and a means of dispersal for shore fauna. Marine Biology 122:13–21. doi: 10.1007/BF00349273.

Jones, D. S., J. T. Anderson, and D. T. Anderson. 1990. Checklist of the Australian Cirripedia. Technical Reports of the Australian Museum 3:1–38. doi: 10.3853/j.1031-8062.3.1990.76.

Karl, D. M., R. R. Bidigare, and R. M. Letelier. 2001. Long-term changes in plankton community structure and productivity in the North Pacific Subtropical Gyre: the domain shift hypothesis. Deep Sea Research Part II: Topical Studies in Oceanography 48:1449–1470. doi: 16/S0967-0645(00)00149-1.

Lesser, M. P., S. E. Shumway, T. Cucci, and J. Smith. 1992. Impact of fouling organisms on mussel rope culture: interspecific competition for food among suspension-feeding invertebrates. Journal of Experimental Marine Biology and Ecology 165:91–102. doi: 10.1016/0022-0981(92)90291-H.

Lewis, P. N., M. J. Riddle, and S. D. A. Smith. 2005. Assisted passage or passive drift: a comparison of alternative transport mechanisms for non-indigenous coastal species into the Southern Ocean. Antarctic Science 17:183–191.

Lomolino, M. V. 2000. Ecology's most general, yet protean pattern: the species-area relationship. Journal of Biogeography 27:17–26.

Lovely, E. C. 2005. The life history of Phoxichilidium tubulariae (Pycnogonida: Phoxichilidiidae). Northeastern Naturalist 12:77–92. doi: 10.1656/1092-6194(2005)012[0077:TLHOPT]2.0.CO;2.

MacArthur, R. H., and E. O. Wilson. 1963. An equilibrium theory of insular zoogeography. Evolution 17:373–387.

Maso, M., E. Garces, F. Pages, and J. Camp. 2003. Drifting plastic debris as a potential vector for dispersing Harmful Algal Bloom (HAB) species. Scientia Marina 67:107–111.

Matassa, C. M., and G. C. Trussell. 2011. Landscape of fear influences the relative importance of consumptive and nonconsumptive predator effects. Ecology 92:2258–2266. doi: 10.1890/11-0424.1.

Matthews, D. C. 1963. Hawaiian records of folliculinids (Protozoa) from submerged wood. Pacific Science 17:438–443.

McDermid, K. J., and T. L. McMullen. 2004. Quantitative analysis of small-plastic debris on beaches in the Hawaiian archipelago. Marine Pollution Bulletin 48:790–794.

Mook, D. H. 1981. Removal of suspended particles by fouling communities. Marine Ecology Progress Series 5:279–281.

Moret-Ferguson, S., K. L. Law, G. Proskurowski, E. K. Murphy, E. E. Peacock, and C. M. Reddy. 2010. The size, mass, and composition of plastic debris in the western North Atlantic Ocean. Marine Pollution Bulletin 60:1873–1878. doi: 10.1016/j.marpolbul.2010.07.020.

Nelson, P. A. 2003. Marine fish assemblages associated with fish aggregating devices (FADs): effects of fish removal, FAD size, fouling communities, and prior recruits. Fishery Bulletin 101:835–850.

Palmer, C., and R. Gates. 2010. Skeletal eroding band in Hawaiian corals. Coral Reefs 29:469–469. doi: 10.1007/s00338-010-0597-2.

Pham, P. H., J. Jung, J. S. Lumsden, B. Dixon, and N. C. Bols. 2012. The potential of waste items in aquatic environments to act as fomites for viral haemorrhagic septicaemia virus. Journal of Fish Diseases 35:73–77. doi: 10.1111/j.1365-2761.2011.01323.x.

Pister, B. 2009. Urban marine ecology in southern California: the ability of riprap structures to serve as rocky intertidal habitat. Marine Biology 156:861–873. doi: 10.1007/s00227-009-1130-4.

Postel, L., H. Fock, and W. Hagen. 2000. Biomass and abundance. Pages 83–192 *in* R. Harris, P. Wiebe, J. Lenz, H. R. Skjolda, and M. Huntley, editors. ICES Zooplankton Methodology Manual. Academic Press, London.

Pratt, M. C. 2008. Living where the flow is right: How flow affects feeding in bryozoans. Integrative and Comparative Biology 48:808–822. doi: 10.1093/icb/icn052.

R Development Core Team. 2011. R: A language and environment for statistical computing. Vienna, Austria. Retrieved from http://www.r-project.org.

Ricciardi, A., and E. Bourget. 1998. Weight-to-weight conversion factors for marine benthic macroinvertebrates. Marine Ecology Progress Series 163:245–251.

Riemann-Zürneck, K. 1998. How Sessile are Sea Anemones? A review of free-living forms in the Actiniaria (Cnidaria: Anthozoa). Marine Ecology 19:247–261. doi: 10.1111/j.1439-0485.1998.tb00466.x.

Ritz, D. A., and D. J. Crisp. 1970. Seasonal changes in feeding rate in Balanus balanoides. Journal of the Marine Biological Association of the United Kingdom 50:223–240. doi: 10.1017/S0025315400000734.

Rodriguez, S., A. Cróquer, H. Guzmán, and C. Bastidas. 2009. A mechanism of transmission and factors affecting coral susceptibility to Halofolliculina sp. infection. Coral Reefs 28:67–77. doi: 10.1007/s00338-008-0419-y.

Rodriguez, S. R., F. P. Ojeda, and N. C. Inestrosa. 1993. Settlement of benthic marine invertebrates. Marine Ecology Progress Series 97:193–207.

Sheldon, R. W., A. Prakash, and W. H. Sutcliffe. 1972. The size distribution of particles in the ocean. Limnology and Oceanography 17:327–340.

Simberloff, D. 1976. Experimental zoogeography of islands: effects of island size. Ecology 57:629–648.

Thiel, M., and L. Gutow. 2005a. The ecology of rafting in the marine environment I: The floating substrata. Oceanography and Marine Biology: An Annual Review 42:181–263.

Thiel, M., and L. Gutow. 2005b. The ecology of rafting in the marine environment II: The rafting organisms and community. Oceanography and Marine Biology: An Annual Review 43:279–418.

Thiel, M., and P. A. Haye. 2006. The ecology of rafting in the marine environment III: Biogeographical and evolutionary consequences. Oceanography and Marine Biology: An Annual Review 44:323–429.

Titmus, A. J., and K. D. Hyrenbach. 2011. Habitat associations of floating debris and marine birds in the North East Pacific Ocean at coarse and meso spatial scales. Marine Pollution Bulletin 62:2496–2506. doi: 10.1016/j.marpolbul.2011.08.007.

Tsikhon-Lukanina, E. A., O. G. Reznichenko, and G. G. Nikolaeva. 2001. Ecology of invertebrates on the oceanic floating substrata in the northwest Pacific ocean. Oceanology 41:525–530.

Tyrrell, M. C., and J. E. Byers. 2007. Do artificial substrates favor nonindigenous fouling species over native species? Journal of Experimental Marine Biology and Ecology 342:54–60.

Venrick, E. L., T. W. Backman, W. C. Bartram, C. J. Platt, M. S. Thornhill, and R. E. Yates. 1973. Man-made objects on the surface of the central North Pacific ocean. Nature 241:271–271. doi: 10.1038/241271a0.

Winston, J. E. 1982. Drift plastic - an expanding niche for a marine invertebrate. Marine Pollution Bulletin 13:348–351.

Winston, J. E., M. R. Gregory, and L. Stevens. 1997. Encrusters, epibionts, and other biota associated with pelagic plastics: a review of biological, environmental, and conservation issues. Pages 81–98 *in* J. M. Coe and D. B. Rogers, editors. Marine debris: sources, impact and solutions. Springer, New York.

Wong, C. S., D. R. Green, and W. J. Cretney. 1974. Quantitative tar and plastic waste distributions in Pacific Ocean. Nature 247:30–32. doi: doi:10.1038/247030a0.

World Register of Marine Species. 2012. Herbstia H. Milne Edwardsm 1834. Retrieved October 26, 2012, from http://www.marinespecies.org/aphia.php?p=taxdetails&id=106902.

Ye, S., and A. L. Andrady. 1991. Fouling of floating plastic debris under Biscayne Bay exposure conditions. Marine Pollution Bulletin 22:608–613. doi: 10.1016/0025-326X(91)90249-R.

Zettler, E. R., T. Mincer, G. Proskurowski, and L. A. Amaral-Zettler. 2011. The “plastisphere”: a new and expanding habitat for marine protists. Journal of Phycology 47:S45–S45.

Appendix

Figure S6.1. Photos of debris
a) Forward half of a small fishing boat, found floating upright; b) *Lepas* barnacles growing on a rope; c) Two *Lepas* barnacles and membraniporid bryozoans growing on a toothbrush handle; d) Close view of fragment showing folliculinid ciliates and other organisms.

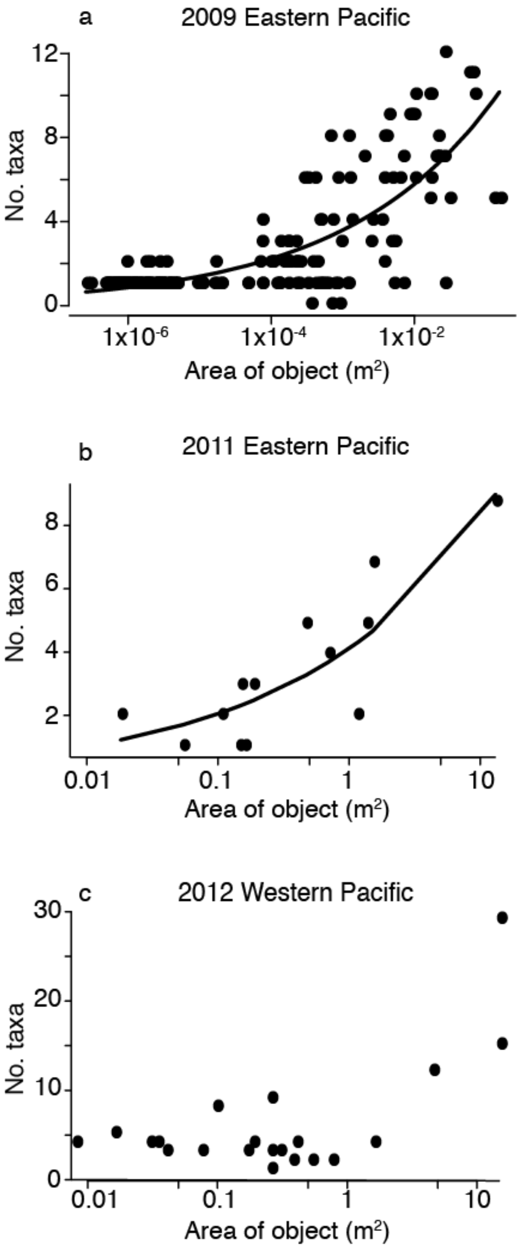


Figure S6.2. Semilog plots of taxa vs. surface area (m^2) of debris object, by cruise Solid line is an exponential non-linear least squares regression, and broken line is a local polynomial regression fitting with a span of 0.5. All following statistics are for Spearman rank correlations. a) 2009 Eastern Pacific, $p<0.001$, $R^2=0.471$. b) 2011 Eastern Pacific, $p=0.002$, $R^2=0.613$. c) 2012 Western Pacific, $p=0.616$, $R^2=0.013$. Differences in x-axis scale between 2009 and 2011/2012 are due to different sampling methodologies.

