Southern California Bight 2013 Regional Monitoring Program

Trash and Marine Debris

BIGHT '13

Southern California Bight
2013 Regional Monitoring
Program
Volume III

SCCWRP Technical Report 928

Southern California Bight 2013 Regional Monitoring Program: Volume III. Trash and Marine Debris

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FOREWORD

The Southern California Bight 2013 Regional Monitoring Program (Bight'13) is an integrated, collaborative effort to provide large-scale assessments of the Southern California Bight (SCB). The Bight'13 survey is an extension of previous regional assessments conducted every five years dating back to 1994. The collaboration represents the combined efforts of nearly 100 organizations. Bight'13 is organized into five elements: 1) Contaminant Impact Assessment (formerly Coastal Ecology), 2) Shoreline Microbiology, 3) Nutrients, 4) Marine Protected Areas, and 5) Trash and Marine Debris. This assessment report presents the results of the Trash and Marine Debris portion of the survey. Copies of this and other Bight '13 reports, as well as work plans and quality assurance plans, are available for download at www.sccwrp.org.

ACKNOWLEDGEMENTS

This report is a result of the dedication and hard work of many individuals who share a common goal of improving our understanding of the environmental quality of the Southern California Bight. The authors wish to thank the members of the Bight'13 Debris Committee for their assistance with study design, sample analysis, data analysis and report review. We also thank the Bight'13 Executive Advisory Committee and Contaminant Impact Assessment Committee for their guidance and support. This study would not have been possible without the remarkable expertise of the field sampling personnel from the following organizations: City of San Diego, Weston Solutions, Orange County Sanitation District, Sanitation Districts of Los Angeles County, City of Los Angeles, Southern California Coastal Water Research Project, Aquatic Bioassay and Consulting Laboratories, and Amec Foster Wheeler. We also wish to express our gratitude to Southern California Stormwater Monitoring Coalition and its member agencies who participate in the Southern California Stream Monitoring Surveys.

EXECUTIVE SUMMARY

Background

The accumulation of discarded objects (a.k.a. trash and debris) in the environment has become an issue of significant, global concern. On land and in freshwater habitats, these objects are typically referred to as trash, and in the marine environment, these objects are referred to as marine debris. Trash and marine debris affect aesthetics and/or aquatic life across every habitat they touch. Marine debris in southern California significantly influences the decision of the public to go to beaches, costing Orange County residents alone an estimated $148 million per year just to travel to cleaner beaches. Debris presents entanglement and ingestion dangers for marine organisms. And plastics in the environment can transport other contaminants, creating a bioaccumulation pathway by which aquatic organisms take up contaminants as they inadvertently consume plastic.

Southern California's management community has proposed and implemented a number of measures to minimize trash in waterways, including recycling programs, plastic bag bans, and other regulations, including establishing total maximum daily loads (TMDLs) for the Los Angeles River that specify that the river contain zero trash pieces greater than 5 mm in diameter by 2025. Despite these recent efforts, southern California had never conducted a comprehensive assessment of the magnitude and extent of trash and marine debris in streams and the nearshore Southern California Bight. In fact, the best region-wide data on trash and marine debris in southern California has historically come from California's Coastal Clean Up Day, a volunteer effort that has resulted in more than a quadrupling of the mass of trash and debris collected from 1989 to 2015. Data inconsistencies, however, have made it difficult to determine quantitative baselines and to estimate trends over time.

Goals of This Study

This study aimed to create southern California's first regionalized assessment of trash and marine debris, with a goal to assess the extent and magnitude of trash and marine debris in southern California waterways. Three key questions were asked:

- **Does the extent and magnitude of trash and marine debris vary among freshwater and marine habitats?**
- **Does the extent and magnitude of trash and marine debris vary over time?**
- **What types of trash and marine debris are most extensive or abundant?**

Marine macro-debris on the surface of the Bight seafloor was quantified comparably to similar Bight surveys dating back to 1994. In addition, Bight marine micro-debris (i.e., particles of 5 millimeters or less in diameter) embedded in seafloor sediment was quantified for the first time, as was trash collected across 7,400 kilometers of Southern California coastal streams. A probability-based stratified-random design sampling more than 795 sites was used to attain unbiased estimates.

Study Findings

Integrated study results indicate that trash and marine debris were found in more than three-fourths of Southern California wadeable streams and along about one-third of the Bight seafloor. Plastic was the most prevalent object found across all habitats, with four of the five most abundant trash items in streams identified as being made of plastic, and about one-third of the Bight seafloor containing plastic particles. The extent of seafloor macro-debris nearly doubled from 1994 to 2013, and the extent of plastic increased threefold.

The study could not conclusively link marine debris to land-based sources, as sampling took place at a discrete point in time, but multiple lines of evidence indicate that land-based trash is a major contributor to debris in the Bight and that marine habitats serve as a sink for plastic accumulation.

Next Steps

The study offers recommendations to both the management community about potential policy implications and to scientists in support of future technical needs.

With billions of dollars spent over the past five years implementing BMPs (Best Management Practices) to comply with trash environmental regulations, as well as controversial source-reduction measures such as bans on single-use plastic shopping bags, trash and marine debris should continue to be monitored in the environment to quantify the effectiveness of these management actions and to guide future action. Furthermore, managers should continue to pursue partnerships that bring together regulatory and regulated agencies, advocacy organizations and plastic industry representatives; collaboration will create the most powerful monitoring program and the resulting dialogue will likely forge the most effective policies.

Managers should continue monitoring for trash and marine debris, with an eye toward improving sampling methods and study design, optimizing monitoring to be more responsive to management questions and metrics, and establishing clear linkages between land-based trash and Bight seafloor debris. In particular, attention should be paid to micro-plastics, given their ubiquity across the Bight.

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CHAPTER ONE: BIGHT 2013 REGIONAL TRASH AND MARINE DEBRIS MONITORING: SYNTHESIS OF DEBRIS FROM LAND TO SEA

I. Background

The accumulation of discarded objects in the environment has become an issue of significant, global concern. On land and in freshwater habitats, these objects are typically referred to as trash, and in the marine environment, these objects are referred to as marine debris. Trash and marine debris affect aesthetics and/or aquatic life across every habitat they touch, from watersheds to the ocean. For example, Leggett *et al.* (2014) found that marine debris in southern California significantly influences the decision of the public to go to beaches, costing Orange County residents alone an estimated $148 million per year just to travel to cleaner beaches. In marine environments, debris presents entanglement and ingestion dangers for marine organisms (Boerger *et al.* 2010, Goldstein and Goodwin, 2013; Lusher *et al.*, 2013; Anastasopoulou *et al.*, 2013; Bond *et al.*, 2013; Di Beneditto and Ramos, 2014; Gall and Thompson, 2015). Furthermore, plastics in the environment can transport other contaminants, creating a bioaccumulation pathway by which aquatic organisms take up contaminants as they consume plastic (Rios *et al.*, 2007; Farrington and Takada, 2014).

Because trash and marine debris have the potential to adversely impact freshwater and marine beneficial uses, Southern California's management community has proposed and implemented a number of measures to minimize the amount of trash in waterways, including recycling programs, plastic bag bans, and other regulations and legislation. In 2011, California Assembly Bill 341 established a goal of reaching 75% recycling statewide by 2020 through source reduction, recycling, and composting (CalRecycle 2015). State and federal regulators also have established total maximum daily loads (TMDLs) for the Los Angeles River that specify that the river contain zero trash pieces greater than 5 mm in diameter by 2025 (CRWQCBLA 2007, CRWQCBLA 2015). The State Water Board adopted similar statewide regulations as part of its Water Quality Control Plan (SWRCB 2015). Meanwhile, more than 100 California municipalities have promulgated bans on single-use plastic bags, and Senate Bill 270 in 2014 established a statewide ban, although its implementation has been delayed pending the outcome of a November 2016 ballot measure.

Despite all of these recent efforts to legislate, regulate and introduce best management practices for trash and debris management, Southern California had never conducted a comprehensive assessment of the magnitude and extent of trash and marine debris in streams and the nearshore Southern California Bight. Apart from local studies, in fact, the best region-wide data on trash and marine debris in southern California had been collected by volunteer-driven coastal cleanups. One prominent cleanup effort, the California Coastal Clean Up Day (http://www.coastal.ca.gov/publiced/ccd/history.html), is a one-day event held in late September of each year. In 2015, more than 28,000 volunteers removed more than 118 metric tons of trash and debris from stream and beaches across four southern California coastal counties. The mass of trash and debris collected during Coastal Clean Up Day has more than quadrupled from 1989 to 2015. While this level of effort is impressive, data inconsistencies have made it difficult to determine quantitative baselines and to estimate trends over time (Moore *et al.*, 2001).

II. Goal of this study

This study aimed to create southern California's first regionalized assessment of trash and marine debris, with a goal to assess the extent and magnitude of trash and marine debris in southern California waterways, from wadeable streams to the marine habitats of the Southern California Bight. The study leveraged the resources and expertise of dozens of Bight'13 participating agencies, and asked three key questions:

- **Does the extent and magnitude of trash and marine debris vary among freshwater and marine habitats?** Quantifying the regional footprint of trash and debris illuminates the scope of this potential problem. By identifying differences among habitats, managers can potentially identify hotspots of trash generation or accumulation.
- **Does the extent and magnitude of trash and marine debris vary over time?** Evaluating trends establishes whether the scope of this potential problem is increasing or decreasing, and provides a baseline with which to indicate the effectiveness of management actions into the future.
- **What types of trash and marine debris are most extensive or abundant?** Determining the most pervasive types of debris enables managers to most effectively narrow the focus of future management efforts.

III. Study Approach

The Bight'13 debris survey examined trash and marine debris in three main habitat types across the land-ocean interface: (1) trash in streams, (2) marine macro-debris on the seafloor, and (3) marine micro-plastic debris in seafloor sediment. Data were collected in all three habitats utilizing a probability-based stratified-random design (Stevens 1997) that allows unbiased estimates of extent (i.e., % of stream-miles or % of seafloor with debris) and magnitude (i.e., average abundance of debris).

Trash in streams: Trash in streams was quantified by leveraging sampling efforts of the Southern California Stormwater Monitoring Coalition (SMC), a group that includes regulated and regulatory agencies that work together to answer scientific questions relevant to stormwater management (www.SoCalSMC.org). A total of 273 sites were sampled from 2011 to 2013, typically in the early- to mid-summer dry weather period (April to July), following a modification made to the California State Rapid Trash Assessment protocol (San Francisco Bay Regional Water Quality Control Board 2004). Each site was defined as a stream reach 30.5 m (100 ft) in length and a width of high water mark (or bankfull height if a high water mark was not discernable). Then, all trash pieces within this stream reach were counted and categorized.

Marine macro-debris on the seafloor: Macro-debris on the seafloor (also referred to as epibenthic macro-debris) of the Southern California Bight was surveyed by leveraging the sampling efforts of the Bight'13 Contaminant Impact Assessment Group (B'13 CIA) trawl survey (Bight'13 Field Committee 2013). A total of 164 samples were collected at depths ranging from 3 m to 500 m from July 2013 to September 2013. Trawls were conducted by hauling nets (7.6-m headrope semi-balloon otter trawl, 1.3 cm cod-end mesh) behind the research vessel at approximately 1.0 m/sec for 10 minutes. Debris caught in the net were counted and categorized. Subsamples of plastic debris were sent to the laboratory to determine polymer type. In addition, ingestion of plastic debris by demersal and pelagic fish was investigated by subsampling demersal fish from trawls and sampling of pelagic fish using mid-water trawls and hook-and-line fishing.

Micro-debris in seafloor sediment: Micro-debris in seafloor sediment (also referred to as benthic micro-debris) was surveyed by leveraging the sampling efforts of the Bight'13 CIA benthic survey. A total of 358 sites were sampled at depths ranging from 0 to 1000 m from July 2013 to September 2013. Benthic samples of 0.1 m^2 (where sediment depth was $\geq$5 cm) were collected from the research vessel using a modified Van Veen grabs (Stubbs *et al*. 1987), then washed through a 1 mm mesh screen. The retained material was sent to the laboratory, where the samples were sorted for benthic marine organisms and debris. The debris was counted and categorized, then analyzed for polymer type.

IV. Results

The integrated findings of the Bight'13 trash and marine debris study are as follows:

- **Trash and marine debris were found in more than three-fourths of Southern California rivers and about one-third of seafloors and seafloor sediment. Plastic was the most prevalent item found across all habitats. Areas with plastic bag bans had lower numbers of plastic bags/plastic bag pieces.**

  Over three-quarters (78%) of the more than 7,400 km of southern California streams contained some trash (Figure 2), with four of the five most abundant watershed-borne trash items identified as plastic (wrappers, bags, pieces and Styrofoam). Plastic bags/plastic bag pieces were found in significantly lower numbers in areas with bans (median of one bag) than they were in areas with bans (median of three bags; Figure 3), providing preliminary evidence that source control may be an effective strategy. In Bight marine habitats, micro-plastic debris was found in 35% of seafloor sediments, while macro-plastic debris was found on the surface of 32% of seafloor sediments. High-density polyethylene (HDPE) was the most common type of plastic, an unsurprising finding given that this polymer is amongst the highest in production and, like other plastics, is highly resistant to breaking down.