Table S6.1. Debris objects by year, location, and taxa

Date	Station	Latitude	Longitude	Size (m^2)	Object Description	Taxon Description	Taxon ID
6-Aug-2009	U12.F19	32.212	-129.75	NA	plastic crate	crab	Planes cyaneus
8-Aug-2009	S2.F20	32.058	-136.081	0.01632	sample of plastic bucket	isopod	Idotea
8-Aug-2009	S2.F20	32.058	-136.081	0.01632	sample of plastic bucket	nudibranch	Fiona pinnata
8-Aug-2009	S2.F20	32.058	-136.081	0.01632	sample of plastic bucket	polychaete	Hipponoe gaudichaudi
8-Aug-2009	S2.F20	32.058	-136.081	0.01632	sample of plastic bucket	bryozoan	Membranipora tenella
8-Aug-2009	S2.F20	32.058	-136.081	0.01632	sample of plastic bucket	hydroid	Unknown
8-Aug-2009	S2.F20	32.058	-136.081	0.01632	sample of plastic bucket	amphipod	Caprella
8-Aug-2009	S2.F21	32.057	-137.91	0.00503	white plastic sheeting	bryozoan	Jellyella tuberculata
8-Aug-2009	S2.F22	32.045	-136.076	0.0011	rope	crab	Planes cyaneus
8-Aug-2009	S2.F22	32.045	-136.076	0.0011	rope	isopod	Idotea
8-Aug-2009	S2.F22	32.045	-136.076	0.0011	rope	amphipod	Gammarid amphipods
8-Aug-2009	S2.F22	32.045	-136.076	0.0011	rope	anemone	Anemone
8-Aug-2009	S2.F22	32.045	-136.076	0.0011	rope	barnacle	Cyprids
8-Aug-2009	S2.F22	32.045	-136.076	0.0011	rope	polychaete	polychaete
8-Aug-2009	S2.F22	32.045	-136.076	0.0011	rope	barnacle	Lepas antifera
8-Aug-2009	S2.F22	32.045	-136.076	0.00121	pieces of bucket	crab	Planes cyaneus
8-Aug-2009	S2.F22	32.045	-136.076	0.00121	pieces of bucket	isopod	Idotea
8-Aug-2009	S2.F22	32.045	-136.076	0.00121	pieces of bucket	polychaete	Hipponoe gaudichaudi
8-Aug-2009	S2.F22	32.045	-136.076	0.00121	pieces of bucket	bryozoan	Membranipora tenella
8-Aug-2009	S2.F22	32.045	-136.076	0.00121	pieces of bucket	hydroid	Obelia spp.
8-Aug-2009	S2.F22	32.045	-136.076	0.00121	pieces of bucket	amphipod	Caprella
9-Aug-2009	F13	32.024	-138.979	0.00332	assorted objects collected by dipmet	anemone	Anthopleura spp.
9-Aug-2009	F13	32.024	-138.979	0.0025	assorted objects collected by dipmet	bryozoan	Tubulipora
9-Aug-2009	F13	32.024	-138.979	0.00068	assorted objects collected by dipmet	crab	Planes minutus
9-Aug-2009	F13	32.024	-138.979	0.00048	assorted objects collected by dipmet	barnacle	Lepas antifera
9-Aug-2009	F14	32.024	-138.979	0.00455	piece of soft plastic stuck together	polychaete	Hipponoe gaudichaudi
9-Aug-2009	F14	32.024	-138.979	0.00455	piece of soft plastic stuck together	barnacle	Lepas antifera
9-Aug-2009	F14	32.024	-138.979	0.00455	piece of soft plastic stuck together	bryozoan	Jellyella eburnea
9-Aug-2009	F14	32.024	-138.979	0.00455	piece of soft plastic stuck together	bryozoan	Jellyella tuberculata
9-Aug-2009	F14	32.024	-138.979	0.00455	piece of soft plastic stuck together	bryozoan	Membranipora tenella
9-Aug-2009	Manta 40.F11	32.058	-136.081	0.1262	half hard round ball; animals scraped off	barnacle	Lepas antifera
9-Aug-2009	Manta 40.F11	32.058	-136.081	0.1262	half hard round ball; animals scraped off	isopod	Idotea
9-Aug-2009	Manta 40.F11	32.058	-136.081	0.1262	half hard round ball; animals scraped off	bryozoan	Jellyella tuberculata
9-Aug-2009	Manta 40.F11	32.058	-136.081	0.1262	half hard round ball; animals scraped off	nudibranch	Fiona pinnata
9-Aug-2009	Manta 40.F11	32.058	-136.081	0.1262	half hard round ball; animals scraped off	hydroid	Obelia spp.
9-Aug-2009	S2.36	32.056	-137.922	0.0012746	piece of comb	bryozoan	Jellyella eburnea
9-Aug-2009	S2.36	32.056	-137.922	0.0012746	piece of comb	bryozoan	Bowerbankia spp.

Table S6.1. Debris items with associated taxa, continued.

Date	Station	Latitude	Longitude	Size (m^2)	Object Description	Taxon Description	Taxon ID
9-Aug-2009	S2.36	32.056	-137.922	0.0012746	piece of comb	hydroid	Obelia spp.
9-Aug-2009	S2.36	32.056	-137.922	0.0012746	piece of comb	unknown	calcarous mat
9-Aug-2009	U22.45	32.029	-138.508	0.0002786	blue irregular fragment	bryozoan	Bowerbankia spp.
9-Aug-2009	U22.45	32.029	-138.508	0.0002786	blue irregular fragment	hydroid	Obelia spp.
9-Aug-2009	U22.45	32.029	-138.508	0.0002786	blue irregular fragment	bryozoan	Filicrisia spp.
9-Aug-2009	U22.45	32.029	-138.508	0.0002786	blue irregular fragment	sponge	unknown
9-Aug-2009	U22.45	32.029	-138.508	0.0002786	blue irregular fragment	bryozoan	Jellyella spp.
9-Aug-2009	U22.45	32.029	-138.508	0.0002786	blue irregular fragment	algae	NA
10-Aug-2009	S3.53	32.898	-140.326	0.0006786	white styrofoam	NA	NA
10-Aug-2009	S3.53	32.898	-140.326	0.0004032	yellow square	bryozoan	Jellyella tuberculata
10-Aug-2009	S3.F1	32.911	-139.679	0.0158	grey bottle	bryozoan	Jellyella eburnea
10-Aug-2009	S3.F1	32.911	-139.679	0.0158	grey bottle	bryozoan	Jellyella eburnea
10-Aug-2009	S3.F1	32.911	-139.679	0.0158	grey bottle	bryozoan	Membranipora tenella
10-Aug-2009	S3.F1	32.911	-139.679	0.0158	grey bottle	hydroid	Obelia spp.
10-Aug-2009	S3.F1	32.911	-139.679	0.0158	grey bottle	bryozoan	Jellyella eburnea
10-Aug-2009	S3.F1	32.911	-139.679	0.0158	grey bottle	hydroid	Obelia spp.
10-Aug-2009	S3.F1	32.911	-139.679	0.0158	grey bottle	bryozoan	Jellyella eburnea
10-Aug-2009	S3.F1	32.911	-139.679	0.0158	grey bottle	hydroid	Obelia spp.
10-Aug-2009	S3.F1	32.911	-139.679	0.0158	grey bottle	copepod	Harpacticoid copepods
10-Aug-2009	S3.F1	32.911	-139.679	0.0158	grey bottle	amphipod	Caprella
10-Aug-2009	S3.F1	32.911	-139.679	0.0158	grey bottle	nudibranch	Fiona pinnata
10-Aug-2009	S3.F12	32.917	-139.694	0.0251	grey plastic fragment	bryozoan	Jellyella eburnea
10-Aug-2009	S3.F12	32.917	-139.694	0.0251	grey plastic fragment	polychaete	Spirorbis spp.
10-Aug-2009	S3.F12	32.917	-139.694	0.0251	grey plastic fragment	bryozoan	Bugula spp.
10-Aug-2009	S3.F12	32.917	-139.694	0.0251	grey plastic fragment	barnacle	Cyprids
10-Aug-2009	S3.F12	32.917	-139.694	0.0251	grey plastic fragment	hydroid	Obelia spp.
10-Aug-2009	S3.F12	32.917	-139.694	0.0251	grey plastic fragment	isopod	Idotea
10-Aug-2009	S3.F12	32.917	-139.694	0.0251	grey plastic fragment	copepod	Harpacticoid copepods
10-Aug-2009	S3.F2	32.911	-139.679	0.02571	part of white plastic jar	bryozoan	Jellyella tuberculata
10-Aug-2009	S3.F2	32.911	-139.679	0.02571	part of white plastic jar	hydroid	Obelia spp.
10-Aug-2009	S3.F2	32.911	-139.679	0.02571	part of white plastic jar	hydroid	Plumularia setacea
10-Aug-2009	S3.F2	32.911	-139.679	0.02571	part of white plastic jar	algae	crustose coralline algae
10-Aug-2009	S3.F2	32.911	-139.679	0.02571	part of white plastic jar	?	single celled something?
10-Aug-2009	S3.F2	32.911	-139.679	0.02571	part of white plastic jar	algae	?
10-Aug-2009	S3.F2	32.911	-139.679	0.02571	part of white plastic jar	bryozoan	Jellyella tuberculata
10-Aug-2009	S3.F2	32.911	-139.679	0.02571	part of white plastic jar	barnacle	Lepas pacifica
10-Aug-2009	S3.F2	32.911	-139.679	0.02571	part of white plastic jar	barnacle	Cyprids
10-Aug-2009	S3.F2	32.911	-139.679	0.02571	part of white plastic jar	bryozoan	Jellyella tuberculata
10-Aug-2009	S3.F2	32.911	-139.679	0.02571	part of white plastic jar	hydroid	Plumularia setacea
10-Aug-2009	S3.F2	32.911	-139.679	0.02571	part of white plastic jar	hydroid	Obelia spp.
10-Aug-2009	S3.F2	32.911	-139.679	0.02571	part of white plastic jar	barnacle	Cyprids
10-Aug-2009	S3.F2	32.911	-139.679	0.02571	part of white plastic jar	isopod	Idotea

Table S6.1. Debris items with associated taxa, continued.

Date	Station	Latitude	Longitude	Size (m^2)	Object Description	Taxon Description	Taxon ID
10-Aug-2009	S3.F2	32.911	-139.679	0.02571	part of white plastic jar	amphipod	Caprella
10-Aug-2009	S3.F2	32.911	-139.679	0.02571	part of white plastic jar	amphipod	Gammarid amphipods
10-Aug-2009	S3.F2	32.911	-139.679	0.02571	part of white plastic jar	flatworm	Flatworm
10-Aug-2009	S3.F2	32.911	-139.679	0.02571	part of white plastic jar	nudibranch	Fiona pinnata
10-Aug-2009	S3.F2	32.911	-139.679	0.02571	part of white plastic jar	isopod	Cirolanid isopod
10-Aug-2009	S3.F4	32.911	-139.679	0.00942	fragment	bryozoan	Membranipora tenella
10-Aug-2009	S3.F4	32.911	-139.679	0.00942	fragment	bryozoan	Jellyella tuberculata
10-Aug-2009	S3.F4	32.911	-139.679	0.00942	fragment	bryozoan	Bowerbankia spp.
10-Aug-2009	S3.F4	32.911	-139.679	0.00942	fragment	hydroid	unknown
10-Aug-2009	S3.F4	32.911	-139.679	0.00942	fragment	algae	crustose coralline algae
10-Aug-2009	S3.F4	32.911	-139.679	0.00942	fragment	bryozoan	Jellyella eburnea
10-Aug-2009	S3.F4	32.911	-139.679	0.00942	fragment	bryozoan	Membranipora tenella
10-Aug-2009	S3.F4	32.911	-139.679	0.00942	fragment	copepod	Harpacticoid copepods
10-Aug-2009	S3.F4	32.911	-139.679	0.00942	fragment	isopod	Cirolanid isopod
10-Aug-2009	S3.F4	32.911	-139.679	0.00942	fragment	isopod	Idotea
10-Aug-2009	S3.F4	32.911	-139.679	0.00942	fragment	flatworm	Flatworm
10-Aug-2009	S3.F4	32.911	-139.679	0.00942	fragment	amphipod	Gammarid amphipods
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	hydroid	Obelia spp.
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	algae	Filamentous algae
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	bryozoan	Jellyella eburnea
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	bryozoan	Victorella spp.
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	bryozoan	Victorella spp.
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	hydroid	Clytia gregaria
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	hydroid	Obelia spp.
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	algae	Filamentous algae
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	bryozoan	Jellyella eburnea
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	bryozoan	Victorella spp.
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	barnacle	Cyprids
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	hydroid	Obelia spp.
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	algae	Filamentous algae
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	bryozoan	Jellyella eburnea
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	bryozoan	Victorella spp.
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	barnacle	Cyprids
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	bryozoan	Jellyella tuberculata
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	hydroid	Clytia gregaria
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	isopod	Idotea
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	nudibranch	Fiona pinnata
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	copepod	Harpacticoid copepods
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	amphipod	Caprella
10-Aug-2009	S3.F5	32.911	-139.679	0.05699	black tarp	amphipod	Gammarid amphipods
10-Aug-2009	S3.F6	32.911	-139.679	0.1544	piece of tarp	barnacle	Lepas pacifica
10-Aug-2009	S3.F6	32.911	-139.679	0.1544	piece of tarp	barnacle	Lepas pacifica

Table S6.1. Debris items with associated taxa, continued.

Date	Station	Latitude	Longitude	Size (m^2)	Object Description	Taxon Description	Taxon ID
10-Aug-2009	S3.F6	32.911	-139.679	0.1544	piece of tarp	hydroid	Hydroids
10-Aug-2009	S3.F6	32.911	-139.679	0.1544	piece of tarp	bryozoan	Jellyella eburnea
10-Aug-2009	S3.F6	32.911	-139.679	0.1544	piece of tarp	isopod	Idotea
10-Aug-2009	S3.F6	32.911	-139.679	0.1544	piece of tarp	amphipod	Gammarid amphipods
10-Aug-2009	S3.F7	32.911	-139.679	0.02556	fragment	bryozoan	Jellyella eburnea
10-Aug-2009	S3.F7	32.911	-139.679	0.02556	fragment	bryozoan	Membranipora tenella
10-Aug-2009	S3.F7	32.911	-139.679	0.02556	fragment	bryozoan	Jellyella tuberculata
10-Aug-2009	S3.F7	32.911	-139.679	0.00676	fragment	bryozoan	Jellyella tuberculata
10-Aug-2009	U27.51	32.353	-140.295	0.0003128	blue Y-shape fragment	bryozoan	Jellyella eburnea
10-Aug-2009	U27.F9	32.355	-139.711	0.00189	black curved fragment	bryozoan	Jellyella eburnea
10-Aug-2009	U27.F9	32.355	-139.711	0.00189	black curved fragment	barnacle	Lepas spp.
10-Aug-2009	U27.F9	32.355	-139.711	0.00082	white thin fragment	bryozoan	Jellyella eburnea
10-Aug-2009	U27.F9	32.355	-139.711	0.0037	bottlecap	anemone	Anthopleura spp.
10-Aug-2009	U27.F9	32.355	-139.711	0.0037	bottlecap	bryozoan	Jellyella eburnea
10-Aug-2009	U27.F9	32.355	-139.711	0.0037	bottlecap	barnacle	Lepas spp.
10-Aug-2009	U27.F9	32.355	-139.711	0.0097	rope clump	bryozoan	unknown
10-Aug-2009	U27.F9	32.355	-139.711	0.00039	white fragment	bryozoan	Jellyella spp.
10-Aug-2009	U27.F9	32.355	-139.711	0.00031	black fragment	bryozoan	Jellyella eburnea
10-Aug-2009	U27.F9	32.355	-139.711	0.00031	black fragment	copepod	Harpacticoid copepods
10-Aug-2009	U27.F9	32.355	-139.711	0.00031	black fragment	amphipod	Gammarid amphipods
10-Aug-2009	U27.F9	32.355	-139.711	0.00031	black fragment	isopod	Sphaeromatidae
10-Aug-2009	U27.F9	32.355	-139.711	0.00031	black fragment	gastropod	Evalea tenuisculpta
10-Aug-2009	U27.F9	32.355	-139.711	0.00031	black fragment	crab	Planes spp.
10-Aug-2009	U28.F10	32.635	-139.689	0.00669	green line	bryozoan	Tubulipora
10-Aug-2009	U28.F10	32.635	-139.689	0.00669	green line	anemone	unknown
10-Aug-2009	U28.F10	32.635	-139.689	0.00669	green line	isopod	Idotea
10-Aug-2009	U28.F10	32.635	-139.689	0.00669	green line	fish eggs	flying fish?
10-Aug-2009	U28.F10	32.635	-139.689	0.00669	green line	amphipod	Gammarid amphipods
10-Aug-2009	U28.F10	32.635	-139.689	0.00669	green line	copepod	Harpacticoid copepods
10-Aug-2009	U28.F10	32.635	-139.689	0.00669	green line	polychaete	Hipponoe gaudichaudi
11-Aug-2009	S3.25	32.916	-139.67	0.02992	scraped off milk crate	polychaete	Hipponoe gaudichaudi
11-Aug-2009	S3.25	32.916	-139.67	0.02992	scraped off milk crate	anemone	Anthopleura spp.
11-Aug-2009	S3.25	32.916	-139.67	0.02992	scraped off milk crate	bryozoan	Tubulipora
11-Aug-2009	S3.25	32.916	-139.67	0.02992	scraped off milk crate	isopod	Idotea
11-Aug-2009	S3.25	32.916	-139.67	0.02992	scraped off milk crate	foraminifera	Planulina ornata
11-Aug-2009	S3.25	32.916	-139.67	0.02992	scraped off milk crate	sponge	Halichondria panacea
11-Aug-2009	S3.F16	32.916	-139.67	0.00116	pink noodle	bryozoan	Jellyella tuberculata
11-Aug-2009	S3.F16	32.916	-139.67	0.0043	white rectangle	bryozoan	Jellyella tuberculata
11-Aug-2009	S3.F16	32.916	-139.67	0.0043	white rectangle	barnacle	Cyprids
11-Aug-2009	S3.F16	32.916	-139.67	0.00064	black tube	bryozoan	Jellyella eburnea
11-Aug-2009	S3.F16	32.916	-139.67	0.0039	pale blue long rectangle	bryozoan	Jellyella eburnea
11-Aug-2009	S3.F16	32.916	-139.67	0.0039	pale blue long rectangle	bryozoan	Membranipora tenella

Table S6.1. Debris items with associated taxa, continued.

Date	Station	Latitude	Longitude	Size (m^2)	Object Description	Taxon Description	Taxon ID
11-Aug-2009	S3.F16	32.916	-139.67	0.00828	pale blue triangle	bryozoan	Membranipora tenella
11-Aug-2009	S3.F16	32.916	-139.67	0.00828	pale blue triangle	bryozoan	Jellyella eburnea
11-Aug-2009	S3.F16	32.916	-139.67	0.00828	pale blue triangle	barnacle	Cyprids
11-Aug-2009	S3.F16	32.916	-139.67	0.01002	medium blue fragment	bryozoan	Jellyella eburnea
11-Aug-2009	S3.F16	32.916	-139.67	0.01002	medium blue fragment	hydroid	Hydroids
11-Aug-2009	S3.F16	32.916	-139.67	0.01002	medium blue fragment	barnacle	Cyprids
11-Aug-2009	S3.F16	32.916	-139.67	0.01632	black rectangle	barnacle	Cyprids
11-Aug-2009	S3.F16	32.916	-139.67	0.01632	black rectangle	bryozoan	Jellyella tuberculata
11-Aug-2009	S3.F16	32.916	-139.67	0.01632	black rectangle	hydroid	Hydroids
11-Aug-2009	S3.F16	32.916	-139.67	0.01632	black rectangle	bryozoan	Jellyella eburnea
11-Aug-2009	S3.F16	32.916	-139.67	0.0089	soft plastic squished into ball	barnacle	Cyprids
11-Aug-2009	S3.F16	32.916	-139.67	0.0089	soft plastic squished into ball	barnacle	Lepas pacifica
11-Aug-2009	S3.F16	32.916	-139.67	0.0089	soft plastic squished into ball	bryozoan	Jellyella eburnea
11-Aug-2009	S3.F16	32.916	-139.67	0.0089	soft plastic squished into ball	hydroid	Hydroids
11-Aug-2009	S3.F16	32.916	-139.67	NA	unattached	isopod	Idotea
11-Aug-2009	S3.F16	32.916	-139.67	NA	unattached	amphipod	Gammarid amphipods
11-Aug-2009	S3.F16	32.916	-139.67	NA	unattached	anemone	Anemone
11-Aug-2009	S3.F16	32.916	-139.67	NA	unattached	flatworm	Flatworm
11-Aug-2009	S3.F16	32.916	-139.67	NA	unattached	gastropod	Evalea tenuisculpta
11-Aug-2009	S3.F16	32.916	-139.67	NA	unattached	nudibranch	Fiona pinnata
11-Aug-2009	S3.F16	32.916	-139.67	NA	unattached	copepod	Harpacticoid copepods
11-Aug-2009	S3.F17	32.916	-139.67	0.06366	Tarp	bryozoan	Tubulipora
11-Aug-2009	S3.F17	32.916	-139.67	0.06366	Tarp	sponge	sponge
11-Aug-2009	S3.F17	32.916	-139.67	0.06366	Tarp	bryozoan	Bugula
11-Aug-2009	S3.F17	32.916	-139.67	0.06366	Tarp	barnacle	Cyprids
11-Aug-2009	S3.F17	32.916	-139.67	0.06366	Tarp	hydroid	Hydroids
11-Aug-2009	S3.F17	32.916	-139.67	0.06366	Tarp	anemone	Anemone
11-Aug-2009	S3.F17	32.916	-139.67	0.06366	Tarp	bryozoan	Tubulipora
11-Aug-2009	S3.F17	32.916	-139.67	0.06366	Tarp	ascidian	ascidian
11-Aug-2009	S3.F17	32.916	-139.67	0.06366	Tarp	polychaete	polychaete
11-Aug-2009	S3.F17	32.916	-139.67	0.06366	Tarp	polychaete	polychaete
11-Aug-2009	S3.F17	32.916	-139.67	0.06366	Tarp	isopod	Idotea
11-Aug-2009	S3.F17	32.916	-139.67	0.06366	Tarp	amphipod	Gammarid amphipods
11-Aug-2009	S3.F17	32.916	-139.67	0.06366	Tarp	barnacle	Cyprids
11-Aug-2009	S3.F17	32.916	-139.67	0.06366	Tarp	anemone	Anemone
11-Aug-2009	S3.F17	32.916	-139.67	0.06366	Tarp	pycnogonid	Phoxichilidium quadradentatum
11-Aug-2009	S3.F18	32.916	-139.67	0.01912	corner of white plastic box	hydroid	Obelia spp.
11-Aug-2009	S3.F18	32.916	-139.67	0.01912	corner of white plastic box	bryozoan	Jellyella eburnea
11-Aug-2009	S3.F18	32.916	-139.67	0.01912	corner of white plastic box	anemone	Metridium spp.
11-Aug-2009	S3.F18	32.916	-139.67	0.01912	corner of white plastic box	nudibranch	Fiona pinnata EGGS
11-Aug-2009	S3.F18	32.916	-139.67	0.01912	corner of white plastic box	hydroid	Obelia spp.