- **Multiple lines of evidence suggest that anthropogenic land-based trash from coastal Southern California watersheds serves as a major contributor to Bight marine debris.**

  Trash was found in greater than 90% of the stream kilometers in urban watersheds, compared to less than 50% of stream kilometers in undeveloped watersheds. Furthermore, trash in urban streams was found at the greatest densities near the largest roadways; trash density decreased as distance to roads increased and as roads decreased in size. In the Bight, micro-plastic debris was more commonly found in shallow inshore habitats proximal to watershed sources (up to 90% of area in ports, bays, and marinas) than further offshore (as low as 25% on the continental shelf and slope) while seafloor macro-debris increased moving offshore. While trash – particularly plastic – was abundant in streams (averaging 0.2 pieces/m^2), the density of micro-plastic was three orders of magnitude higher in Bight sediments than in streams (Table 1), indicating that marine habitats likely serve as a sink and are accumulating plastic over time. More than 10^{14} micro-plastic pieces are estimated to be lying in Bight seafloor sediment. Of a total of 1554 demersal and pelagic fish sampled in marine nearshore habitats, only 4 had plastic pieces, but a special study in San Diego Bay found that 25% of fish at the mouth of Chollas Creek contained microplastics, and that fish preferred plastic types that often resembled prey items, including filamentous algae, nematodes and fish eggs (Talley et al., in review).

- **Historical Bight data indicate the amount of marine debris on the seafloor is increasing.**

  Historical Bight data dating back to 1994 show that the extent of seafloor macro-debris nearly doubled from 1994 and 2013 and that plastic increased threefold (Figure 4). The only habitat type for which this data could be analyzed temporally was seafloor macro-debris, which has historically been documented via trawls.

While these findings are striking, there is uncertainty in how they should be interpreted and their relevance for management action. First, each of these components measured standing stock of trash and marine debris as single snapshots in time. The rates of transport into these habitats, of accumulation and breakdown, and of subsequent loss cannot be inferred from standing stock or information on size or type of debris. Second, while it is readily apparent that there is a linkage between watershed trash and marine debris, the linkage between Bight habitats and land-based sources is poorly understood, particularly with respect to seasonality of the linkage and the transport of debris. Third, it is not clear how much of the debris is coming from Southern California watersheds vs. other ocean-derived sources. Finally, because this study of trash and debris was highly leveraged on other Bight and SMC regional monitoring program study components, the study is not necessarily optimized to fully characterize the magnitude and extent of trash and marine debris found in all habitats. For example, when analyzing macro-debris from San Diego Bay, disparities in sampling methods can lead to different outcomes: Otter trawls in San Diego Bay found little to no macro-debris; however, when a finer trawl mesh size was used during a special trawl study of San Diego Bay and its contributing watersheds, a high abundance of macro-debris on the Bay seafloor was documented. While tremendous effort was expended to ensure sampling comparability amongst the many participating organizations in Bight '13, standardized methods for trash sampling and monitoring currently does not exist in California.

V. Recommendations

Recommendations based on the conclusions from this study have both management and technical implications regarding future needs. These recommendations are presented below.

- **As managers pursue policies that focus on trash source control and source reduction in urban areas, additional monitoring should be conducted to evaluate effectiveness of these policies.**

  Based on the Bight'13 survey results, it is apparent that urban areas have both the largest extent and magnitude of trash of Southern California streams, likely contributing to debris found in nearshore marine environments. Existing policies emphasizing trash source control and reduction in urban land uses are in place through statewide laws, regional regulatory policies, and local ordinances (SWRCB, 2015), including Trash Amendments adopted by the State Water Resources Control Board (State Water Board) in April 2015 to control trash in state waters. In response to these policies, local stormwater agencies have spent large amounts of money and dedicated many resources over the last five years implementing source reduction measures, including catch basin inserts, trash booms and litter separation devices as part of their Municipal Separate Storm Sewer System (MS4) Discharge Permits. Continued monitoring of stream trash will help illuminate the degree to which source reduction strategies are helping. However, it is important to acknowledge the limitation of source reduction strategies, particularly in capturing small trash of < 5 mm in size, which was the most widespread and abundant trash identified in Bight '13. To address this limitation of source reduction technology, managers have increased their emphasis on true source control whereby trash items of concern are not produced. For example, California passed the nation's first statewide ban on single-use plastic bags in 2014 (Senate Bill 270), which – if it goes into effect following a referendum challenge in November 2016 – should reduce the use of commonly used light-weight plastic bags made of high-density polyethylene (HDPE), one of the most common polymer types found in the Bight'13 debris survey. Continued future monitoring will document the effectiveness of these contentious management actions providing the information managers need to make decisions about increasing, decreasing, or modifying additional source reduction strategies.

- **New partnerships should be forged to address future monitoring and research, specifically aimed at non-regulatory approaches to managing plastic trash and marine debris.**

While additional monitoring is recommended to quantify the most effective management actions, regulatory or regulated agencies should not do this additional information gathering in isolation. New partnerships that bring together regulatory and regulated agencies will be key to effective management success. Moreover, there are a large number of active groups that could also be important contributors to the conversation about trash and debris management, including advocacy organizations and plastics industry representatives. The range and form of these partnerships are varied, depending upon the motivation and willingness of managers to address the large extent and magnitude of trash and debris observed in southern California, ranging from informal interactions in the next Bight regional monitoring program to more formal partnerships not unlike the Brake Pad Partnership (http://www.suscon.org/bpp/). To help address true source control for widespread aquatic copper contamination, the Brake Pad Partnership helped negotiate a 2015 memorandum of understanding between the U.S. automotive industry and state and federal regulators committed to redesigning brake pads with a fraction of the current copper content within 10 years.

- **The study design for monitoring of trash and marine debris should be optimized.**

  One key caveat of the Bight'13 trash and debris study findings is the fact that the study was leveraged onto an existing study design that is targeted at answering management questions about pollutants other than trash and marine debris. To get a better understanding of the magnitude and extent of trash and marine debris, establish the linkage to sources, and quantify transport, accumulation and loss rates, there is a need for improved methods and study designs. This study should include development of a model monitoring program for trash and marine debris that is driven by identification of key management questions and metrics to evaluate the implementation of source control and reduction strategies. The advantages and disadvantages of different measurement methods should be weighed, balancing precision of information vs. cost. Disparate monitoring by stormwater agencies should be unified to compare the effects of localized management efforts with regional trends and information.

- **The extent, magnitude, and source(s) of micro-plastic in marine sediment should be prioritized for future research.**

  Micro-plastic in marine sediment may be coming from a wide variety of sources. In addition to larger pieces breaking down, it has been shown that fully intact micro-plastic products also can enter inland surface waters and the ocean; these intact micro-plastic pieces come from cosmetics and personal care products, fibers from washing garments of synthetic clothing and textiles, preproduction pellets and powders, atmospheric deposition, and other processes such as bead blasting, overland sludge application, etc. (Browne *et al*., 2007). Although this study showed that micro-plastic is indeed present in large quantities in the Southern California Bight, the extent and magnitude of micro-plastic, and the relative portions coming from various sources, are unknown. Most recently, California passed Assembly Bill (AB) 888, the Plastic Microbeads Nuisance Prevention Law, which will ban the sale of rinse-off personal care products containing plastic microbeads used to exfoliate or cleanse in 2020. Further attention should be paid to microbeads to generate baseline information necessary to evaluate whether such bans result in desired reductions.

- **Future studies should address data gaps regarding fate and transport, mass balance, and temporal trends of southern California trash and debris.**

  While this first-of-its-kind screening survey documented a large extent and magnitude of debris in southern California waterways, it has raised several unaddressed questions. First, the fate and transport of the debris remain unknown, which is information that managers need to link debris to specific sources and to identify “hotspots” for remediation. Managers also need documentation of accumulation rates to better allow for targeted debris removal during peak accumulation periods. Second, extent and abundance estimates derived from this study are insufficient to allow for quantification of total mass of debris. Because large macro-plastic breaks down and fragments into micro-plastic, this study was unable to properly link data from land and sea, and to assess trends. The preferred method of evaluating temporal trends is to be able to estimate total mass; however, better methodologies for measuring mass are required to address problems with weighing debris items, such as plastic, which often include encrusting organisms, sediment or water. Third, once mass estimates are incorporated into future studies, additional questions about trends should be addressed. This survey was able to assess trends in macro-debris on the seafloor only; there were insufficient data available on macro-debris in streams and on micro-plastic in seafloor sediment. Especially as management measures are implemented in response to policy and legislations, trend monitoring will become crucial for assessing effectiveness of these measures.

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VII. Figures

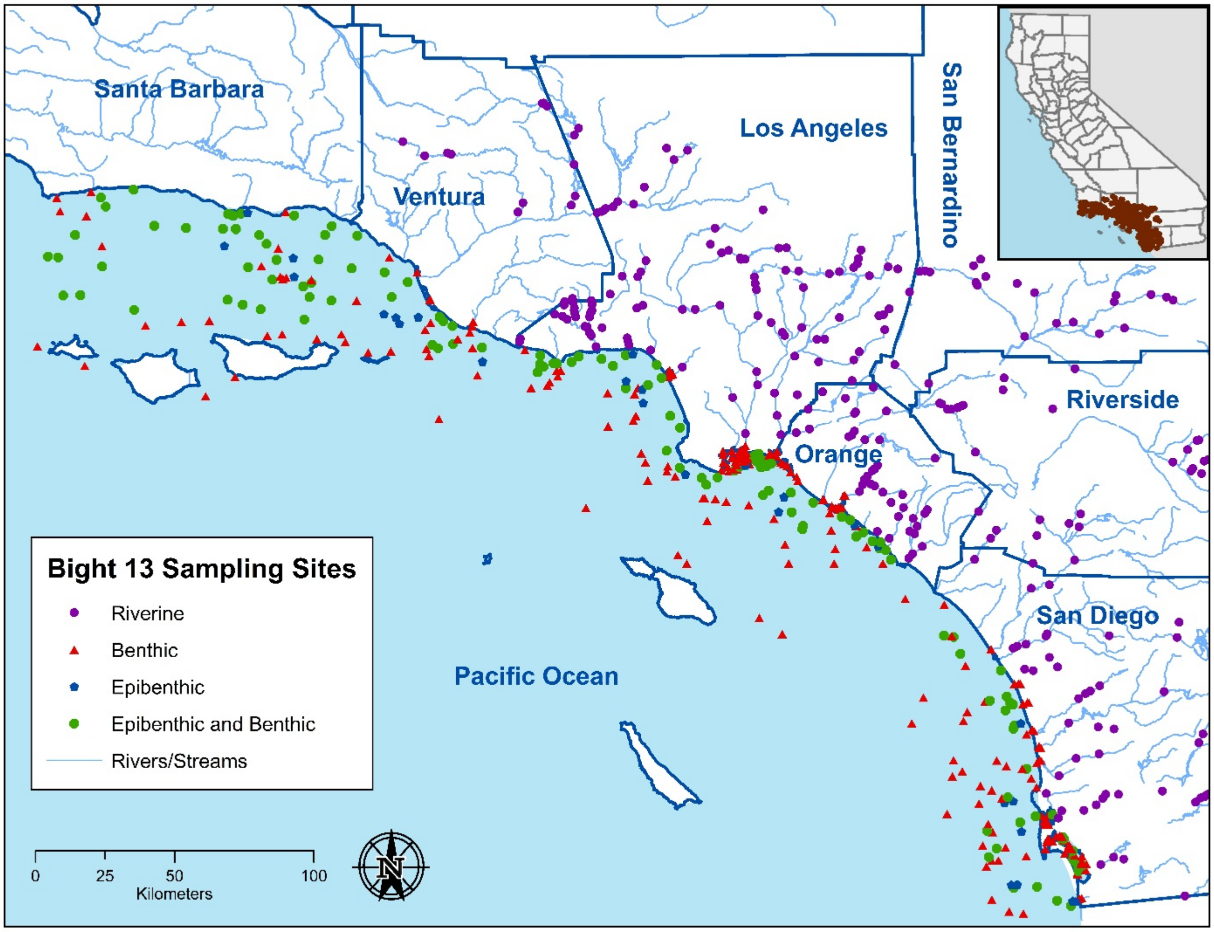

Figure 1: Map of sampling sites for all three components of the Bight 13 Trash and Marine Debris Survey.

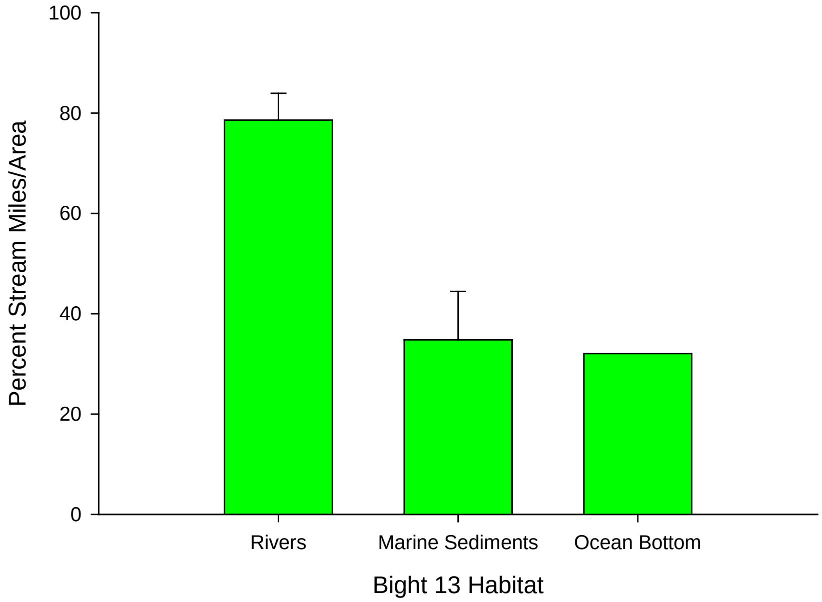

Figure 2: Extent of trash and marine debris in different habitats of interest for the 2013 Southern California Bight Survey. River trash is given as a percent of stream miles, while microplastic debris in marine sediments and macrodebris on the ocean bottom is given as a percent of area.

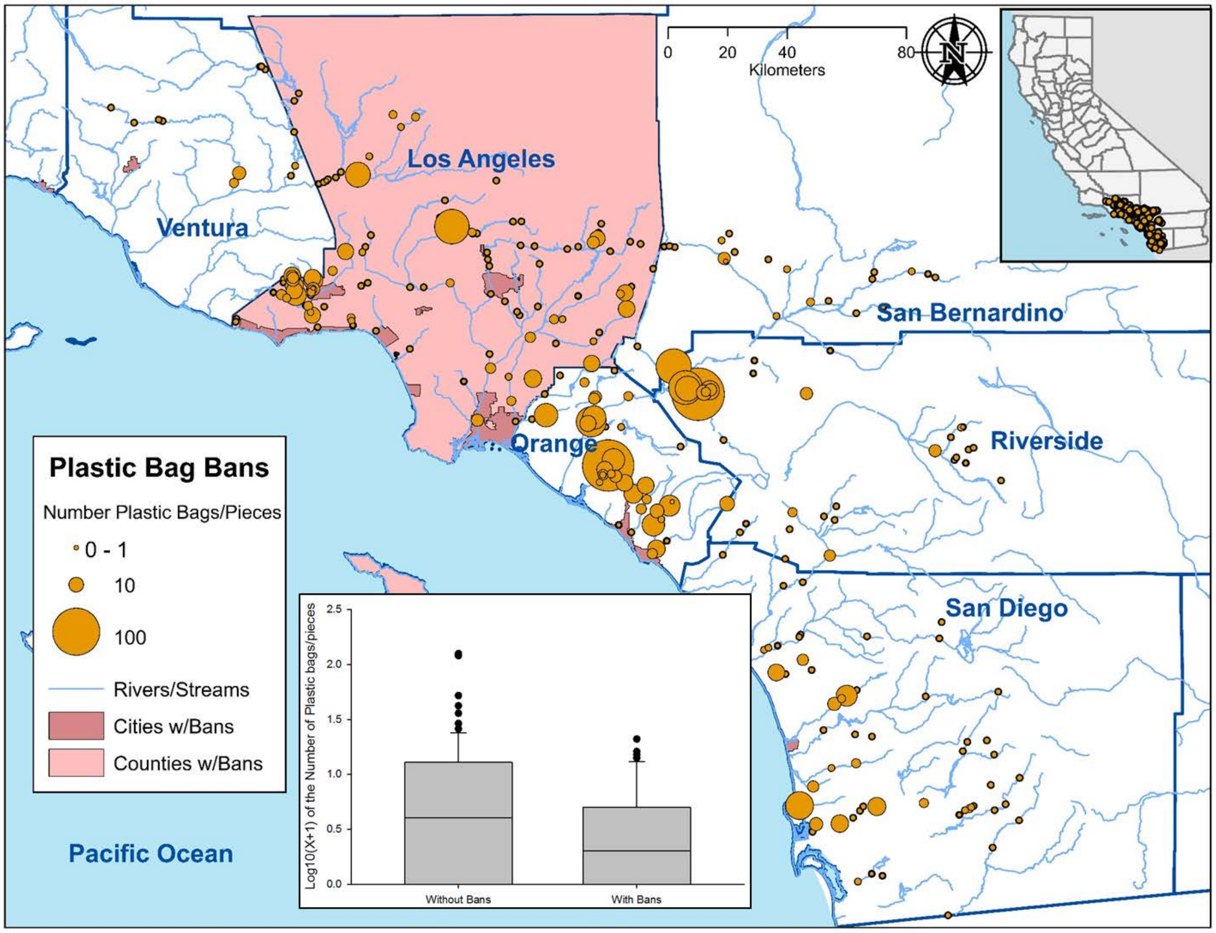

Figure 3: Map of areas with and without plastic bag bans in 2013 and the relative number of plastic bags/plastic bag pieces at each sampling site. Graph reflects log10(x+1) of the median number of plastic bags/plastic bag pieces.

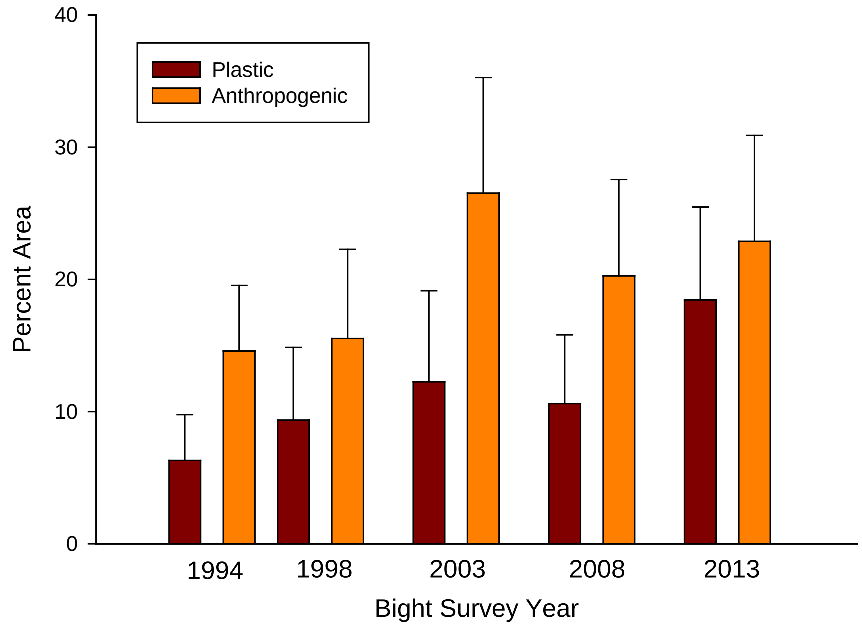

Figure 4: Trends in overall and plastic marine debris on the ocean bottom over all Bight surveys in the Southern California Bight from 1994 through 2013. Graph reflects only strata in common between all 5 surveys (inner, middle and outer shelf).

VIII. Tables

Table 1: Estimated plastic density and abundance by type and habitat from the 2013 Southern California Bight Survey.

Habitat	Plastic in the Southern California Bight		
	Type	Average Density (#/m^2)	Estimated Total Abundance
Riverine	Macro-plastic (visible)	0.2	1.3×10^7
On Top of Seafloor	Macro-plastic (>1.3 cm)	0.00016	0.1×10^7
In Seafloor Sediment	Micro-plastic (<1 cm)	18	$26{,}000{,}000 \times 10^7$

Chapter Two: Regional Assessment of Trash in Wadeable Streams of the Southern California Coastal Watershed

I. Abstract

Trash, particularly plastic, has become a pollutant of global concern. However, most research on the extent and magnitude of trash has occurred in marine habitats; surprisingly little research has occurred in streams and rivers. The abundance of trash in these streams and rivers is important not only for the potential effect on freshwater food webs but also as an important conduit for transport to marine environments. The goal of this study was three-fold: 1) assess the extent and magnitude of trash found in southern California's wadeable streams; 2) quantify the types of trash, and; 3) identify relationships between land use and trash. In this study of a region with a population of 22 million, over 80% of the nearly 9,500 km of wadeable streams contained some trash, with the total number of pieces estimated at 32 million. Plastic accounted for more than 60% of the trash found. Urban land use was associated with the greatest extent and magnitude of trash, with levels roughly double those found in more natural areas. Trash was more abundant at sites closer to roads and at sites near larger multiple-lane roads, suggesting roads are an important source of trash to streams. This probabilistic survey of trash in wadeable streams is the first-of-its-kind in the published literature.

II. Introduction

Trash and marine debris, particularly plastic, has become a pollutant of global concern found not only in populated areas, but also on remote shorelines and in mid-oceanic gyres thousands of miles from shore (Derraik 2002, NRC 2009). Trash can be an aesthetic pollutant as well as a risk to wildlife (Ryan *et al.* 2009, Boerger *et al.* 2010, Gall and Thompson, 2015) and possibly human health (Thompson *et al.* 2009). Surveys in marine environments indicate that plastic comprises the majority of anthropogenic marine debris, as much as 60-80% by number (Derraik *et al.* 2002), and the amount of plastic marine debris in the North Pacific Gyre has increased by an order of magnitude between 1980s and 1990s (Day *et al.* 1990, Moore *et al.* 2001).

Although marine studies have been nearly universal in their claim that a large fraction of oceanic debris comes from land-based sources (GESAMP 1991), sources of ocean debris are generally not well quantified, and few studies have supported this assertion by assessing the abundance of trash in rivers and streams (Thompson *et al.* 2009, Hollein *et al.* 2014). The few studies of riverine environments generally focus on quantifying the sources of trash, rather than the abundance of trash within the channel. For example, approximately 0.1 metric tons per day of trash are estimated to come from terrestrial sources into the Seine River (Gasperia *et al.* 2014) and 4.2 metric tons per day into the Danube River (Lechnera *et al.* 2014). Estimates of magnitude, abundance, and types of trash in streams and rivers are important because they convey to managers and policymakers the extent of the problem. Such information could also convey priority sources and land uses that can be targeted for intensive management action.

Southern California is a region where trash would be expected to be prevalent in streams and rivers. With a population of 22 million, this heavily-urbanized coastal region contains over 7800 km^2 of developed landscape. Moreover, this region has a Mediterranean climate with sparse rainfall, particularly during the dry months of April to October, which make for long dry periods to build up trash. The coastal watersheds of southern California are important because they drain into the Southern California Bight, a coastal zone prized for its beaches and other ecotourism, as well as for the biodiversity and endemism of its marine and estuarine ecosystems.

In such a region, quantifying the extent, magnitude and types of trash found in wadeable streams is an important step towards guiding and evaluating the effect of trash policy and management actions. In some parts of the region, state and federal regulators have established total maximum daily loads (TMDLs) for trash greater than 5 mm diameter (CRWQCBLA 2007, CRWQCBLA 2015). The State of California recently adopted similar regulations for extending comparable trash reduction policies statewide. Several municipalities have recently established or are considering the establishment of single use plastic bag bans. However, prior to this study, no estimate of trash abundance in southern California stream channels had been made that could be used as a baseline from which to evaluate the efficacy of management actions.

This study was part of a collaborative effort by many agencies over a three-year period to assess overall conditions in rivers and streams in southern California. As part of this wider study, trash was assessed in an effort to provide the first regional scale study of extent and magnitude in rivers and streams. The goal of this study was three-fold: 1) to assess the extent and magnitude of trash found in southern California's wadeable streams; 2) to quantify the types of trash; and 3) to identify relationships between the intensity of land use, presence of trash management policies (e.g. single use plastic bag bans) and trash.

III. Methods

A. Study Design

This study used a probabilistic design to produce unbiased estimates of trash extent (stream-miles) and magnitude (abundance). Details of the study design based on surveys for other stream health indicators (e.g., algae, benthic macroinvertebrates) are described elsewhere (Mazor 2015). Briefly, the sampling frame included all perennial, wadeable, second-order and higher streams in southern California coastal watersheds from Ventura County to the U.S.-Mexico border (NHD Plus, US Geological Survey and US Environmental Protection Agency 2005). Wadeable streams are those that during dry weather are shallow enough to sample without boats (i.e. by "wading"). This represents approximately 28,051 km^2 of watershed area and 9,492 km of stream length (Figure 1). Stream sites were selected from the sampling frame using a spatially balanced, stratified random, master list design (Stevens and Olsen, 2004, Larsen *et al.* 2008).

Trash was surveyed at 273 sites independently stratified by county or land use over a period of three years (Table 1). Fifteen watersheds were delineated in southern California, roughly approximating HUC 18 from NHD Plus. County stratification included the five counties that comprise these coastal watersheds: Ventura, Los Angeles, Orange, Riverside, San Bernardino, and San Diego Counties. Three land uses were defined - urban, agriculture, and open - based on the National Oceanic and Atmospheric Association's Coastal Change Analysis Program (C-CAP, NOAA 1995, 2001). For the purposes of site selection, land use was assigned to each stream segment using a 500-m streamline buffer. If the buffer was more than 75% natural or open land, that segment was considered open space. Otherwise, land use was classified as urban or agricultural, depending on which land use dominated.

B. Sample Collection

All sites were sampled during the spring (April-June) in 2011-2013. Sampling followed a modification of the California State Rapid Trash Assessment protocol, originally developed by the San Francisco Bay Regional Water Quality Control Board (2004). Briefly, each site was defined as a stream reach with a length of 30.5m (100 ft.) and a width equal to the high water mark, also referred to as the ordinary high water mark if a visible high water level was not discernable. All trash, visible to the eye, within this stream reach was counted and classified (see Supplemental Information for example Trash Talley Sheet). The ten general trash classifications were: plastic (i.e., wrappers, bags, pieces, bottles), glass, metal (i.e., aluminum cans), cloth, biohazard (i.e., pet waste), biodegradable (i.e., paper), construction (i.e., concrete, asphalt), large (i.e., refrigerators, sofas), toxic (i.e., cigarette butts, spray paint cans), and miscellaneous (i.e., sports balls, ceramics). If an item fit multiple categories, the category that fit the greatest proportion of material was recorded, with comments made on any additional categories for minor material types. Field audits were conducted on at a subset of samples to ensure standardization of sample collection.