Table S6.1. Debris items with associated taxa, continued.

Date	Station	Latitude	Longitude	Size (m^2)	Object Description	Taxon Description	Taxon ID
11-Aug-2009	S3.F18	32.916	-139.67	0.01912	corner of white plastic box	bryozoan	Jellyella tuberculata
11-Aug-2009	S3.F18	32.916	-139.67	0.01912	corner of white plastic box	sponge	Halichondria panacea
11-Aug-2009	S3.F18	32.916	-139.67	0.01912	corner of white plastic box	isopod	Idotea
11-Aug-2009	S3.F18	32.916	-139.67	0.01912	corner of white plastic box	amphipod	Gammarid amphipods
13-Aug-2009	F26	35.985	-139.983	0.06666	pieces of crate	bryozoan	Bugula
13-Aug-2009	F26	35.985	-139.983	0.06666	pieces of crate	hydroid	Hydroids
13-Aug-2009	F26	35.985	-139.983	0.06666	pieces of crate	bryozoan	Membranipora tenella
13-Aug-2009	F26	35.985	-139.983	0.06666	pieces of crate	copepod	Harpacticoid copepods
13-Aug-2009	F26	35.985	-139.983	0.06666	pieces of crate	bryozoan	Jellyella tuberculata
13-Aug-2009	F26	35.985	-139.983	0.06666	pieces of crate	barnacle	Lepas antifera
13-Aug-2009	F26	35.985	-139.983	0.06666	pieces of crate	amphipod	Caprella
13-Aug-2009	F26	35.985	-139.983	0.06666	pieces of crate	isopod	Idotea
13-Aug-2009	F26	35.985	-139.983	0.06666	pieces of crate	amphipod	Gammarid amphipods
13-Aug-2009	F26	35.985	-139.983	0.06666	pieces of crate	polychaete	polychaete
13-Aug-2009	F26	35.985	-139.983	0.06666	pieces of crate	flatworm	Flatworm
13-Aug-2009	G1.12.82	35.983	-139.759	0.0004586	dock chunk	bryozoan	Bowerbankia spp.
13-Aug-2009	G1.12.82	35.983	-139.759	0.0004586	dock chunk	hydroid	Obelia spp.
13-Aug-2009	G1.12.82	35.983	-139.759	0.0004586	dock chunk	bryozoan	Jellyella eburnea
13-Aug-2009	G1.12.82	35.983	-139.759	0.0004586	dock chunk	sponge	Halichondria panacea
13-Aug-2009	G1.13	35.953	-139.653	0.0004622	white fragment	bryozoan	Membranipora spp.
13-Aug-2009	G1.13	35.953	-139.653	0.0008726	line triangle	NA	NA
13-Aug-2009	G1.15	35.809	-139.648	0.0003668	white fragment	bryozoan	Jellyella eburnea
13-Aug-2009	G1.15	35.809	-139.648	0.0003668	white fragment	bryozoan	unknown
13-Aug-2009	G1.2	35.804	-139.983	0.0008006	white fragment	bryozoan	Jellyella spp.
13-Aug-2009	G1.3.73	35.893	-139.983	0.0005482	orange fragment	bryozoan	Jellyella eburnea
13-Aug-2009	G1.3.73	35.893	-139.983	0.000585	white fragment	bryozoan	Membranipora tenella
14-Aug-2009	F29	35.99	-138.241	0.02066	cut-up eel trap	anemone	Anemone
14-Aug-2009	F29	35.99	-138.241	0.02066	cut-up eel trap	hydroid	Hydroids
14-Aug-2009	F29	35.99	-138.241	0.02066	cut-up eel trap	bryozoan	Membranipora tenella
14-Aug-2009	F29	35.99	-138.241	0.02066	cut-up eel trap	isopod	Idotea
14-Aug-2009	F29	35.99	-138.241	0.02066	cut-up eel trap	amphipod	Gammarid amphipods
14-Aug-2009	F29	35.99	-138.241	0.02066	cut-up eel trap	flatworm	Flatworm
14-Aug-2009	F29	35.99	-138.241	0.02066	cut-up eel trap	crab	Planes minutus
14-Aug-2009	F29	35.99	-138.241	0.02066	intact eel trap	hydroid	Hydroids
14-Aug-2009	F29	35.99	-138.241	0.02066	intact eel trap	bryozoan	Jellyella eburnea
14-Aug-2009	F29	35.99	-138.241	0.02066	intact eel trap	amphipod	Gammarid amphipods
14-Aug-2009	F29	35.99	-138.241	0.02066	intact eel trap	amphipod	Caprella
14-Aug-2009	F29	35.99	-138.241	0.02066	intact eel trap	anemone	Anemone

Table S6.1. Debris items with associated taxa, continued.

Date	Station	Latitude	Longitude	Size (m^2)	Object Description	Taxon Description	Taxon ID
14-Aug-2009	F29	35.99	-138.241	0.02066	intact eel trap	isopod	Idotea
14-Aug-2009	F29	35.99	-138.241	0.02066	intact eel trap	copepod	Harpacticoid copepods
14-Aug-2009	F29	35.99	-138.241	0.02066	intact eel trap	nudibranch	Fiona pinnata
14-Aug-2009	S4.F27	34.061	-138.023	0.02109	wavy black fragments	bryozoan	Jellyella eburnea
14-Aug-2009	S4.F27	34.061	-138.023	0.02109	wavy black fragments	bryozoan	Jellyella tuberculata
14-Aug-2009	S4.F27	34.061	-138.023	0.02109	wavy black fragments	copepod	Harpacticoid copepods
14-Aug-2009	S4.F27	34.061	-138.023	0.02109	wavy black fragments	isopod	Idotea
14-Aug-2009	S4.F27	34.061	-138.023	0.02109	wavy black fragments	flatworm	Flatworm
14-Aug-2009	S4.F27	34.061	-138.023	0.02109	wavy black fragments	amphipod	Gammarid amphipods
14-Aug-2009	S4.F27	34.061	-138.023	0.02109	wavy black fragments	isopod	Cirolanid isopod
14-Aug-2009	S4.F27	34.061	-138.023	0.02109	wavy black fragments	crab	Unknown brachyuran
14-Aug-2009	S4.F30	34.08	-138.072	0.00471	rope clump	barnacle	Lepas pacifica
14-Aug-2009	S4.F30	34.08	-138.072	0.00471	rope clump	hydroid	Hydroids
14-Aug-2009	S4.F30	34.08	-138.072	0.00471	rope clump	anemone	Anemone
14-Aug-2009	S4.F30	34.08	-138.072	0.00471	rope clump	barnacle	Lepas pacifica
14-Aug-2009	S4.F30	34.08	-138.072	0.00471	rope clump	bryozoan	Jellyella tuberculata
14-Aug-2009	S4.F30	34.08	-138.072	0.00471	rope clump	barnacle	Lepas antifera
14-Aug-2009	S4.F30	34.08	-138.072	0.00471	rope clump	bryozoan	Jellyella tuberculata
14-Aug-2009	S4.F30	34.08	-138.072	0.00471	rope clump	crab	Planes minutus
14-Aug-2009	S4.F30	34.08	-138.072	0.00471	rope clump	crab	Planes cyaneus
14-Aug-2009	S4.F30	34.08	-138.072	0.00471	rope clump	anemone	Anemone
14-Aug-2009	S4.F30	34.08	-138.072	0.00471	rope clump	amphipod	Gammarid amphipods
14-Aug-2009	S4.F30	34.08	-138.072	0.00471	rope clump	barnacle	Nauplius larvae
14-Aug-2009	S4.F31	34.078	-139.528	0.0154	clump green line	mussel	Mytilus galloprovincialis
14-Aug-2009	S4.F31	34.078	-139.528	0.0154	clump green line	anemone	Anthopleura spp.
14-Aug-2009	S4.F31	34.078	-139.528	0.0154	clump green line	anemone	Metridium spp.
14-Aug-2009	S4.F31	34.078	-139.528	0.0154	clump green line	hydroid	Obelia spp.
14-Aug-2009	S4.F31	34.078	-139.528	0.0154	clump green line	bushy fine hydroid	unknown
14-Aug-2009	S4.F31	34.078	-139.528	0.0154	clump green line	amphipod	Caprella
14-Aug-2009	S4.F31	34.078	-139.528	0.0154	clump green line	bryozoan	Filicrisia spp.
14-Aug-2009	S4.F31	34.078	-139.528	0.0154	clump green line	amphipod	Gammarid amphipods
14-Aug-2009	S4.F31	34.078	-139.528	0.0154	clump green line	polychaete	Hipponoe gaudichaudi
14-Aug-2009	S4.F31	34.078	-139.528	0.0154	clump green line	foraminifera	unknown
15-Aug-2009	L2.1	34.061	-141.596	0.0023538	large white fragment	bryozoan	Jellyella tuberculata
15-Aug-2009	L2.1	34.061	-141.596	0.0023538	large white fragment	bryozoan	Bowerbankia spp.
15-Aug-2009	L2.1	34.061	-141.596	0.0023538	large white fragment	hydroid	Obelia spp.
15-Aug-2009	L2.2	34.064	-141.605	0.0002332	black strap	bryozoan	Jellyella eburnea
15-Aug-2009	L2.2	34.064	-141.605	0.0002332	black strap	algae	NA
15-Aug-2009	L2.2	34.064	-141.605	0.000739	clear fragment	bryozoan	Bowerbankia spp.
15-Aug-2009	L2.2	34.064	-141.605	0.000739	clear fragment	algae	NA
15-Aug-2009	L2.4	34.067	-141.622	0.000477	blue fragment	bryozoan	Jellyella spp.
15-Aug-2009	L2.4	34.067	-141.622	0.000477	blue fragment	bryozoan	Membranipora tenella

Table S6.1. Debris items with associated taxa, continued.