C. Data Analysis

Sampling weights were assigned to each site for each stratum definition, to account for differences in total stratum stream length. These weights were used when estimating magnitude (area-weighted mean abundances) and spatial extent (percent of stream miles) using the Horvitz-Thompson estimator (Horvitz-Thompson 1952). Confidence intervals (CIs) were based on local neighborhood variance estimators (Stevens and Olsen 2004). Data analyses were conducted using R version 3.0.3 (R Core Team 2014, Kincaid and Olsen 2013). Kruskal-Wallis one-way analyses of variance (ANOVA) were used to test differences in trash abundance among the three land use categories and by county.

To understand the effect of intensity of land use on trash abundance in the channel, three types of analyses were done. First, the relationship between trash abundance and percent imperviousness in land adjacent to and upstream of the channel was investigated. For each site, percent imperviousness within a

1-km buffer adjacent to the site and within a 1-km buffer in the upstream catchment of the site was delineated and the percent imperviousness of land use (USGS 2005) within those polygons computed. Quantile regression was used to quantify relationships between log-transformed trash counts and percent imperviousness in the adjacent and upstream catchments.

Second, the relationship between trash abundance and ease of access to the site was explored. Ease of access was evaluated in categories of “not difficult,” ”moderately difficult,” and “very difficult” based on whether thick riparian canopy and understory, fences or vertical channel walls obstructed access. Kruskal-Wallis one-way ANOVA was used to test differences in trash abundance by ease of access to the channel.

Third, trash abundance was assessed as a function of roadway type (paved, unpaved, bike path), size (the number of available lanes which ranged from single lane (1) to multiple lane roads (4+), and distance upstream of or downstream from the site. Observations of roadways were made via Google Earth (Version 7.1.5.1557). Kruskal-Wallis one-way ANOVA was used to compare trash abundance by roadway type and size. Quantile regression was used to examine the effect of distance from roadway on log-transformed trash abundance. Finally, conditional probability analyses (CPA) was used to identify distance upstream or downstream from roadways at which the probability of trash abundance falls below 10 items per site, a threshold that designates sites as having high aesthetic condition, according to the trash survey protocol.

Finally, the effect of municipal or county-wide single-use plastic bag bans on plastic bag density in the stream channel was investigated. Los Angeles County and several municipalities throughout Southern California have adopted ordinances regulating the use of single use plastic bags (http://dpw.lacounty.gov/epd/aboutthebag/legislation4.cfm#cacities_date). Sites within and outside of these locations were assessed for plastic bag abundance, using a Mann-Whitney Rank Sum Test.

IV. Results

A. Extent, Amount and Type of Trash

An estimated 78% of wadeable stream miles in southern California had trash either in the stream or along its banks (Figure 2). This extent and amount of trash varied among land uses. Urban land use had the greatest extent, with more than 92% of stream miles with measurable trash. Open land use had the least extent; 48% of stream miles had measureable trash. Similarly, a median count of 31 trash items per site were found in urban sites, which was significantly greater than the median of 1-2 items per site found for Agriculture and Open sites (H= 73.3, $p < 0.001$).

No southern California County had a substantially greater extent of trash in its streams within the urban land use category (Figure 2); the extent was quite large amongst all counties ranging from about 90% (Los Angeles and San Diego) to 100% (Ventura, Orange, Riverside and San Bernardino). However, Orange County had significantly higher trash counts (H= 29.5, $p < 0.001$), with the median trash count of 41 per site roughly four times that of LA County (11 per site) and an order of magnitude higher than San Diego, Riverside, and San Bernardino Counties (median of 3-8 trash items per site)

An estimated 32.3×10^6 trash items occurred in southern California wadeable streams during this survey, with a mean of 31± 2.5 (mean count ± 95% confidence interval). The most common item was plastic (Table 2; 18.7 pieces ±2.5 pieces of plastic per site). The most common types of plastic were wrappers or wrapper pieces (5.3 ± 0.9 per site), bags or bag pieces (3.7 ±0.5 per site), hard and soft miscellaneous plastic pieces (3.4 ±0.9 per site), expanded polystyrene (also known as Styrofoam®) pieces (3.1 ±0.9 per site) and plastic bottles (1.1 ±0.2 per site). These plastic items comprised five of the top ten most abundant trash items (Table 3). The other top-ten most abundant trash items included glass pieces, sports balls, cigarette butts, paper/cardboard, and concrete/asphalt.

Plastic was the most common trash type regardless of county or land use (Figure 3). The Plastic and Miscellaneous (sports balls, ceramics) categories were the number one and two trash categories, accounting for about 70% of all trash items. Trash in urban areas mimicked the overall distribution; however, construction items were the second most abundant in areas with agriculture as the primary land use, and glass items were the second most abundant in open land use areas.

B. Relationships of Trash Abundance with Percent Imperviousness, Site Access, Road Distance and Road Type

We examined multiple variables to determine which landscape based attributes were positively correlated with trash abundance, which included percent imperviousness, public accessibility to each site, and the influence of adjacent roads. The median quantile regression of percent imperviousness was significantly correlated with trash abundance. Regression slopes were positive (~0.88 trash items/% imperviousness) and the relationship between and percent imperviousness based on the upstream 1-km buffer and the adjacent 1-km, yielding the same level of significance ($p<0.0001$).

Proximity to a road and type of roadway were correlated with trash abundance whereas ease of access was not. Kruskal-Wallis One Way ANOVA relating ease of access to trash abundance showed no significant effect (H= 3.0, p = 0.22). Stream reaches closest to roads had the greatest median abundance of trash (Figure 4), with the peak abundance at any site >500 pieces co-located with a road crossing. Trash abundance significantly declined as road distance increased either upstream or downstream of the site (slope of 0.38 trash items/km, p, 0.0001). In particular, the probability of low trash counts (< 10 items/ site) increased above baseline at 0.1 km, but markedly increased at 0.3 km (Figure 5).

The type of road made a significant difference when examining median trash abundance ($H=73.5$, $p<0.001$; Figure 6). The greatest median trash abundance occurred at sites adjacent to the largest roads and to dirt roads. Sites in close proximity to roads with four lanes or more exceeded 40 items per stream reach. Median trash abundance declined as road size also declined. The solitary exception was the median trash abundance near dirt roads, where median counts exceeded 30 pieces of trash per reach.

C. Relationships of Single Use Plastic Bag Density with Presence of Plastic Bag Ban Policies

Single use plastic bag bans are in place in Los Angeles (LA) County, as well as several municipalities throughout LA, Orange, San Diego, and Ventura County. Plastic bags/plastic bag pieces were found in significantly lower numbers in areas with county-wide or municipal bans (median = 1 bag) than they were in areas without bans (median = 3 bags; Mann-Whitney Rank Sum Test $p=0.012$; Figure 7).

V. Discussion

In this study of a region with a large population and extensive watershed development, 78% of the nearly 9,500 stream kilometers contained some trash accounting for an estimated 32 x 10^6 pieces. Not surprisingly, urban land use contained the greatest extent and magnitude of trash of any land use, roughly double the extent and magnitude of that found in open land use. This regional probabilistic survey of the extent and magnitude of trash in streams is the first-of-its-kind in the published literature.

The large extent and magnitude observed in this survey is consistent with the large quantities of trash discharged to the marine environment from southern California's river mouths during storm events. Moore *et al.* (2011) estimated that 2.3 x 10^9 pieces of trash, cumulatively weighing at least 30 metric tons, was discharged from three of southern California's urban watersheds during a range of typical storm events. While it is tempting to compare our abundance estimates (32 x 10^6 trash pieces) to those of Moore *et al*. (2011), we note that the latter represents a wet weather transport process (fluxes) rather than dry weather accumulation (standing stock). A better understanding of accumulation rates during dry weather and immediately following storm events is needed to better characterize the wet weather measured fluxes (e.g. Moore *et al*. 2011) within the context of estimates of standing stock (this study). Most studies of trash accumulation rates have focused on beaches, measuring accumulated trash at varying times following clearing. Such accumulation rates have varied tremendously, in part from the length of time trash is allowed to accumulate. Studies with shorter revisit times, as short as one day, had larger accumulation rates suggesting that longer revisit time periods underestimate true accumulation rates (Eriksson *et al.* 2013). Summertime dry weather accumulation rates in southern California streams had an estimated mean of 0.02 items/m/day during this study (data not shown), but this value is likely underestimating the true value given that revisit dates were conducted several months apart.

This survey found that plastic was by far the leading type of trash in both extent and magnitude. In other studies of trash in freshwater systems, plastic was also the most common type of trash. Studies from the Seine River (Gasperia *et al.* 2014), Chicago River (Hollein *et al.* 2014), and Southern California (Moore *et al.* 2011) all found plastic to be the most abundant trash items. Lechnera (2014) found that plastic trash outnumbered fish larvae in the Danube River. The loading of plastic trash from southern California coastal watersheds undoubtedly contributes to the region's unusually high density of marine shoreline (Moore *et al.* 2001), floating (Moore *et al*. 2002), epibenthic (Moore *et al*. in prep-a), and benthic (Moore *et al*. in prep-b) plastic trash.

Finding that plastic is a common trash item provides some insight into where focused environmental management actions may be most effective. For example, plastic wrappers and Styrofoam ranked as the first and fourth most abundant trash items (see Table 3). Reductions of both these items could be achieved through alternative material selection, or reduction of packaging materials. Plastic bags were the second most common trash item. Many southern California municipalities are attempting to address this problem through local ordinances that prohibit the use of single-use plastic bags. Interestingly, California has both a $0.05 plastic bottle redemption program and nearly every city has a curbside recycling program. Yet, plastic bottles were still one of the top 10 most abundant trash items in this study.

Trash deposited in stream corridors occurs through several primary sources and pathways including, but is not limited to: 1) land use based sources, 2) incidental or wind-blown trash from adjacent areas, and 3) direct deposit of trash through homeless encampments, littering and illegal dumping (Ryan *et al.* 2009). Regardless of exact mechanisms, it is clear that roadways play a key role in trash source accumulation processes for streams. Survey results indicated that trash abundance increased as study sites approached roadways at distances less than 0.3 km, and that the largest roads had the greatest influence on stream sites. The relationship between stream trash and roadway contribution suggests that a management focus on roadway-associated trash will likely increase the cost-effectiveness of trash source reduction efforts.

Because trash and marine debris have the potential to adversely impact freshwater and marine beneficial uses, Southern California's management community has proposed and implemented a number of measures to minimize the amount of trash in waterways, including recycling programs, plastic bag bans, and other regulations and legislation. More than 100 California municipalities have promulgated bans on single-use plastic bags, and Senate Bill 270 in 2014 established a statewide ban, although its implementation has been delayed pending the outcome of a November 2016 ballot measure. In this study, we found that areas with bans had significantly lower median density of bags, providing preliminary evidence that source control may be an effective strategy.

One limitation of this study is the lack of trash mass. The study design sacrificed weighing trash to measure more sites, which was an important tradeoff to increase confidence in estimates of extent and magnitude. However, mass estimates will be one key attribute for linking land-based trash and trash measured in the near coastal oceans. This linkage becomes especially important for plastics that can break into smaller pieces, thereby increasing abundance, but will not increase total mass. Now that this survey has measured extent and trash counts, future studies focused on accumulation rates, and especially accumulation rates of trash mass, are logical next steps.

VI. Acknowledgments

The Stormwater Monitoring Coalition (SMC) portion of this study was funded jointly by the California State Water Resources Control Board, the Stormwater Monitoring Coalition, and the SMC member agencies. We thank the following for their sampling efforts and for providing data for this study: The California Surface Water Ambient Monitoring Program; Ventura County Watershed Protection District; Los Angeles County Flood Control District; Los Angeles and San Gabriel Rivers Watershed Council; Orange County Public Works; San Bernardino County Stormwater Program; Riverside County Flood Control and Water Conservation District; San Diego County and Co-Permittees; California Regional Water Quality Control Boards—Los Angeles, Santa Ana, and San Diego Regions; California State Water Resources Control Board; California Department of Fish and Game Aquatic Bioassessment Laboratory; Aquatic Bioassay and Consulting Laboratories; Nautilus Environmental; and Weston Solutions, Inc.

We also wish to thank the following organizations who provided citizen volunteers in support of the Bight 13 trash sampling effort during the Fall of 2013: Los Angeles Waterkeeper, San Diego Coastkeeper, Orange County Coastkeeper, and Heal the Bay.

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VIII. Figures

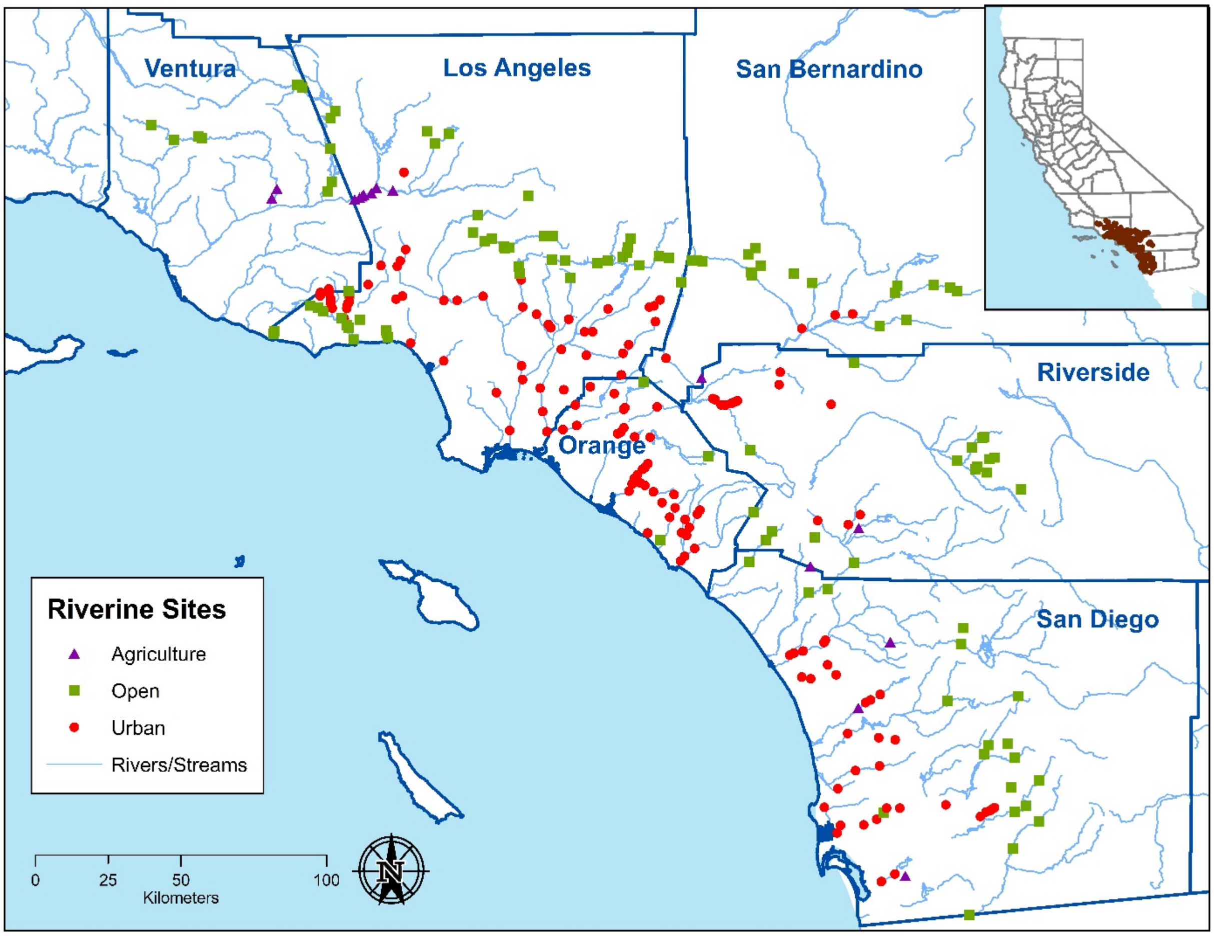

Figure 1. Map of sample sites by county and land use in the Southern California Stream Survey.

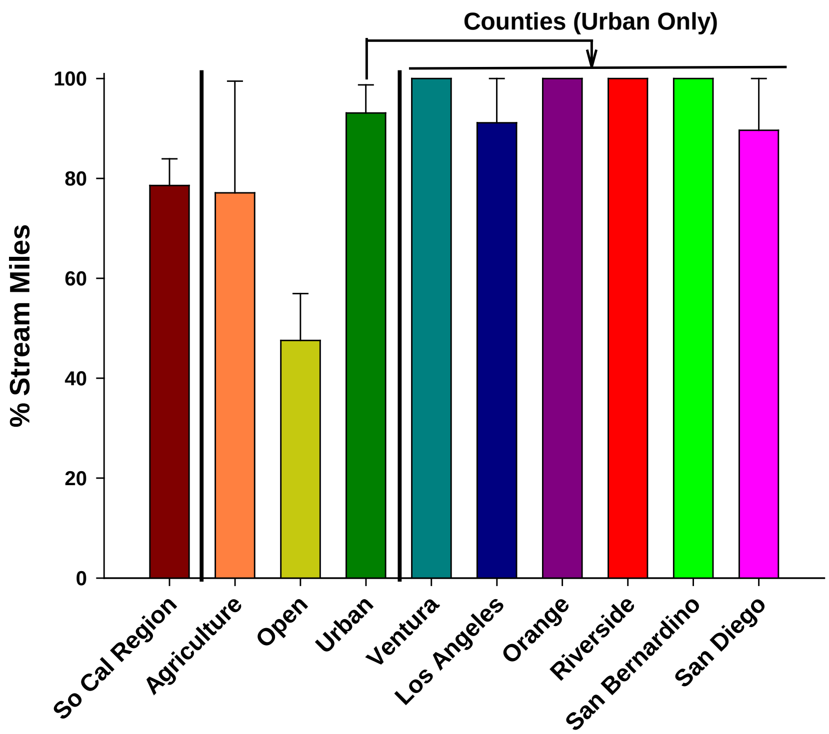

Figure 2: Areal extent of trash in southern California perennial rivers and streams.

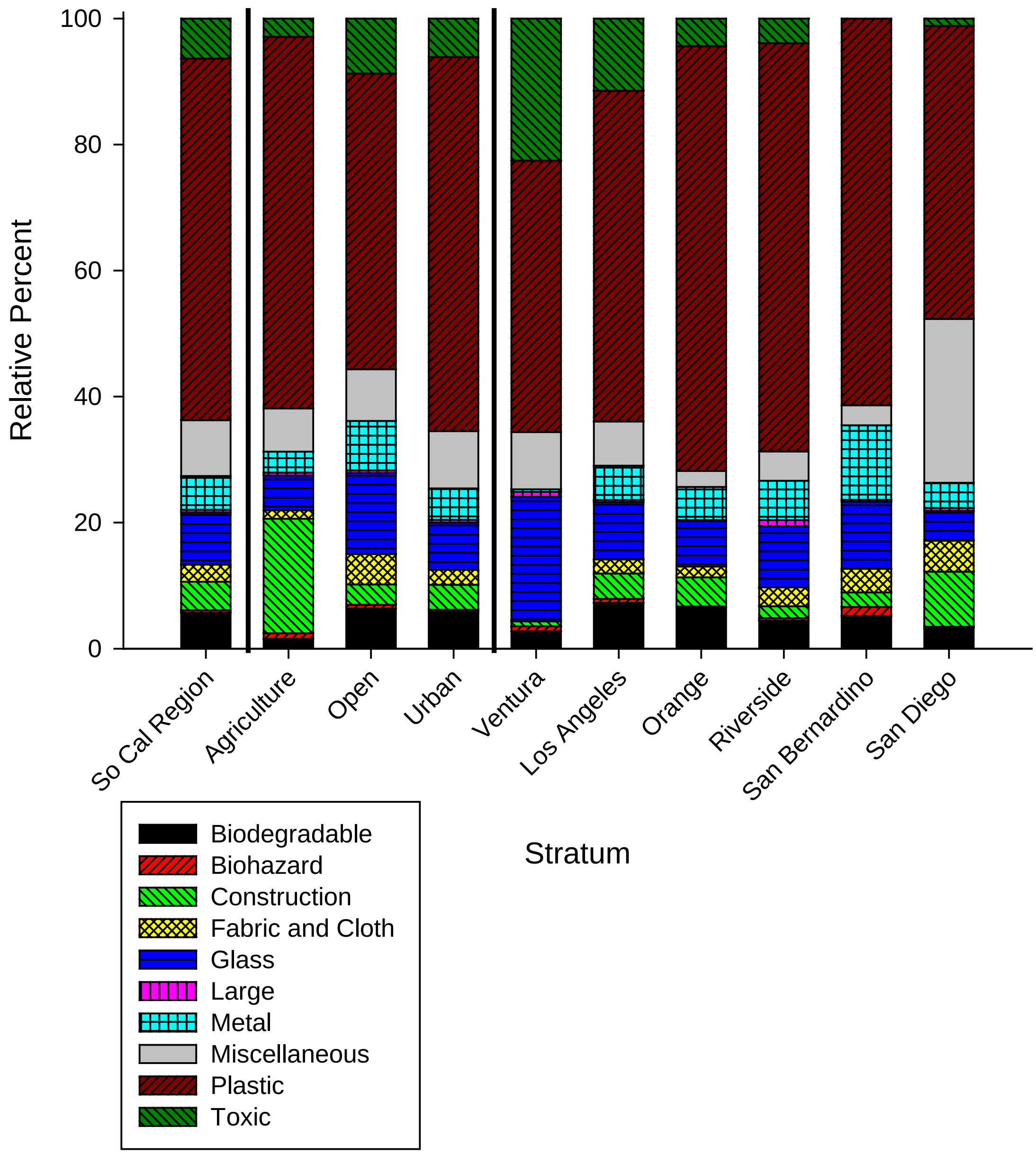

Figure 3: Relative percent of trash by land and County (urban only) strata in southern California perennial wadeable rivers and streams.

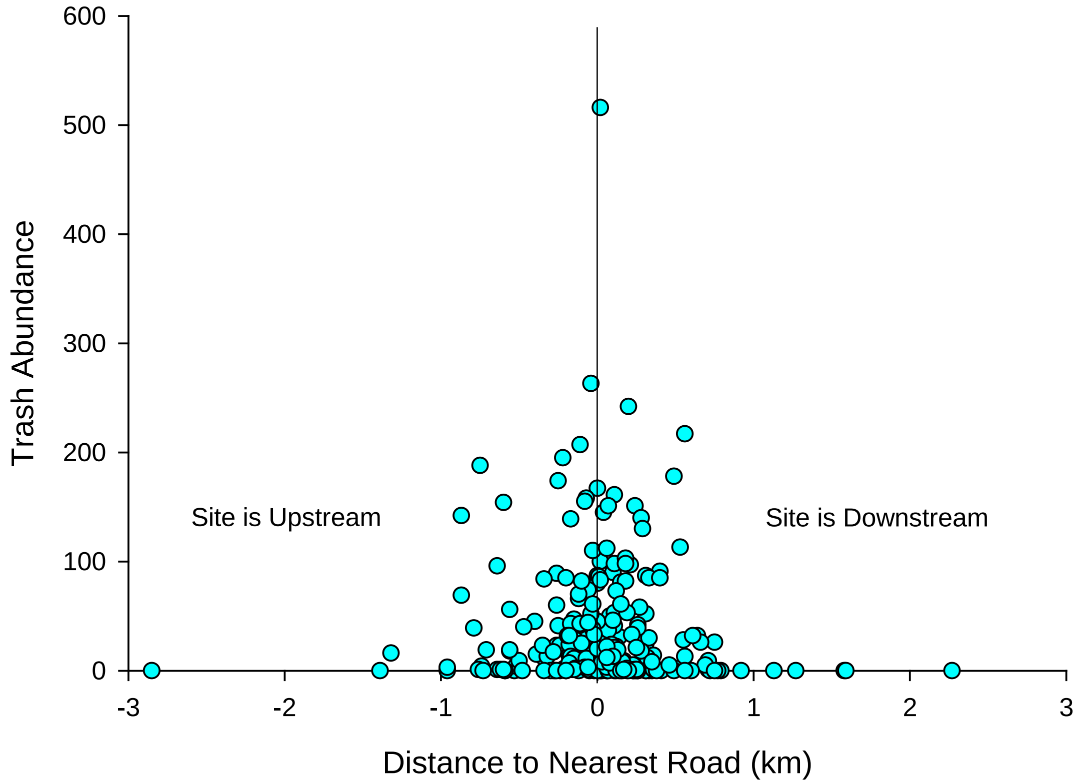

Figure 4: Trash abundance based on closest (upstream or downstream) distance to nearest road crossing.