Date	Station	Latitude	Longitude	Size (m^2)	Object Description	Taxon Description	Taxon ID
15-Aug-2009	L2.5	34.069	-141.631	0.0004232	white fragment	bryozoan	Membranipora tenella
15-Aug-2009	L2.5	34.069	-141.631	0.0004232	white fragment	hydroid	Obelia spp.
15-Aug-2009	L2.5	34.069	-141.631	0.0009104	white-green fragment	bryozoan	Jellyella eburnea
15-Aug-2009	L2.5	34.069	-141.631	0.0009104	white-green fragment	bryozoan	Jellyella tuberculata
15-Aug-2009	L2.5	34.069	-141.631	0.0009104	white-green fragment	hydroid	Obelia spp.
15-Aug-2009	L2.5	34.069	-141.631	0.0009104	white-green fragment	sponge	Halichondria panacea
15-Aug-2009	L2.5	34.069	-141.631	0.0009104	white-green fragment	algae	NA
15-Aug-2009	L3.1	34.065	-141.813	0.0050542	fragment	bryozoan	Jellyella eburnea
15-Aug-2009	L3.1	34.065	-141.813	0.0050542	fragment	hydroid	Obelia spp.
15-Aug-2009	L3.1	34.065	-141.813	0.0050542	fragment	bryozoan	Stomatopora spp.
15-Aug-2009	L3.F35	34.065	-140.144	NA	unknown-off larger piece of debris	crab	Plagusia squamosa
16-Aug-2009	U40.121	35.016	-141.738	0.0036008	bottlecap	bryozoan	Jellyella tuberculata
16-Aug-2009	U40.121	35.016	-141.738	0.0036008	bottlecap	hydroid	Obelia spp.
17-Aug-2009	U43.F36	38.154	-137.074	0.00358	small pieces of plastic	nudibranch	Fiona pinnata
17-Aug-2009	U43.F36	38.154	-137.074	0.00358	small pieces of plastic	bryozoan	Membranipora tenella
17-Aug-2009	U43.F36	38.154	-137.074	0.00358	small pieces of plastic	crab	Planes minutus
17-Aug-2009	U43.F36	38.154	-137.074	0.00358	small pieces of plastic	bryozoan	Jellyella eburnea
17-Aug-2009	U43.F36	38.154	-137.074	0.00358	small pieces of plastic	barnacle	Lepas antifera
17-Aug-2009	U43.F36	38.154	-137.074	0.00358	small pieces of plastic	bryozoan	? Double check
17-Aug-2009	U43.F36	38.154	-137.074	0.00358	small pieces of plastic	bryozoan	Jellyella eburnea
17-Aug-2009	U43.F36	38.154	-137.074	0.00358	small pieces of plastic	bryozoan	Jellyella eburnea
17-Aug-2009	U43.F36	38.154	-137.074	0.00358	small pieces of plastic	bryozoan	Bowerbankia spp.
17-Aug-2009	U43.F36	38.154	-137.074	0.00358	small pieces of plastic	hydroid	Obelia spp.
17-Aug-2009	U47.F37	38.579	-136.043	0.0011631	black piece	bryozoan	Jellyella eburnea
17-Aug-2009	U47.F37	38.579	-136.043	0.0060866	curved fragment	fish eggs	flying fish?
17-Aug-2009	U47.F37	38.579	-136.043	0.0060866	curved fragment	hydroid	Obelia spp.
17-Aug-2009	U47.F37	38.579	-136.043	0.0060866	curved fragment	bryozoan	Bowerbankia spp.
17-Aug-2009	U47.F37	38.579	-136.043	0.0060866	curved fragment	bryozoan	Jellyella tuberculata
17-Aug-2009	U47.F37	38.579	-136.043	0.0060866	curved fragment	nudibranch	Fiona pinnata
17-Aug-2009	U47.F37	38.579	-136.043	0.0060866	curved fragment	copepod	Harpacticoid copepods
11-Jul-2011		31° 33.78 N	156° 51.59 W	0.1	Black sharktastic / fragment 01	Lacey Bryozoan	*Jellyela / Membranipora*
12-Jul-2011		31° 33.78 N	156° 51.59 W	0.1	Black sharktastic / fragment 02	Columbus Crab	*Planes sp.*
11-Jul-2011		32° 12.16 N	156° 49.99 W	0.14	Netball 01 (packing band, jar 04)	Pink encrustation	
11-Jul-2011		32° 12.16 N	156° 49.99 W	0.14	Netball 01 (packing band, jar 04)	Branching Bryozoans	*Bugula sp.*
11-Jul-2011		32° 12.16 N	156° 49.99 W	0.144	Netball 01 (cage, jar 02)	Orange encrustation (same as pink?)	
11-Jul-2011		32° 12.16 N	156° 49.99 W	0.144	Netball 01 (cage, jar 02)	Hydroids	Class *Hydrozoa*
11-Jul-2011		32° 12.16 N	156° 49.99 W	0.144	Netball 01 (cage, jar 02)	Stony Coral	Class *Anthozoa*
11-Jul-2011		32° 12.16 N	156° 49.99 W	0.154	Netball 01 (nest, jar 03)	Small white sponges	*Sycon sp.*
11-Jul-2011		32° 12.16 N	156° 49.99 W	0.18	Netball 01 (strap, jar 01)	Small brown anemone	Order *Corallimorpharia*
11-Jul-2011		32° 12.16 N	156° 49.99 W	0.18	Netball 01 (strap, jar 01)	Roundworm	
11-Jul-2011		32° 12.16 N	156° 49.99 W	0.18	Netball 01 (strap, jar 01)	Flatworm	Unknown *Turbellaria*

Table S6.1. Debris items with associated taxa, continued.

Date	Station	Latitude	Longitude	Size (m^2)	Object Description	Taxon Description	Taxon ID
11-Jul-2011		32° 12.16 N	156° 49.99 W	15	Netball 01 (associated fishes)	Seargeant Majors	*Abudefduf sp.(vaigiensis?)*
11-Jul-2011		32° 12.16 N	156° 49.99 W	15	Netball 01 (associated fishes)	Spotted Chubs	*Kyphosus sp. (vaigiensis?)*
11-Jul-2011		32° 12.16 N	156° 49.99 W	15	Netball 01 (associated fishes)	Rainbow Runners	*Elagatis bipinnulata*
11-Jul-2011		32° 12.16 N	156° 49.99 W	15	Netball 01 (associated fishes)	Mahi Mahis	*Coryphaena hippurus*
14-Jul-2011		40° 12.03 N	156° 42.42 W	0.016	Trawl fragments	Clear fish eggs	
14-Jul-2011		40° 12.03 N	156° 42.42 W	0.016	Trawl fragments	Blue Isopod	*Idotea sp.1*
15-Jul-2011		41° 10.32 N	156° 07.77 W	1.2	Argentina bag	Blue fish embryos	
15-Jul-2011		41° 10.32 N	156° 07.77 W	1.2	Argentina bag	Brown Isopod	*Idotea sp.1*
15-Jul-2011		41° 10.32 N	156° 07.77 W	1.414	Black buoy	Gooseneck barnacles	*Lepas sp.*
15-Jul-2011		41° 10.32 N	156° 07.77 W	1.414	Black buoy	Nudibranch	*Fiona pinnata*
15-Jul-2011		41° 10.32 N	156° 07.77 W	1.414	Black buoy	Columbus Crab	*Planes sp.*
15-Jul-2011		41° 10.32 N	156° 07.77 W	1.414	Black buoy	Acorn Barnacle	*(Amphi)balanus amphitrite*
15-Jul-2011		41° 10.32 N	156° 07.77 W	1.414	Black buoy	Lacey Bryozoan skeletons	*Jellyela / Membranipora*
15-Jul-2011		41° 19.20 N	156° 46.74 W	0.707	Yellow foam	Scaled Polychaete	*Halosydna sp.*
15-Jul-2011		41° 19.20 N	156° 46.74 W	0.707	Yellow foam	Piddock	*Zirfaea sp. (pilsbryi?)*
15-Jul-2011		41° 19.20 N	156° 46.74 W	0.707	Yellow foam	Gooseneck barnacles	*Lepas sp.*
15-Jul-2011		41° 19.20 N	156° 46.74 W	0.707	Yellow foam	Columbus Crab	*Planes sp.*
16-Jul-2011		41° 02.27 N	153° 29.73 W	0.05	White styrofoam fragment	Translucent Gooseneck barnacles	*other Lepas*
16-Jul-2011		41° 00.51 N	153° 27.95 W	0.471	Banana float	Amphinomid Polychaete 1	*Hipponoa gaudichaudi*
16-Jul-2011		41° 00.51 N	153° 27.95 W	0.471	Banana float	Brown Isopod	*Idotea sp.1*
16-Jul-2011		41° 00.51 N	153° 27.95 W	0.471	Banana float	Gooseneck barnacles	*Lepas sp.*
16-Jul-2011		41° 00.51 N	153° 27.95 W	0.471	Banana float	Nudibranch	*Fiona pinnata*
16-Jul-2011		41° 00.51 N	153° 27.95 W	0.471	Banana float	Columbus Crab	*Planes sp.*
16-Jul-2011		40° 46.88 N	153° 12.42 W	1.6	Foam mat	Megalopae	
16-Jul-2011		40° 46.88 N	153° 12.42 W	1.6	Foam mat	Gooseneck barnacles	*Lepas sp.*
16-Jul-2011		40° 46.88 N	153° 12.42 W	1.6	Foam mat	Gammarid amphipod	Family *Isaeidae*
16-Jul-2011		40° 46.88 N	153° 12.42 W	1.6	Foam mat	Pelagic Nudibranch	*Fiona pinnata*
16-Jul-2011		40° 46.88 N	153° 12.42 W	1.6	Foam mat	Columbus Crab	*Planes sp.*
16-Jul-2011		40° 46.88 N	153° 12.42 W	1.6	Foam mat	Pacific Oyster	*Crassostrea gigas*
16-Jul-2011		40° 46.88 N	153° 12.42 W	1.6	Foam mat	Lacey Bryozoan	*Jellyela / Membranipora*
10-May-2012		19° 08.19 N	156° 14.6 E	0.016	Yellowed screwtop fragment	Beige Filamentous Algae	
10-May-2012		19° 08.19 N	156° 14.6 E	0.016	Yellowed screwtop fragment	Gooseneck barnacles	*Lepas sp.*
10-May-2012		19° 08.19 N	156° 14.6 E	0.016	Yellowed screwtop fragment	Lacey Bryozoan skeletons	*Jellyela / Membranipora*
10-May-2012		19° 08.19 N	156° 14.6 E	0.016	Yellowed screwtop fragment	Tiny gastropods	*Litiopa melanostoma*
10-May-2012		19° 08.19 N	156° 14.6 E	0.016	Yellowed screwtop fragment	Stony Coral skeletons?	
10-May-2012		19° 08.19 N	156° 14.66 E	0.034	Light-blue degraded fragment	Beige Filamentous Algae	

Table S6.1. Debris items with associated taxa, continued.

Date	Station	Latitude	Longitude	Size (m^2)	Object Description	Taxon Description	Taxon ID
10-May-2012		19° 08.19 N	156° 14.66 E	0.034	Light-blue degraded fragment	Stony Coral skeletons?	
10-May-2012		19° 08.19 N	156° 14.66 E	0.034	Light-blue degraded fragment	Folliculinids	*Halofolliculina sp.*
10-May-2012		19° 08.19 N	156° 14.66 E	0.034	Light-blue degraded fragment	long, thin flatworms	
11-May-2012		19° 53.05 N	155° 04.22 E	0.03	Large white fragment	Dark brown/green filamentous algae	
11-May-2012		19° 53.05 N	155° 04.22 E	0.03	Large white fragment	Tiny gastropods	*Litiopa melanostoma*
11-May-2012		19° 53.05 N	155° 04.22 E	0.03	Large white fragment	Pelagic Nudibranch	*Fiona pinnata*
11-May-2012		19° 53.05 N	155° 04.22 E	0.03	Large white fragment	Folliculinids	*Halofolliculina sp.*
11-May-2012		19° 53.05 N	155° 04.22 E	0.008	Small white fragment	large black anemones	*Anthopleura dixoniana*
11-May-2012		19° 53.05 N	155° 04.22 E	0.008	Small white fragment	small beige anemones	unidentified juveniles
11-May-2012		19° 53.05 N	155° 04.22 E	0.008	Small white fragment	Gooseneck barnacles	*Lepas sp.*
11-May-2012		19° 53.05 N	155° 04.22 E	0.008	Small white fragment	Tiny gastropods	*Litiopa melanostoma*
11-May-2012		19° 53.05 N	155° 04.22 E	0.187	Blue detergent bottle	Hydroids	Class *Hydrozoa*
11-May-2012		19° 53.05 N	155° 04.22 E	0.187	Blue detergent bottle	small beige anemones	unidentified juveniles
11-May-2012		19° 53.05 N	155° 04.22 E	0.187	Blue detergent bottle	Gooseneck barnacles	*Lepas sp.*
11-May-2012		19° 53.05 N	155° 04.22 E	0.187	Blue detergent bottle	Amphinomid polychate 2	*Amphinome rostrata*
11-May-2012		19° 53.05 N	155° 04.22 E	0.3	Giant marshmellow dock float	filamentous algae	
11-May-2012		19° 53.05 N	155° 04.22 E	0.3	Giant marshmellow dock float	Gooseneck barnacles	*Lepas sp.*
11-May-2012		19° 53.05 N	155° 04.22 E	0.3	Giant marshmellow dock float	bottom oyster valve	Unknown Bivalve
12-May-2012		22° 05.21 N	155° 24.49 E	0.098	White fragment	Gooseneck barnacles	*Lepas anitifera*
12-May-2012		22° 05.21 N	155° 24.49 E	0.098	White fragment	Beige broad Flatworm	Order *Polycladida*
12-May-2012		22° 05.21 N	155° 24.49 E	0.098	White fragment	long, thin flatworms	Order *Rhabdocoela?*
12-May-2012		22° 05.21 N	155° 24.49 E	0.098	White fragment	Tiny gastropods	*Litiopa melanostoma*
12-May-2012		22° 05.21 N	155° 24.49 E	0.098	White fragment	Pelagic Nudibranch	*Fiona pinnata*
12-May-2012		22° 05.21 N	155° 24.49 E	0.098	White fragment	Folliculinids	*Halofolliculina sp.*
12-May-2012		22° 05.21 N	155° 24.49 E	0.098	White fragment	filamentous algae	
12-May-2012		22° 05.21 N	155° 24.49 E	0.098	White fragment	Columbus Crab	*Planes sp.*
12-May-2012		22° 11.06 N	155° 22.07 E	0.76	"Yu Tong" white buoy	Gooseneck barnacles	*Lepas anitifera*
12-May-2012		22° 11.06 N	155° 22.07 E	0.76	"Yu Tong" white buoy	Columbus Crab	*Planes sp.*
12-May-2012		22° 11.06 N	155° 22.07 E	0.377	White bleach bottle	Gooseneck barnacles	*Lepas anitifera*
12-May-2012		22° 11.06 N	155° 22.07 E	0.377	White bleach bottle	Columbus Crab (white top)	*Planes sp.*
12-May-2012		22° 11.06 N	155° 22.07 E	0.377	White bleach bottle	Juvenile Triggerfish	*Canthidermis maculata*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Pycnogonid	Unknown
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Pearl Oyster	*Pinctata sp.*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Bay Mussel	*Mytilus galloprovincialis*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Pink Acorn Barnacle	*Megabalanus rosa*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Crab Megalopa	*Planes sp.*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Majid Crab 1	*Herbstia sp.*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Caridean Shrimp	*Palaemon affinis*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Sargassum Frogfish	*Histrio histrio*

Table S6.1. Debris items with associated taxa, continued.

Date	Station	Latitude	Longitude	Size (m^2)	Object Description	Taxon Description	Taxon ID
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Warbonnet	*Chirolophis sp.*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Amphinomid polychate 2	*Amphinome rostrata*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Long black polychaete	*Eunice sp.*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Small white polychaete	*Nereis sp.*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Small black polychaete	Family *Phyllodocidae*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Pink Acontia Anemone	*Calliactis sp.*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Beige Polyclad Flatworm	Order *Polycladida* 1
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Black Polyclad Flatworm, white gut	Order *Polycladida* 2
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Lacey Bryozoan skeletons	*Jellyela / Membranipora*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Hydroids	
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Tiny gastropods	*Litiopa melanostoma*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Small white sponges	*Sycon sp.*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Green anemone, white acontia	Order *Actiniaria*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Spirorbid polychaete	Subfamily *Spirorbinae*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Large serpulid polychaete	Subfamily *Serpulinae*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Small tube-dwelling polychaete	*Salmacina sp.*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Acorn barnacle	*Chthamalus sp.*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Columbus Crab	*Planes cyaneus*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Grapsid Crab	*Plagusia sp.*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Cancrid crab	*Pilumnus sp.*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Pink Scallop	*Chlamys sp.*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Shipworm	
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02	Gooseneck barnacles	*Lepas sp.*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02 (associated fishes)	Seargeant Majors	*Abudefduf sp.(vaigiensis?)*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02 (associated fishes)	Spotted Chubs	*Kyphosus sp. (vaigiensis?)*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02 (associated fishes)	Oceanic Triggerfish	*Canthidermis maculata*
12-May-2012		22° 13.35 N	155° 21.17 E	15	Net Ball 02 (associated fishes)	Almaco Jacks	*Seriola rivoliana*
13-May-2012		23° 39.44 N	155° 17.75 E	1.608	Hi-zex orange buoy	Gooseneck barnacles	*Lepas sp.*
13-May-2012		23° 39.44 N	155° 17.75 E	1.608	Hi-zex orange buoy	Pink Acorn Barnacle	*Megabalanus rosa*
13-May-2012		23° 39.44 N	155° 17.75 E	1.608	Hi-zex orange buoy	Branching Bryozoans	*Bugula sp.*
13-May-2012		23° 39.44 N	155° 17.75 E	1.608	Hi-zex orange buoy	Columbus Crab	*Planes cyaneus*
13-May-2012		23° 39.44 N	155° 17.75 E	0.258	Clear plastic water bottle	Tiny gastropods	*Litiopa melanostoma*
13-May-2012		23° 39.44 N	155° 17.75 E	0.258	Clear plastic water bottle	Lacey Bryozoan skeletons	*Jellyela / Membranipora*
13-May-2012		23° 39.44 N	155° 17.75 E	0.258	Clear plastic water bottle	Acorn barnacle scars	

Table S6.1. Debris items with associated taxa, continued.

Date	Station	Latitude	Longitude	Size (m^2)	Object Description	Taxon Description	Taxon ID
14-May-2012		25° 07.42 N	154° 06.41 E	0.04	Aquaculture spacer	Lacey Bryozoan skeletons	*Jellyela / Membranipora*
14-May-2012		25° 07.42 N	154° 06.41 E	0.04	Aquaculture spacer	Large Serpulid polychaete	Subfamily *Serpulinae*
14-May-2012		25° 07.42 N	154° 06.41 E	0.04	Aquaculture spacer	Tiny gastropods	*Litiopa melanostoma*
14-May-2012		25° 07.42 N	154° 06.41 E	0.075	Oil quart fragment	Lacey Bryozoan skeletons	*Jellyela / Membranipora*
14-May-2012		25° 07.42 N	154° 06.41 E	0.075	Oil quart fragment	Tiny gastropods	*Litiopa melanostoma*
14-May-2012		25° 07.42 N	154° 06.41 E	0.075	Oil quart fragment	Unknown Circular Pattern	
15-May-2012		26° 26.56 N	152° 07.44 E	0.4	2 black buoys' rope	Gooseneck barnacles	*Lepas sp.*
15-May-2012		26° 26.56 N	152° 07.44 E	0.4	3 black buoys' rope	Columbus Crab	*Planes cyaneus*
15-May-2012		26° 26.56 N	152° 07.44 E	0.4	4 black buoys' rope	Amphinomid polychate 2	*Amphinome rostrata*
15-May-2012		26° 26.56 N	152° 07.44 E	0.4	5 black buoys' rope	Pelagic Nudibranch	*Fiona pinnata*
15-May-2012		26° 39.78 N	151° 51.24 E	0.527	White float cylinder	Gooseneck barnacles	*Lepas sp.*
15-May-2012		26° 39.78 N	151° 51.24 E	0.527	White float cylinder	Columbus Crab	*Planes cyaneus*
16-May-2012		26° 39.78 N	151° 51.24 E	4.55	Giant rope	Gooseneck barnacles	*Lepas sp.*
16-May-2012		26° 39.78 N	151° 51.24 E	4.55	Giant rope	Columbus Crab	*Planes cyaneus*
16-May-2012		26° 39.78 N	151° 51.24 E	4.55	Giant rope	Crab parasite	*Heterosaccus sp.*
16-May-2012		26° 39.78 N	151° 51.24 E	4.55	Giant rope	Grapsid Crab	*Plagusia sp.*
16-May-2012		26° 39.78 N	151° 51.24 E	4.55	Giant rope	Amphinomid polychate 2	*Amphinome rostrata*
16-May-2012		26° 39.78 N	151° 51.24 E	4.55	Giant rope	Pearl Oyster	*Pinctata sp.*
16-May-2012		26° 39.78 N	151° 51.24 E	4.55	Giant rope	Brittle Star	*Ophioroidea sp. 1*
16-May-2012		26° 39.78 N	151° 51.24 E	4.55	Giant rope	Brittle Star	*Ophioroidea sp. 2*
16-May-2012		26° 39.78 N	151° 51.24 E	4.55	Giant rope	Gammarid Amphipod	Family *Pleustidae*
16-May-2012		26° 39.78 N	151° 51.24 E	4.55	Giant rope	Caprelid Amphipod	*Caprella sp.*
16-May-2012		26° 39.78 N	151° 51.24 E	4.55	Giant rope	Turbellarian Flatworm	Order *Polycladida*
16-May-2012		26° 39.78 N	151° 51.24 E	4.55	Giant rope	Small white sponges	*Sycon sp.*
17-May-2012		30° 11.44 N	147° 20.87 E	15	Net Ball 03	Columbus Crab (+Megalopae)	*Planes cyaneus*
17-May-2012		30° 11.44 N	147° 20.87 E	15	Net Ball 03	Grapsid Crab	*Plagusia sp.*
17-May-2012		30° 11.44 N	147° 20.87 E	15	Net Ball 03	Majid Crab 2	*Chorilia sp.*
17-May-2012		30° 11.44 N	147° 20.87 E	15	Net Ball 03	Brittle Star	*Ophioroidea sp. 2*
17-May-2012		30° 11.44 N	147° 20.87 E	15	Net Ball 03	Brittle Star	*Ophioroidea sp. 3*
17-May-2012		30° 11.44 N	147° 20.87 E	15	Net Ball 03	Gooseneck barnacles	*Lepas sp.*
17-May-2012		30° 11.44 N	147° 20.87 E	15	Net Ball 03	New Polychaete (forked tail)	Family *Nereididae*
17-May-2012		30° 11.44 N	147° 20.87 E	15	Net Ball 03	Sponges	
17-May-2012		30° 11.44 N	147° 20.87 E	15	Net Ball 03	Nudibranch	*Fiona pinnata*

Table S6.1. Debris items with associated taxa, continued.

Date	Station	Latitude	Longitude	Size (m^2)	Object Description	Taxon Description	Taxon ID
17-May-2012		30° 11.44 N	147° 20.87 E	15	Net Ball 03	Notaspidean Opisthobranch	*Berthella sp.*
17-May-2012		30° 11.44 N	147° 20.87 E	15	Net Ball 03	Purple Anemone	*Actinia sp.*
17-May-2012		30° 11.44 N	147° 20.87 E	15	Net Ball 03	Sargassum Frogfish	*Histrio histrio*
17-May-2012		30° 11.44 N	147° 20.87 E	15	Net Ball 03	New, Striped Blenny	*Meiacanthus sp.*
17-May-2012		30° 11.44 N	147° 20.87 E	15	Net Ball 03	Arcshell	Family *Arcidae*
17-May-2012		30° 11.44 N	147° 20.87 E	15	Net Ball 03	Pearl Oyster	*Pinctata sp.*
17-May-2012		30° 11.44 N	147° 20.87 E	15	Net Ball 03	Pacific Oyster	*Crassostrea gigas*
17-May-2012		30° 11.44 N	147° 20.87 E	15	Net Ball 03	Cowries	*Erronea sp.*
17-May-2012		30° 11.44 N	147° 20.87 E	15	Net Ball 03 (associated fishes)	Seargeant Majors	*Abudefduf sp.(vaigiensis?)*
17-May-2012		30° 11.44 N	147° 20.87 E	15	Net Ball 03 (associated fishes)	Spotted Chubs	*Kyphosus sp. (vaigiensis?)*
18-May-2012		32° 04.20 N	144° 56.87 E	0.258	Coke bottle float + fishing line	Gooseneck barnacles	*Lepas sp.*
18-May-2012		32° 04.20 N	144° 56.87 E	0.258	Coke bottle float + fishing line	Columbus Crab	*Planes cyaneus*
18-May-2012		32° 04.20 N	144° 56.87 E	0.258	Coke bottle float + fishing line	Branching Bryozoans	*Bugula sp.*
18-May-2012		32° 04.20 N	144° 56.87 E	0.258	Coke bottle float + fishing line	Nudibranch	*Fiona pinnata*
18-May-2012		32° 04.20 N	144° 56.87 E	0.258	Coke bottle float + fishing line	Beige fish eggs	
18-May-2012		32° 04.20 N	144° 56.87 E	0.258	Coke bottle float + fishing line	Blue fish eggs	
18-May-2012		32° 04.20 N	144° 56.87 E	0.258	Coke bottle float + fishing line	Tiny Gastropods	*Litiopa melanostoma*
18-May-2012		32° 04.20 N	144° 56.87 E	0.258	Coke bottle float + fishing line	Gammarid amphipod	
18-May-2012		32° 04.20 N	144° 56.87 E	0.258	Coke bottle float + fishing line	New Polychaete (forked tail)	Family *Nereididae*
19-May-2012		32° 57.01 N	143° 31.02 E	0.168	Yellow foam square	Gooseneck barnacles	*Lepas sp.*
19-May-2012		32° 57.01 N	143° 31.02 E	0.168	Yellow foam square	Tiny Gastropods	*Litiopa melanostoma*
19-May-2012		32° 57.01 N	143° 31.02 E	0.168	Yellow foam square	Amphipods	
19-May-2012		32° 57.01 N	143° 31.02 E	0.258	Water bottle	Isopod	*Idotea sp.*