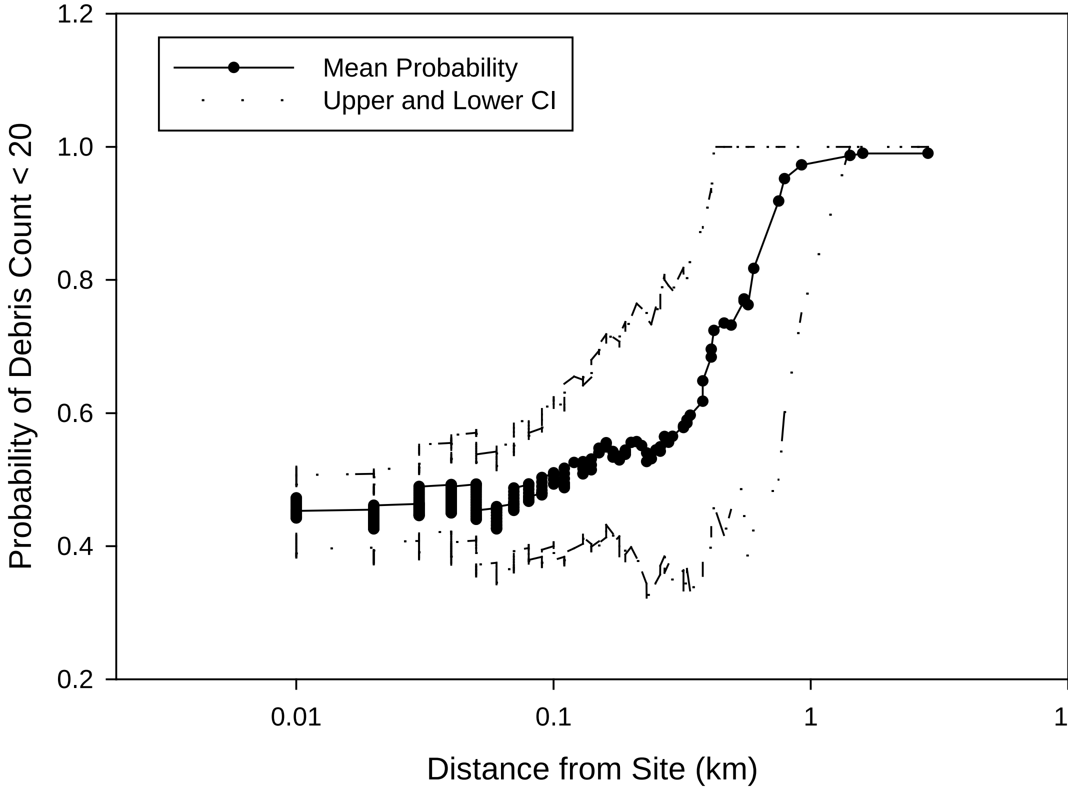

Figure 5: Conditional probability debris counts less than 10 as a function of increasing distance from site. Inflection points of interest include an increase above baseline probability (~0.4) at approximately 0.1 km, with greatly increased probability at 0.3 km.

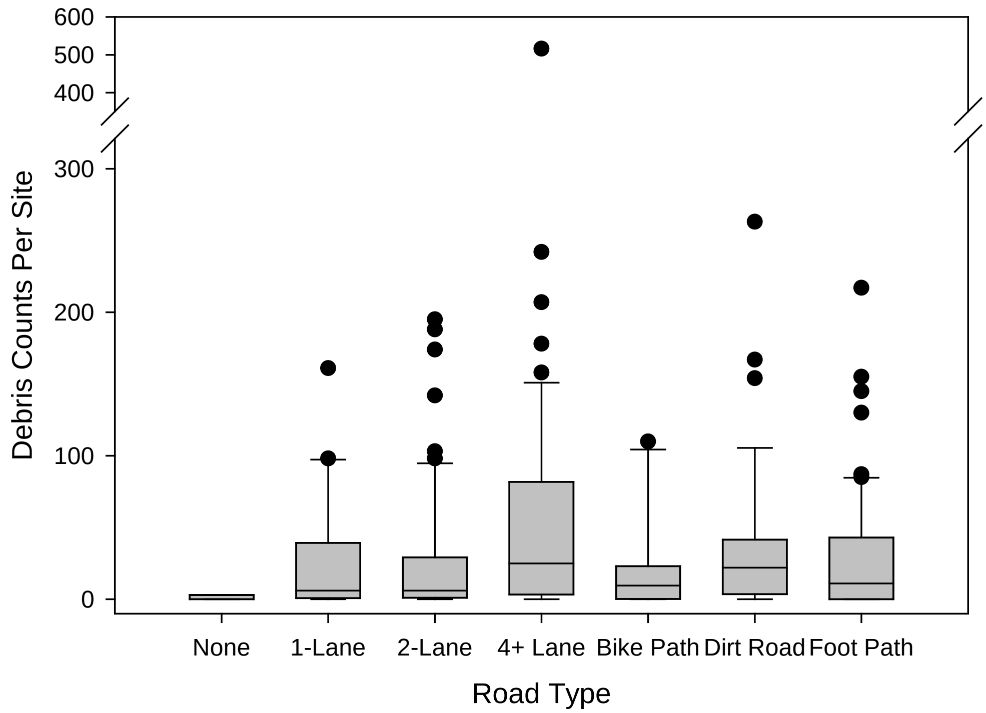

Figure 6: Box and whiskers plots of debris abundance at sites with the nearest road of a given size or type. Sample size for categories are as follows: none= 3, 1-lane= 26, 2-lane = 62, 4+lane= 81, bike path= 12, dirt road = 32, foot path = 61.

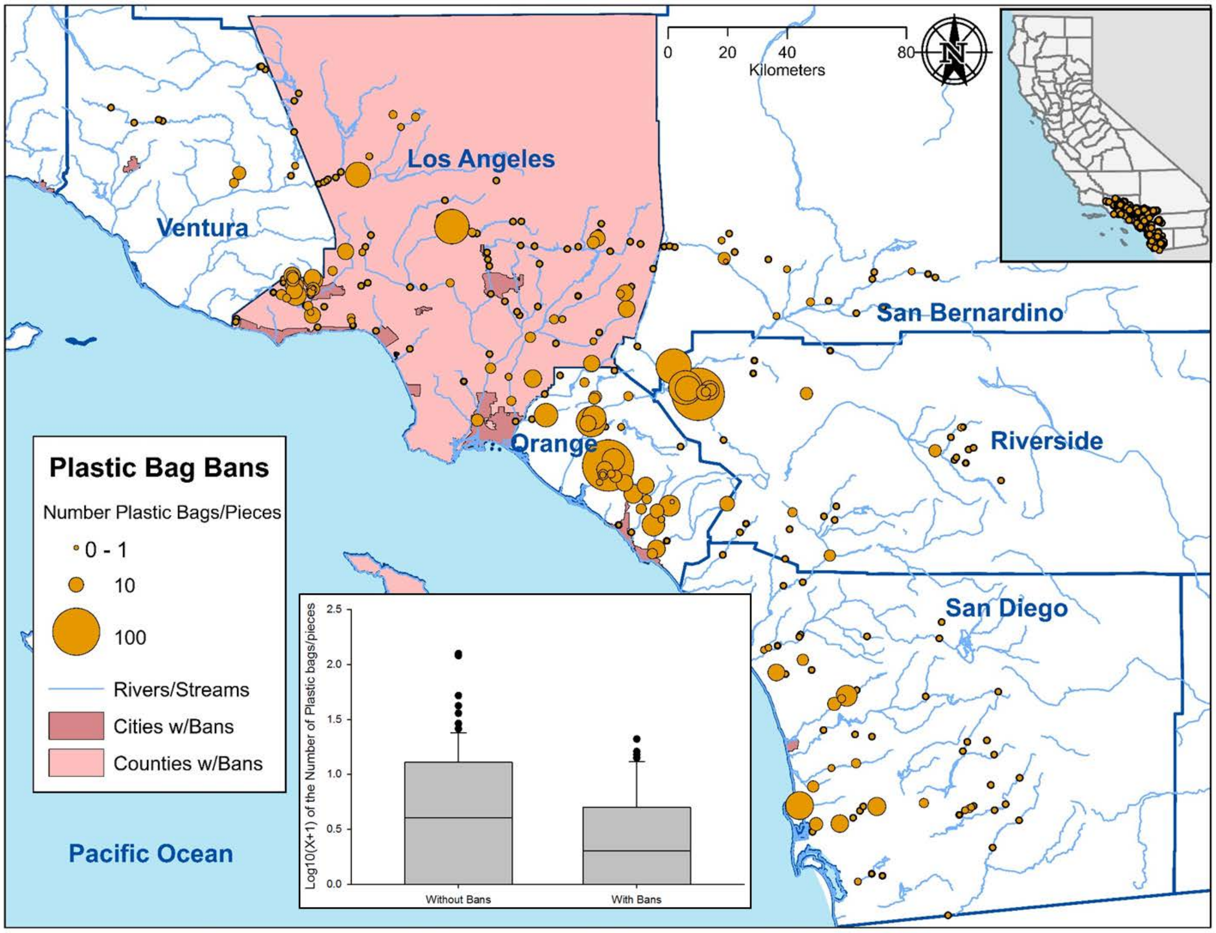

Figure 7: Map of areas with and without plastic bag bans in 2013 and the relative number of plastic bags/plastic bag pieces at each sampling site. Graph reflects log10(x+1) of the median number of plastic bags/plastic bag pieces.

IX. Tables

Table 1: Number of study sample sites by strata.

Stratum	Number of sites
By Land Use Stratum	
Agriculture	15
Open	111
Urban	147
By County Stratum	
Los Angeles	105
Orange	42
Riverside	33
San Bernardino	22
San Diego	55
Ventura	16
All Southern California	273

Table 2: Summary statistics of debris abundance during this survey of southern California streams.

Debris Category	Debris Item*	Number of pieces per site (Area Weighted Mean)	Standard Error	95%CI	Maximum Number of Pieces Found at a Site
Plastic		18.7	2.49	4.88	217
	Plastic wrapper/pieces	5.3	0.85	1.67	70
	Plastic bags/pieces	3.7	0.53	1.04	124
	Plastic misc pieces (soft/hard)	3.4	0.88	1.73	56
	Styrofoam pieces	3.1	0.94	1.85	77
	Plastic Bottles	1.1	0.21	0.41	39
Biodegradable		2.1	0.37	0.73	46
	Paper/cardboard	1.8	0.35	0.68	46
Glass		1.9	0.56	1.09	119
	Glass pieces	1.6	0.55	1.08	119
	Glass Bottles	0.3	0.07	0.13	25
Toxic		1.8	0.37	0.72	29
	Cigarette Butts	1.6	0.35	0.69	27
Miscellaneous		2.5	1.05	2.05	390
	Sports balls	1.4	1.00	1.95	388
Construction		1.9	0.88	1.73	80
	Concrete/Asphalt debris	1.2	0.85	1.67	77
Metal		1.5	0.18	0.36	33
Fabric and Cloth		0.7	0.12	0.24	58
Biohazard		0.1	0.04	0.08	5
Large		0.1	0.02	0.04	9
Any Anthropogenic Debris		**31.3**	**3.81**	**7.47**	**516**

*Not all debris items are listed under each category. For larger categories only debris items with values above 1 are listed.

Table 3: Top 10 items making up 75% of the total debris in the Southern California Regional Stream Survey.

Rank	Debris Item	% Total	% Cumulative
1	Plastic wrappers	14.8	14.8
2	Plastic bags	14.1	28.9
3	Persistent plastic pieces (soft/hard)	9.0	37.9
4	Styrofoam pieces	8.8	46.6
5	Glass pieces	6.7	53.3
6	Sports balls	6.1	59.4
7	Cigarette Butts	5.3	64.7
8	Paper and cardboard	5.2	69.8
9	Plastic Bottles	3.7	73.5
10	Concrete/Asphalt debris	2.1	75.7

X. Supplemental Information

Trash Assessment Tally Sheet

STATION ID: ____________ INITIALS: ____________ DATE: ____________

PLASTIC	Right Bank	Left Bank
Bags (single use plastic)		
Bags (takeout or other)		
Wrapper/pieces		
Bottles		
Container Caps/pieces		
Cups/plates		
Lid / Straw		
Plastic straw wrapper		
Pipe (PVC…)		
Styrofoam pieces		
Styrofoam containers		
Styrofoam pellets		
Soft plastic pieces		
Hard plastic pieces		
6-pack rings		
Foam balls		
Tarp		
Other:		

BIOHAZARD	Right Bank	Left Bank
Human Waste/Diapers		
Medical/Personal Hygiene		
Pet Waste		
Syringes or Pipettes		
Dead Domestic Animals		
Other:		

CONSTRUCTION	Right Bank	Left Bank
Concrete/Asphalt debris		
Rebar		
Bricks		
Wood Debris		
Other:		

MISCELLANEOUS	Right Bank	Left Bank
Rubber pieces		
Ribbon		
Balloons		
Ceramic pots/shards		
Hose Pieces		
Waxed Paper Cups / Plates		
Sports balls		
CDs / DVDs		
Other:		

METAL	Right Bank	Left Bank
Aluminum Foil		
Steel Cans		
Aluminum Cans		
Bottle Caps		
Metal Pipe/Bar Segments		
Auto Parts		
Nails, screws, bolts, etc.		
Wire (barb, chicken, etc.)		
Metal Object		
Other:		

LARGE	Right Bank	Left Bank
Appliances		
Furniture		
Garbage Bags of Trash		
Computers		
Televisions		
Tires		
Shopping Carts		
Other:		

TOXIC	Right Bank	Left Bank
Chemical Containers		
Pens or Markers		
Cigarette Butts		
Spray Paint Cans		
Lighters		
Small Batteries		
Vehicle Batteries		
E-waste		
Other:		

BIODEGRADABLE	Right Bank	Left Bank
Paper/cardboard		
Food Waste		
Yard Waste/Leaf piles		
Other:		

GLASS	Right Bank	Left Bank
Bottles		
Pieces		

FABRIC AND CLOTH	Right Bank	Left Bank
Synthetic		
Natural (cotton, wool)		
Other:		

	Right Bank	Left Bank		Right Bank	Left Bank
TOTAL ITEMS:			TOTAL ITEMS:		
			GRAND TOTAL:		

Note: Right and Left Bank are defined by looking downstream, Right and Left Bank extend from Bank Full Width to Thalweg,

Southern California Bight Regional Monitoring Program *July 2013*

CHAPTER THREE: EPIBENTHIC MARINE DEBRIS IN THE SOUTHERN CALIFORNIA BIGHT

I. Abstract

Anthropogenic marine debris has become a global problem due to impacts on aesthetics and aquatic life through entanglement and ingestion. To date, most studies have focused on debris stranded on beaches or floating in the open ocean, and most have been short-term studies that do not assess trends over time. Few studies have examined long-term trends of epibenthic debris found on the nearshore seabed. The goals of this study were to: (1) assess the extent and magnitude of epibenthic debris (>1.3 cm) in the Southern California Bight (SCB) by debris type and by habitat; and (2) characterize the trends in epibenthic debris from 1994 to 2013. Using a probabilistic study design that stratified sampling on depth and marine habitat, 164 epibenthic trawl samples were collected in the SCB. Approximately 32% of epibenthic area in SCB contained anthropogenic debris. Debris items were typically found in low abundances at any single site and its extent generally increased with depth and in MPAs. Plastic, particularly high-density polyethylene (HDPE), had the greatest extent and magnitude of any debris type in the SCB. Surveys conducted during the nearly 20 years of the Bight program from 1994 to 2013 show that the extent of anthropogenic debris has increased from 14% to 23% in sampled habitats on the continental shelf of the SCB and plastic has consistently remained the most frequently encountered debris type.