CHAPTER 7: Summary of the Dissertation

The purpose of this dissertation was to provide scientific information on the extent and ecological impacts of microplastic in the North Pacific Subtropical Gyre (NPSG). In this concluding chapter, I summarize the key findings and connections between the chapters and suggest future avenues of research. Because this dissertation was originally motivated by substantial public interest in oceanic plastic pollution, I conclude by putting the findings of this dissertation in the context of public policy.

Most North Pacific plastic is small and offshore

The data presented in Chapters 2 and 5 demonstrate that a substantial quantity of microplastic debris is widely distributed at the surface of the North Pacific Subtropical Gyre (NPSG). Chapter 2 provides a snapshot of microplastic distribution, abundance and size in the NPSG, California Current, and transition region between them, taken over multiple spatial scales in 2009 and 2010. Though microplastic is detectable in the California Current (Gilfillan et al. 2009, Doyle et al. 2011), concentrations are several orders of magnitude higher in the NPSG (Goldstein et al. 2012). Despite this general pattern, microplastic is more spatially heterogeneous than biophysical variables such as temperature, salinity, and chlorophyll. Chapter 2 also presents size distributions of both microplastic and macroplastic, demonstrating that the vast numerical majority of plastic debris meets the definition of microplastic (<5 mm in diameter), although most of the surface area is in large debris items. Future research on ecological impacts should consider small-scale and submesoscale variability in assessing ecological impacts of microplastic. Understanding the abundance and distribution of sub-333 μm microplastic is key to this endeavor.

NPSG microplastic increased over the last four decades, but the rate of increase is unknown, and is unlikely to be detected with current levels of sampling

The analysis in Chapter 5 demonstrates that microplastic has increased by two orders of magnitude over the last four decades. However, the analysis looked at a relatively limited subsample of total NPSG plastic debris. The size spectra presented in Chapter 2 suggest that a substantial portion of microplastic is smaller than 333 μm, and was therefore not sampled by the 202-505 μm zooplankton nets used in this study. Additionally, the inverse relationship detected here between wind speed and plastic concentration suggests that microplastic is mixed down in high wind conditions, and is thus undersampled in the neuston tow. A study in the North Atlantic suggested that under moderate wind conditions an average of 2.5 times more plastic may be mixed below the surface than is found on the surface (Kukulka et al. 2012). These factors contribute to high variability in measurements of surface plastic concentration, which could lead to difficulty in detecting temporal trends. Under a sampling plan similar to that of SEAPLEX in 2009, my analysis showed that 250 manta tows would be required to detect a 50% increase in plastic with 80% statistical power. Monitoring programs, particularly those designed to assess the efficacy of plastic mitigation strategies, should take into account the difficulty of detecting short- and medium-term changes in abundance.

Microplastic is more weathered offshore, suggesting a coastal source

In Chapter 3, changes in microplastic composition over the eastern North Pacific are attributed to differential rates of weathering between plastic types. A greater proportion of polypropylene, which is less resistant to weathering, was found in the California Current and a greater proportion of polyethylene, which is more resistant to weathering, was found offshore in the NPSG. The analysis of particle diameter and circularity in Chapter 2, which found that the circularity of similarly-sized particles increased with distance from shore, also suggested that more weathered particles were found in the NPSG as compared to the California Current. From a weathering experiment and analysis of naturally weathered oceanic particles, Chapter 3 showed that weathering time in the ocean is linked to carbonyl formation in high-density polyethylene, low-density polyethylene, and polypropylene. However, the rate of carbonyl formation in the ocean is likely to be nonlinear, due to the interactions of temperature and microbes. The role of microbes in the ecology of oceanic plastic debris is discussed in more depth below. A qualitative understanding of the "age" of oceanic microplastic may be possible, but should be combined with an assessment of the sub-333 μm size spectrum as discussed above.

The importance of ingestion by invertebrates remains unclear

Ingestion of microplastic is one metric of the ecological impact of microplastic. However, in chapter 4, neustonic copepods were shown to ingest only minimal quantities of microplastic when offered fluorescent polyethylene microspheres, even when plastic was present in high concentrations. In contrast, lepadid barnacles did ingest microplastic. It is likely that the rate of plastic ingestion depends on feeding strategy as well as the presence of microplastic. Copepods are selective feeders that have the ability to reject unsuitable particles (Ayukai 1987), while lepadid barnacles are nonselective feeders (Evans 1958). Other NPSG fauna that have been found to ingest plastic are also nonselective feeders (Fry et al. 1987, Davison and Asch 2011).

Even when ingestion does occur, its ecological importance remains unclear. Intestinal blockage and rupture has primarily been documented in necropsies performed on cetaceans and sea turtles (Bugoni et al. 2001, Jacobsen et al. 2010). However, it is unknown if plastic ingestion leading to fatalities is occurring in smaller vertebrates (e.g., mesopelagic fishes) or invertebrates, or if ingestion affects the long-term viability of individuals. Sub-lethal and/or chronic effects of plastic ingestion on marine invertebrates are also a concern, and should be examined using laboratory studies. In the case of the ingestion of microplastic by *Lepas* spp. documented in Chapter 4, it is likely that the overall *Lepas* population has benefitted from the increase in plastic substrate for colonization, even if individuals experience deleterious effects from plastic ingestion.

The ingestion studies in Chapter 4 focused on animals that inhabit the neuston, since in Chapter 2 I found that the majority of microplastic was on the surface. However, as discussed above, wind can mix plastic from the neuston into the mixed layer. Future work should therefore consider the vertical distribution of microplastic, since the majority of ocean life is found below the surface. Ingestion experiments should also consider the ratio of artificial to natural particles, as copepod feeding may be inhibited by high concentrations of inedible particles.

Substrate-dependent organisms benefit from plastic debris

Chapters 5 and 6 examined the effect of plastic debris on hard-substrate-dependent invertebrates. The fauna considered in these chapters appear to be benefitting from increased habitat and dispersal potential. The oceanic insect *Halobates sericeus* has increased access to suitable substrate for laying eggs, though the data were insufficient to resolve an overall population increase. The indigenous Pacific rafting assemblages, particularly membraniporid bryozoans, *Obelia* hydroids, and *Lepas* barnacles, has access to increased habitat, including microplastic. Coastal taxa such as *Mytilus* mussels and acorn barnacles have enhanced dispersal potential.

Chapter 2 demonstrated that the numerical majority of objects are small particles, but the majority of debris surface area is found in large objects. Though large objects were relatively rare, they hosted more diverse rafting assemblages and included potentially harmful species such as a ciliate that infects scleractinian corals (Chapter 6). Large objects may therefore have a disproportionate role in transport of rafting taxa.

It is not yet clear whether the success of rafting organisms comes at the expense of planktonic species. The estimate of *Lepas* barnacle predation in Chapter 6 suggests that top-down predation on zooplankton may not yet be important, but this result does not rule out more subtle changes in biogeochemical cycling and food webs. Potential changes include reworking of the particle size spectrum (Mook 1981), changes in the surrounding nutrient gradient (Lobelle and Cunliffe 2011), and the transport of plastic-associated toxins up the food web (Teuten et al. 2009). Future work should also consider the role of microbes, which are linked with both plastic weathering (Chapter 3) and rafting communities (Chapter 6). Microbes are likely metabolizing carbonyl and other compounds formed by polymer weathering (Satoto et al. 1997), as well as forming biofilms that can enhance invertebrate settlement (Rodriguez et al. 1993). The presence of nutrient plumes associated with rafting assemblages, such as dissolved organic nitrogen compounds, may also influence pelagic microbes (Stocker et al. 2008). A detailed look at the small-scale biochemical changes associated with rafting communities would be an interesting and valuable future direction.

Policy implications

While the public is fascinated by oceanic plastic, scientists have been comparatively uninterested. Plastic debris was documented in the open ocean in the early 1970s (Carpenter and Smith 1972, Venrick et al. 1973, Wong et al. 1974), but received relatively little attention in subsequent decades (Day et al. 1990). With Charles Moore's founding of Algalita Marine Research Foundation and Ebbesmeyer's coining of the term "garbage patch," citizen scientists have filled the void. Moore and his colleagues have published peer-reviewed papers (Moore et al. 2001, 2002, Lattin et al. 2004, Boerger et al. 2010), the Ocean Conservancy collects data on beached debris (Ocean Conservancy 2012a), and college students enrolled in the Sea Education Association Semester at Sea program collect data on neustonic microplastic (Law et al. 2010, Moret-Ferguson et al. 2010).

The high level of public interest in oceanic plastic debris has led to increased involvement by corporations and lobbying groups. Coca-Cola is a major sponsor of the Ocean Conservancy's Trash Free Seas initiative (Ocean Conservancy 2012b). The plastics industry lobbying group American Chemistry Council partially funded basic scientific research in both the Pacific (Doyle et al. 2011) and the Atlantic (Sea Education Association 2010). As with the Keep America Beautiful campaign of the 1950s and 1960s, these companies desire to frame oceanic plastic pollution as an individual behavior problem, not an inherent materials problem (Steinberg 2010).

In contrast, anti-plastic citizen lobbying groups argue that oceanic plastic is a materials problem, not solely the responsibility of individuals, and have supported the banning of products such as plastic bags, expanded polystyrene ("Styrofoam") containers, and disposable water bottles (Save Our Shores 2011, Llanos 2012, Surfrider San Diego 2012). They have also encouraged plastics manufacturers to adopt "cradle-to-cradle" manufacturing strategies (McDonough et al. 2003). For example, one of the challenges at the NGO-organized TEDxGreatPacificGarbagePatch conference was for plastic manufacturers to "… own the responsibility of your product till the very end. The packaging you choose to for your products is your responsibility, not the buyer's (TEDxGreatPacificGarbagePatch 2010)." Many of these groups have also tried to link oceanic plastic to human health, such as through Surfrider's "What Goes In the Ocean Goes In You" advertising campaign, which features images of sushi wrapped in plastic bags (Surfrider Vancouver 2012). However, there is currently no research linking oceanic plastic debris with human health impacts (Thompson et al. 2009).