II. Introduction

Marine debris has become a global concern in recent years, impacting aesthetics and aquatic life not only in populated coastal areas but also the most remote parts of the world's oceans (NRC, 2009; Moore, *et al.* 2001). Marine debris has been problematic in many different habitats, including estuaries, bays, shorelines, and open ocean waters at the surface, water column and benthos. Sources of marine debris can be either ocean- or land-based, often through illegal dumping, accidental loss, or natural disasters (EPA 2008, Sheavly 2007). Marine debris can effect local economies through loss of revenue from decreased tourism (Leggett *et al.* 2014), and it can harm marine organisms through ingestion and entanglement (Balaz 1985, Wallace 1985, Ryan *et al.*, 1990, Moser and Lee 1992, Robards 1993, Eriksson and Burton 2003, Phillips *et al.*, 2007, Boerger *et al.*, 2010, Waluda and Staniland, 2013; Adimey *et al.*, 2014; Anderson and Alford, 2014, Goldstein and Goodwin, 2013; Lusher *et al.*, 2013; Anastasopoulou *et al.*, 2013; Bond *et al.*, 2013; Di Beneditto and Ramos, 2014). An estimated 693 species have had detrimental encounters with marine debris in some form and an estimated 92% of these encounters were with plastic debris (Gall and Thompson, 2015).

Most coastal studies quantifying marine debris have been localized, short-term surveys focused primarily on beach debris (Gabrielides *et al.*, 1991; Moore *et al.*, 2001; Ribic *et al*,. 1992;) and floating debris (Aliani et al., 2003; Barnes, 2002; Barnes and Milner, 2005; Day and Shaw, 1987; Lecke-Mitchel and Mullin, 1992; Thiel and Haye, 2006). Few coastal studies have focused on epibenthic habitats of the continental shelf (Galgani *et al.*, 1995, 2000; Keller *et al.*, 2010; Moore and Allen, 2000; Stefatos et al., 1999; Watters *et al.*, 2010), and none have been regional in scale nor conducted over extended temporal periods. This lack of regional assessment becomes especially problematic as environmental managers attempt to regulate the amounts of debris entering marine environments (i.e., CRWQCB 2007). Assessing the effectiveness of regulation requires information about the extent and magnitude of marine debris in a variety of habitats, collected over sufficient time periods to determine trends.

Since 1994, trawl surveys of marine debris have been conducted approximately every five years as part of the Southern California Bight (SCB) Regional Marine Monitoring Program (Allen *et al.*, 1998, 2002, 2007, 2011). These surveys are an integrated, collaborative effort by both regulatory and regulated agencies to assess environmental conditions on a region-wide scale (Schiff et al in press). Scientific trawls for environmental monitoring typically examine demersal fish and benthic invertebrate assemblages, but this monitoring program has also documented epibenthic marine debris caught in each trawl sample.

Based on the SCB regional monitoring, the objectives of this study were to: (1) assess the extent and magnitude of epibenthic debris (>1.3 cm) in the Southern California Bight (SCB) by debris type and by habitat; and (2) characterize the trends in debris over the period of 1994 and 2013.

III. Methods

The SCB represents an area of 6003 km^2 extending from Point Conception, California, to the United States-Mexico International Border, and has bottom depths ranging from 10 to 500 m (Figure 1, Table 1). Regional trawl surveys of the SCB used a stratified random sampling design as detailed in Stevens (1997). For the 2013 survey, seafloor debris was sampled July through September at 164 trawl stations in bays and mainland continental shelf of the SCB (Bight'13 Coastal Ecology Committee 2013). Sites were selected using a generalized random tessellation stratified (GRTS) procedure, to ensure spatial balance among sampled sites and unbiased inference for regional condition. The sample frame included six specific habitats of interest as strata, with a target of 30 sites from each. The six strata were: Bays (5-30 m); Inner Shelf (5-30 m); Middle Shelf (31-120 m); Outer Shelf (121-200 m); Upper Slope (201-500 m); and Marine Protected Areas (MPAs). The continental shelf zones are bathymetric life zone divisions of the continental shelf and slope along the west coast of North America (Allen and Smith 1988, Allen

2006). MPAs comprise a new habitat of interest recently promulgated by the State of California as harvest refugia in an effort to rebuild commercial fish populations and protect ecosystem function (CDFG 2008).

Trawl methods are described in detail in the Bight ‘13 Field Operations Manual (2013). Trawls were conducted using a semi-balloon otter trawl with a 7.6 m (25 ft) headrope, 8.8 m (29 ft) footrope, 3.8 cm (1.5 in) body mesh, and 1.3 cm (0.5 in) cod-end mesh. Trawls were towed along isobaths at a speed-over-ground of 1.0 m/sec (or 1.5 to 2.0 kn) for 10 minutes. Trawl debris was sorted and quantified by recording the specific types of material and the number of pieces of each type. Types of debris included the broad categories of plastic, glass bottles, cans, metal debris, lumber, and other (fishing gear, tires, cloth, tape, paper, fiberglass, clinkers (bricks) and caulk). Only debris larger than 1.3 cm was collected and sorted.

After all of the trawl-caught debris had been categorized and counted, a piece (about the size of a quarter) of each plastic debris item was bagged and sent to the laboratory for analysis of plastic type, using the method developed by A. Andrady (pers. comm; supplemental information). This method entails dropping the plastic into fresh water, determining if it floats, and then treating it with a series of solvents, including Acetone, Isopropanol or Glycerol. Type of plastic was determined by whether or not the piece floated, sank or dissolved in each one of these media of different density. The plastic types identified using this method included: PET (polyethylene terephthalate), HDPE (high-density polyethylene), LDPE (low-density polyethylene), PS (polystyrene), PP (polypropylene), PVC (polyvinyl chloride), PU (polyurethane), and Nylon (polyamide).

Data analysis focused on determining spatial extent (percentage of area) and magnitude (abundance) of debris in the SCB. Spatial extent was calculated using a ratio estimator (Thompson, 1992; Stevens, 1997; Allen *et al*., 1998). Debris data were expressed as counts per standard 10-min trawl haul (Allen *et al*., 1998). The spatial coverage of a debris type in a stratum was defined as the occurrence of a debris type in a standard trawl haul collected at stations representing a given percent of the total stratum (e.g. depth or location) area.

For analysis of trends, trawl surveys conducted in 1994, 1998, 2003, 2008, and 2013 were used. For comparability among years, the extent and magnitude of debris was based on the three strata sampled in all years (Inner Shelf, Middle Shelf, and Outer Shelf). The number of samples for each year ranged from 113 in 1994 to 314 in 1998. Sampling methods for all trawl surveys were the same throughout each of the years evaluated.

IV. Results

Anthropogenic (man-made) debris was found in 32% of the SCB area (Figure 2). Not all habitats had the same extent of debris; however, the greatest extent of anthropogenic debris occurred in Marine Protected Areas (43% of area) followed closely by the Upper Slope of the mainland continental shelf (41% of area). The Bay stratum had the smallest extent of anthropogenic debris (13% of area).

Anthropogenic debris consisted of plastic, cans, glass bottles, metal, lumber, and other debris (Figure 3). Plastic had the greatest extent (23% of the SCB). The “other” category had the second greatest extent (10% of SCB area) and included items such as cloth, tape, paper fiberglass, clinkers, and caulk. Lumber debris had the smallest extent (2% of SCB area).

In general, the abundance of debris was low (Table 2). In the vast majority of the SCB area where debris was found, debris abundance numbered one item per trawl. Plastic debris was the most abundant. The maximum number of plastic debris items found at any single site was 68. Plastic was found throughout the SCB, with the exception of San Diego Bay (Figure 4).

High-density polyethylene (HDPE) had the greatest extent and magnitude of the plastic items (Table 3). HDPE occurred in 20% of the SCB and comprised over half of the 161 plastic items sampled. Nylon had the second greatest extent and magnitude; it occurred in 13% of the SCB and comprised one-fifth of the plastic items sampled. PP, PET PS, PVC, and PU were far less abundant.

The extent of anthropogenic debris in the SCB epibenthos has increased over the last 20 years (Figure 5). Between 1994 and 2013, there has been a nearly monotonic increase in the percent of area with anthropogenic debris from 14% to 23% (continental shelf only; exception in 2003). Likewise, plastic has increased in extent from 6% to 18% of the area, an increase of 3-fold. It is important to note that this increase is not associated with changes in sampling frequency, techniques or measurement as these were held consistent throughout all surveys.

V. Discussion

In 2013, anthropogenic debris was found in the epibenthos of about one-third of the SCB. It occurred in relatively low abundance at depths between 10 and 500 m, and its extent generally increased with depth. Accumulation of debris at depth is common in areas where there are strong bottom currents or intense storm activity, as debris may be pushed farther out on the continental shelf, accumulate around rocky ledges and outcrops, or be deposited in offshore canyons or other depressions (e.g., Galgani *et al*., 1996, Bauer *et al*., 2008, Wei *et al*., 2012, Schlining *et al*., 2013). In the SCB, down-shelf movement is likely because this same phenomenon occurs with naturally-occurring terrestrial (i.e., branches and leaves) and nearshore kelp debris (Moore and Allen 2000, Allen *et al*. 2011).

Of the debris types in this study, plastic was the most abundant and widespread. This finding is consistent with a multitude of anthropogenic debris surveys from other marine habitats around the world, including beaches, surface of the ocean, and the water column (see Derraik 2002 for a review). Polyethylene is the most abundant type of plastic produced in the world (Piringer and Baner 2008). One type of polyethylene, HDPE or high-density polyethylene, was found in both the greatest extent and magnitude of any plastic type in the SCB. HDPE, the sturdiest and most inflexible type of plastic, is commonly used to make containers as it can withstand large temperature ranges (Bal *et al.* 2007).

One of the primary sources of anthropogenic debris to the SCB marine environment is land-based inputs. Large quantities of anthropogenic debris are known to occur in coastal watersheds of the SCB, extending over 90% of the stream miles in near-coastal urban areas (Von Bitner *et al*. in prep). Also, large quantities of anthropogenic debris are discharged during the intense, but infrequent storm events that occur in the SCB. Moore *et al*. (2011) measured as many as 10^9 items cumulatively weighing over 10^3 metric tons being discharged during a single storm event from the Los Angeles urban area alone. Like the findings in the current study, the most frequently occurring and most abundant debris type in the SCB's coastal watersheds was plastic.

The large extent of anthropogenic debris observed in MPAs relative to other strata in the SCB may be the result of additional ocean-based discharges. MPAs were recently promulgated in the SCB, first receiving protection in 2012. Prior to MPA promulgation, these locations received tremendous fishing pressure, up to 7,000 vessels per year (Santa Barbara County Air Pollution Control District 2006). We assume that this intensive use resulted in an accumulation of overboard discharges. Only future debris monitoring in MPAs will help reveal if the diminished vessel activity intended to reduce fishing pressure also results in reduced debris extent and magnitude.

Not only does anthropogenic debris extend across a large area of the SCB, but this potential environmental threat has generally worsened over the last two decades. The estimate of debris extent has increased on the continental shelf between 1994 and 2013 and this estimate does not include two strata with the greatest extent of debris measured in 2013 (Upper Slope and MPAs). One unexplained exception is 2003, which had an extent of almost 27% (Figure 5). Recently, regulatory actions have been taken to stem the tide of land-based debris, including a number of plastic bag bans in coastal cities and a total maximum daily load for trash in the Los Angeles area (CRWQCB 2007). Once again, only future monitoring will reveal if these management actions will reverse the debris trends observed.

While the trawl surveys showed that anthropogenic debris extended across 32% of the SCB epibenthos in 2013, and that the debris extent has grown worse with time, trawl surveys likely underestimate the true extent and magnitude of debris for several reasons. First, the mesh size of the net (1.3 cm) limits the trawl-collected debris to only larger items. Smaller debris likely passes through the net or is pushed out of the way during sampling. This is problematic because smaller items are more numerous than larger items in most debris surveys (Ryan *et al*. 2009). Second, trawling is limited to the smoother, flatter, more easily sampled areas of the seafloor, and these are not the typical debris accumulation areas (Galgani *et al*., 1995a). Third, when conducting trawl sampling, variability in the vessel, crew, depth sampled, and weather can affect capture efficiency (Ribic *et al*., 1992). Despite these recognized limitations in methodology, trawl surveys provide at least a minimum estimate of debris extent and abundance and, because net types and trawl methodology remained constant between 1994 and 2013, one can have confidence in identified trends.