When policymakers address marine debris issues, they must consider these different perspectives on the role of corporations and consumers, as well as science-based results, logistics, and economic concerns. However, it is difficult for a discussion on solutions to plastic pollution to be productive when it is based on incorrect premises. The enormous volume of low-quality information on the Internet can make high-quality information difficult to find. I will therefore end this dissertation with a brief summary, aimed at a non-scientific audience, of this research and its possible policy implications.

1. More than 90% of plastic in the North Pacific Subtropical Gyre (NPSG) is less than the size of an M&M candy. It is spread out over the ocean's surface, not gathered together in a visible mass. Since the plastic is floating on the surface, it can move closer together or father apart, and therefore comparisons to the state of Texas may or may not be accurate at any given time.
2. The plastic found in the NPSG is primarily small, degraded pieces of larger objects made of the three most common types of plastic that float: polyethylene (Resin ID #2 and 4), polypropylene (#5), and polystyrene (#6). At this time, there is no way to tell where the objects came from (e.g., the United States, China, a ship) or what type of objects they were. Technology exists to recycle these types of plastic, even after it has been degraded by weathering, but most of the NPSG plastic is so small that there is currently no way to collect it without killing an equal mass of sea life.
3. The amount of plastic in the NPSG has increased by 100 times over the past four decades. A parcel of water that had one particle of plastic in the 1970s would have 100 particles of plastic today.
4. The North Pacific is an area of the ocean without very much floating material except for plastic. The increase of plastic has allowed animals that live on and around floating material to proliferate. These include the sea skater *Halobates sericeus*, which lays its eggs on plastic, and animals like barnacles and sea anemones that grow directly on the plastic. There is evidence that plastic is transporting harmful

organisms such as a type of coral disease. Even though most plastic debris in the North Pacific is small, targeted removal of large debris may be helpful in preventing harmful organism transport.

5. Some animals, such as seabirds, small fishes, and barnacles, are ingesting plastic pieces. However, most seafood eaten by people does not come from the NPSG, so we do not know how this may be affecting human health.
6. All data presented here are from 2009 and 2010, before the 2011 Japanese tsunami. Debris from the tsunami is predicted to end up in the NPSG, but since the amount of floating tsunami debris is unknown, it is unclear whether tsunami debris will alter the status quo.
7. There are many other potential impacts of plastic debris, such as toxin accumulation and alteration of the oceanic nutrient balance. Additional scientific research can help to understand the situation and potentially predict future problems. Since debris removal is improbable under current technology (with the exception of targeted removal of large objects to limit invasive species transport), mitigation strategies should focus on prevention.

References

Ayukai, T. 1987. Discriminate feeding of the calanoid copepod Acartia clausi in mixtures of phytoplankton and inert particles. Marine Biology 94:579–587. doi: 10.1007/BF00431404.

Boerger, C. M., G. L. Lattin, S. L. Moore, and C. J. Moore. 2010. Plastic ingestion by planktivorous fishes in the North Pacific Central Gyre. Marine Pollution Bulletin 60:2275–2278. doi: 10.1016/j.marpolbul.2010.08.007.

Bugoni, L., L. Krause, and M. V. Petry. 2001. Marine debris and human impacts on sea turtles in southern Brazil. Marine Pollution Bulletin 42:1330–1334. doi: 10.1016/S0025-326X(01)00147-3.

Carpenter, E. J., and K. L. Smith. 1972. Plastics on the Sargasso Sea surface. Science 175:1240. doi: 10.1126/science.175.4027.1240.

Davison, P., and R. G. Asch. 2011. Plastic ingestion by mesopelagic fishes in the North Pacific Subtropical Gyre. Marine Ecology Progress Series 432:173–180. doi: 10.3354/meps09142.

Day, R. H., D. G. Shaw, and S. E. Ignell. 1990. The quantitative distribution and characteristics of neuston plastic in the North Pacific Ocean, 1984-1988. Pages 247–266 Proceedings of the Second International Conference on Marine Debris, April 2-7, 1989, Honolulu, Hawaii. U. S. Department of Commerce, NOAA Technical Memorandum, NMFS, NOAA-TM-NMFS-SWFC-154.

Doyle, M. J., W. Watson, N. M. Bowlin, and S. B. Sheavly. 2011. Plastic particles in coastal pelagic ecosystems of the Northeast Pacific ocean. Marine Environmental Research 71:41–52. doi: 10.1016/j.marenvres.2010.10.001.

Evans, F. 1958. Growth and maturity of the barnacles Lepas hillii and Lepas anatifera. Nature 182:1245–1246. doi: 10.1038/1821245b0.

Fry, D. M., S. I. Fefer, and L. Sileo. 1987. Ingestion of plastic debris by Laysan Albatrosses and Wedge-tailed Shearwaters in the Hawaiian Islands. Marine Pollution Bulletin 18:339–343. doi: 10.1016/S0025-326X(87)80022-X.

Gilfillan, L. R., M. D. Ohman, M. J. Doyle, and W. Watson. 2009. Occurrence of plastic micro-debris in the southern California Current system. CalCOFI Report 50:123–133.

Goldstein, M. C., M. Rosenberg, and L. Cheng. 2012. Increased oceanic microplastic debris enhances oviposition in an endemic pelagic insect. Biology Letters 8:817–820. doi: 10.1098/rsbl.2012.0298.

Jacobsen, J. K., L. Massey, and F. Gulland. 2010. Fatal ingestion of floating net debris by two sperm whales (Physeter macrocephalus). Marine Pollution Bulletin 60:765–767. doi: 10.1016/j.marpolbul.2010.03.008.

Kukulka, T., G. Proskurowski, S. Morét-Ferguson, D. W. Meyer, and K. L. Law. 2012. The effect of wind mixing on the vertical distribution of buoyant plastic debris. Geophysical Research Letters 39:6 pp. doi: 201210.1029/2012GL051116.

Lattin, G. L., C. J. Moore, A. F. Zellers, S. L. Moore, and S. B. Weisberg. 2004. A comparison of neustonic plastic and zooplankton at different depths near the southern California shore. Marine Pollution Bulletin 49:291–294. doi: 10.1016/j.marpolbul.2004.01.020.

Law, K. L., S. Moret-Ferguson, N. A. Maximenko, G. Proskurowski, E. E. Peacock, J. Hafner, and C. M. Reddy. 2010. Plastic accumulation in the North Atlantic Subtropical Gyre. Science 329:1185–1188. doi: 10.1126/science.1192321.

Llanos, M. 2012, February 7. Grand Canyon banning sales of bottled water. U.S. News. Retrieved October 31, 2012, from http://usnews.nbcnews.com/_news/2012/02/07/10340196-grand-canyon-banning-sales-of-bottled-water.

Lobelle, D., and M. Cunliffe. 2011. Early microbial biofilm formation on marine plastic debris. Marine Pollution Bulletin 62:197–200. doi: 10.1016/j.marpolbul.2010.10.013.

McDonough, W., M. Braungart, P. T. Anastas, and J. B. Zimmerman. 2003. Applying the Principles of Green Engineering to Cradle-to-Cradle Design. Environmental Science & Technology 37:434A–441A. doi: 10.1021/es0326322.

Mook, D. H. 1981. Removal of suspended particles by fouling communities. Marine Ecology Progress Series 5:279–281.

Moore, C. J., S. L. Moore, M. K. Leecaster, and S. B. Weisberg. 2001. A comparison of plastic and plankton in the North Pacific central gyre. Marine Pollution Bulletin 42:1297–1300. doi: 10.1016/S0025-326X(01)00114-X.

Moore, C. J., S. L. Moore, S. B. Weisberg, G. L. Lattin, and A. F. Zellers. 2002. A comparison of neustonic plastic and zooplankton abundance in southern California's coastal waters. Marine Pollution Bulletin 44:1035–1038. doi: 10.1016/S0025-326X(02)00150-9.

Moret-Ferguson, S., K. L. Law, G. Proskurowski, E. K. Murphy, E. E. Peacock, and C. M. Reddy. 2010. The size, mass, and composition of plastic debris in the western North Atlantic Ocean. Marine Pollution Bulletin 60:1873–1878. doi: 10.1016/j.marpolbul.2010.07.020.

Ocean Conservancy. 2012a. 2012 Data Release. Retrieved October 31, 2012, from http://www.oceanconservancy.org/our-work/marine-debris/2012-data-release.html.

Ocean Conservancy. 2012b. Trash Free Seas: International Coastal Cleanup Sponsoring Partner: Coca Cola. Retrieved October 31, 2012, from http://www.oceanconservancy.org/our-work/marine-debris/international-coastal-cleanup-3.html.

Rodriguez, S. R., F. P. Ojeda, and N. C. Inestrosa. 1993. Settlement of benthic marine invertebrates. Marine Ecology Progress Series 97:193–207.

Satoto, R., W. S. Subowo, R. Yusiasih, Y. Takane, Y. Watanabe, and T. Hatakeyama. 1997. Weathering of high-density polyethylene in different latitudes. Polymer Degradation and Stability 56:275–279. doi: 10.1016/S0141-3910(96)00213-3.

Save Our Shores. 2011. Banning Styrofoam Take-Out Containers. Retrieved October 31, 2012, from http://www.saveourshores.org/what-we-do/banning-styrofoam-containers.php.

Sea Education Association. 2010. Plastics at SEA North Atlantic Expedition 2010. Retrieved October 31, 2012, from http://www.sea.edu/plastics2010/.

Steinberg, T. 2010. Can Capitalism Save the Planet? On the Origins of Green Liberalism. Radical History Review 2010:7–24. doi: 10.1215/01636545-2009-032.

Stocker, R., J. R. Seymour, A. Samadani, D. E. Hunt, and M. F. Polz. 2008. Rapid chemotactic response enables marine bacteria to exploit ephemeral microscale nutrient patches. Proceedings of the National Academy of Sciences 105:4209–4214. doi: 10.1073/pnas.0709765105.

Surfrider San Diego. 2012, August. Help Support State-Wide Plastic Legislation. Retrieved October 31, 2012, from http://sandiego.surfrider.org/help-support-state-wide-plastic-legislation.

Surfrider Vancouver. 2012, May 11. What goes into the ocean, goes into you. Retrieved from http://vancouverbc.surfrider.org/what-goes-into-the-ocean-goes-into-you/.

TEDx GreatPacificGarbagePatch. 2010. Four Challenges. Retrieved October 31, 2012, from http://www.tedxgreatpacificgarbagepatch.com/four-challenges/.

Teuten, E. L., J. M. Saquing, D. R. U. Knappe, M. A. Barlaz, S. Jonsson, A. Bjorn, S. J. Rowland, R. C. Thompson, T. S. Galloway, R. Yamashita, D. Ochi, Y. Watanuki, C. Moore, V. Pham Hung, T. S. Tana, M. Prudente, R. Boonyatumanond, M. P. Zakaria, K. Akkhavong, Y. Ogata, H. Hirai, S. Iwasa, K. Mizukawa, Y. Hagino, A. Imamura, M. Saha, and H. Takada. 2009.

Transport and release of chemicals from plastics to the environment and to wildlife. Philosophical Transactions of the Royal Society of London B 364:2027–2045. doi: 10.1098/rstb.2008.0284.

Thompson, R. C., C. J. Moore, F. S. vom Saal, and S. H. Swan. 2009. Plastics, the environment and human health: current consensus and future trends. Philosophical Transactions of the Royal Society B: Biological Sciences 364:2153–2166. doi: 10.1098/rstb.2009.0053.

Venrick, E. L., T. W. Backman, W. C. Bartram, C. J. Platt, M. S. Thornhill, and R. E. Yates. 1973. Man-made objects on the surface of the central North Pacific ocean. Nature 241:271–271. doi: 10.1038/241271a0.

Wong, C. S., D. R. Green, and W. J. Cretney. 1974. Quantitative tar and plastic waste distributions in Pacific Ocean. Nature 247:30–32. doi: doi:10.1038/247030a0.