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VII. Figures

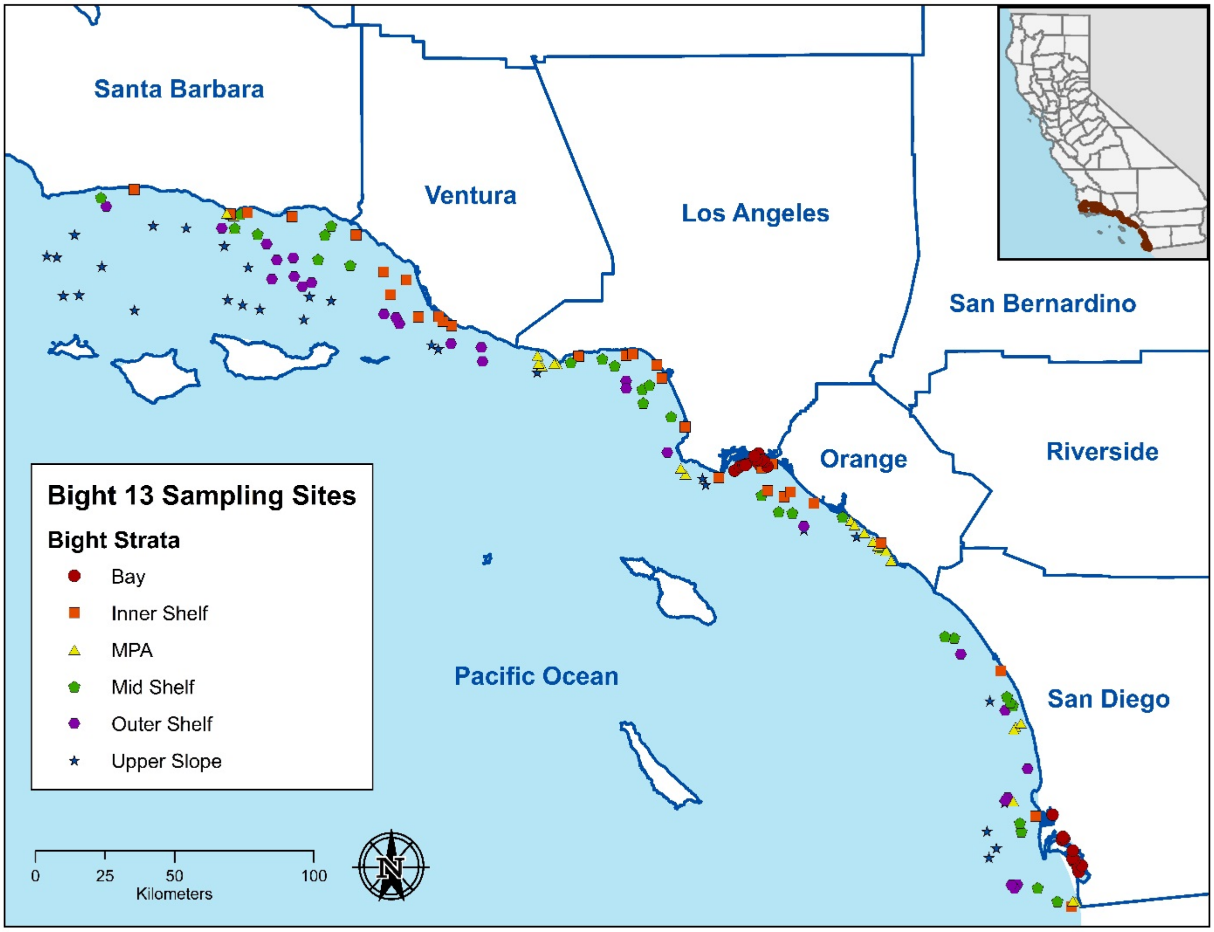


Figure 1: Stations sampled by trawl in the Southern California Bight at depths of 10-500 m, July-September 2013. Different symbols represent the strata used in this study.

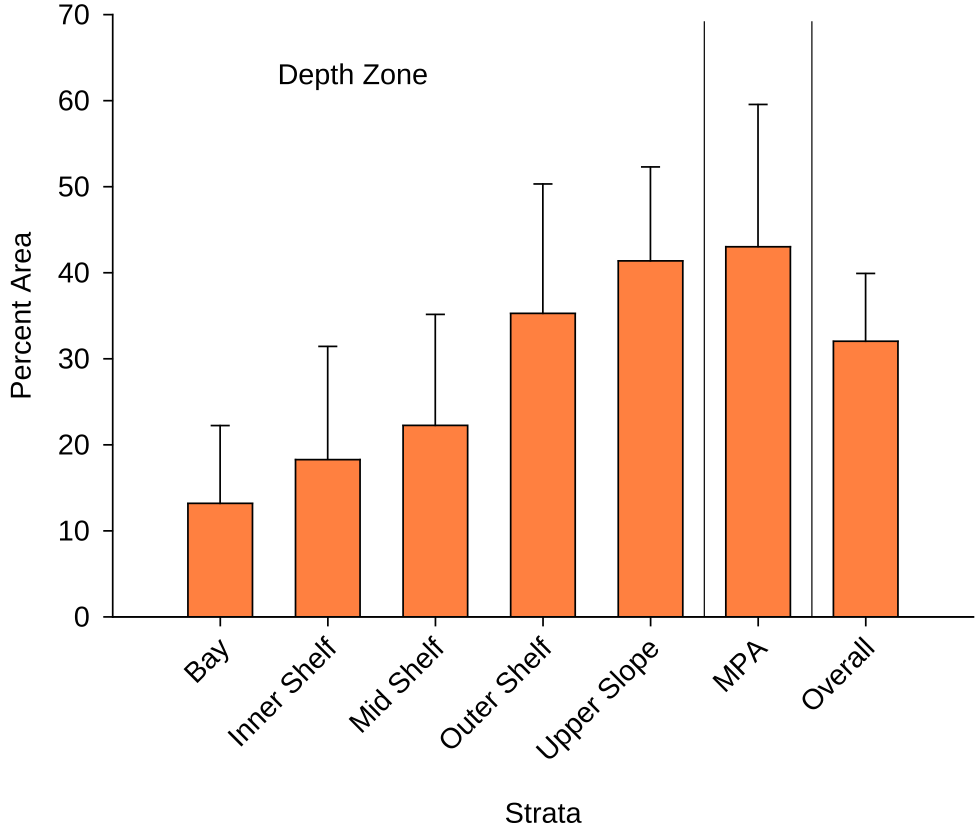


Figure 2: Extent of anthropogenic debris (% of area) in 2013 in the Southern California Bight by stratum and overall.

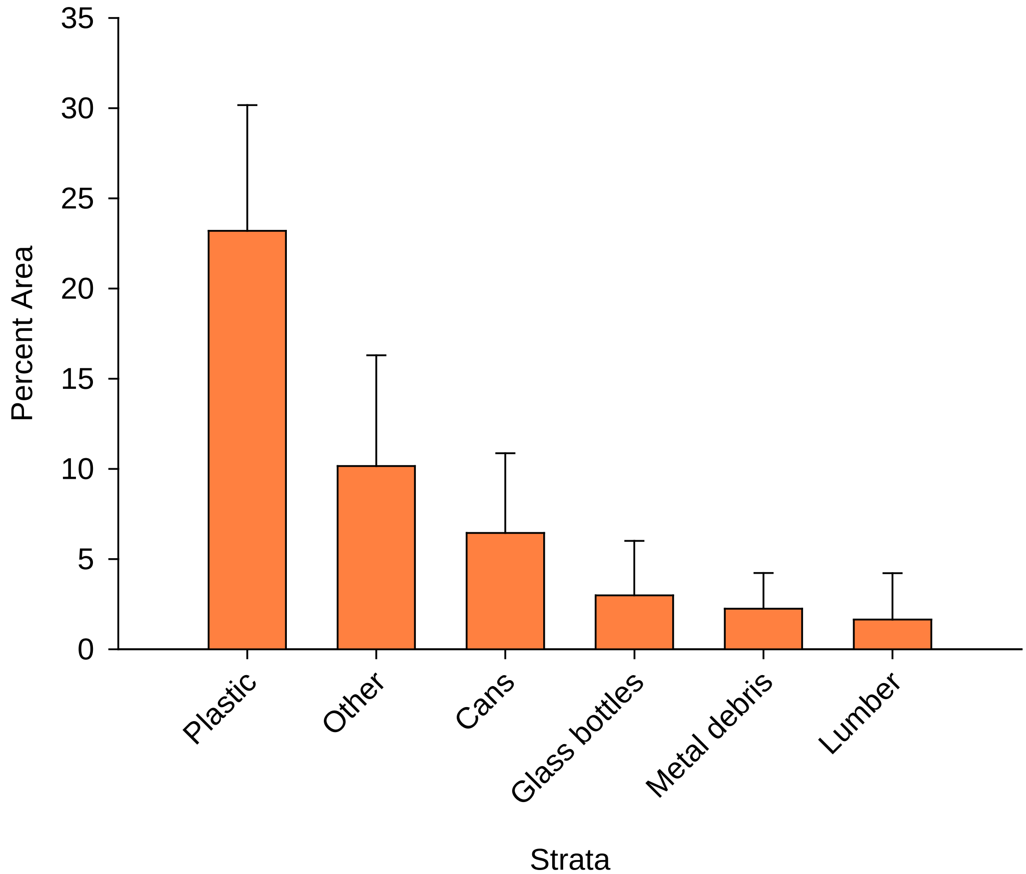


Figure 3: Extent of anthropogenic debris (% of area) in 2013 in the Southern California Bight by debris type.

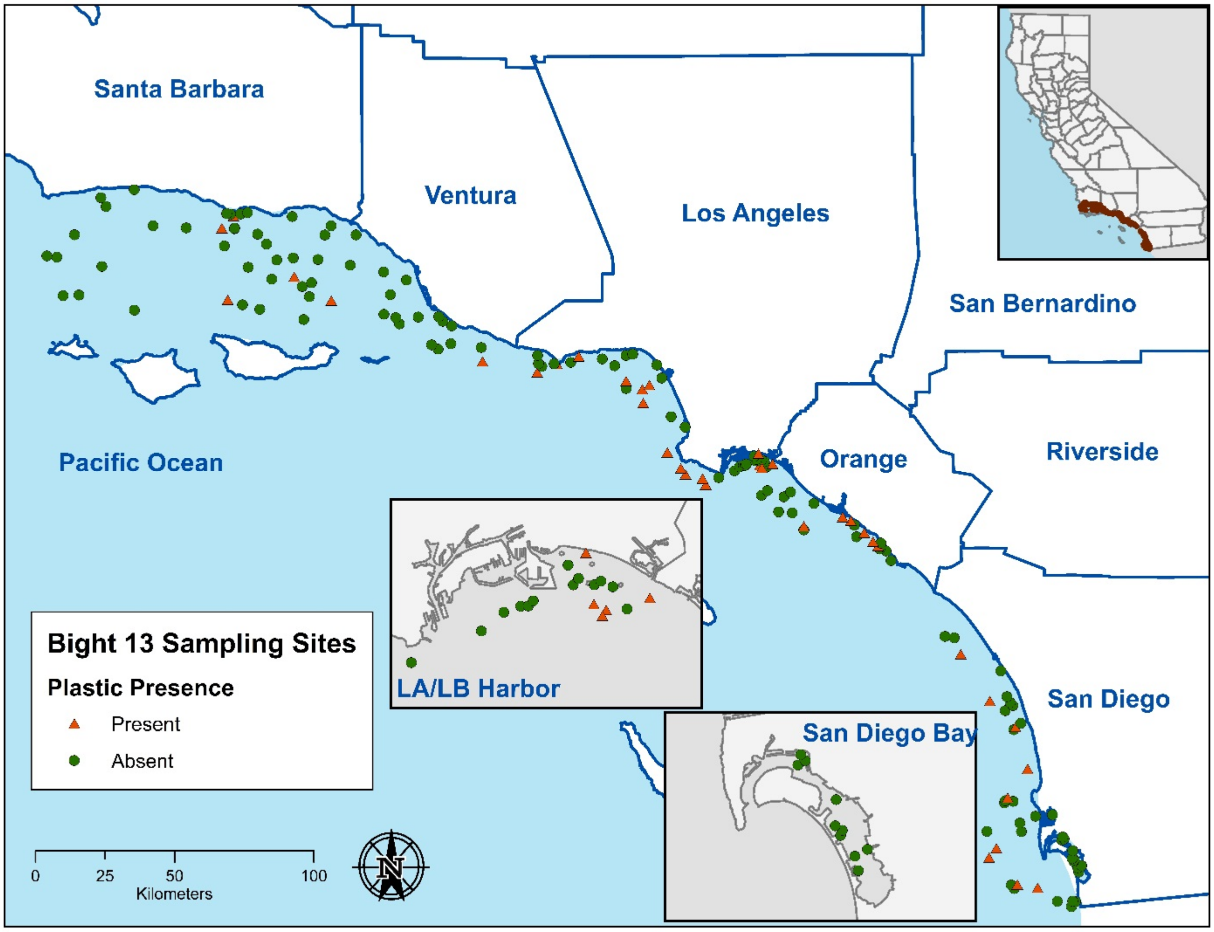


Figure 4: Plastic debris presence-absence in the Southern California Bight in 2013.

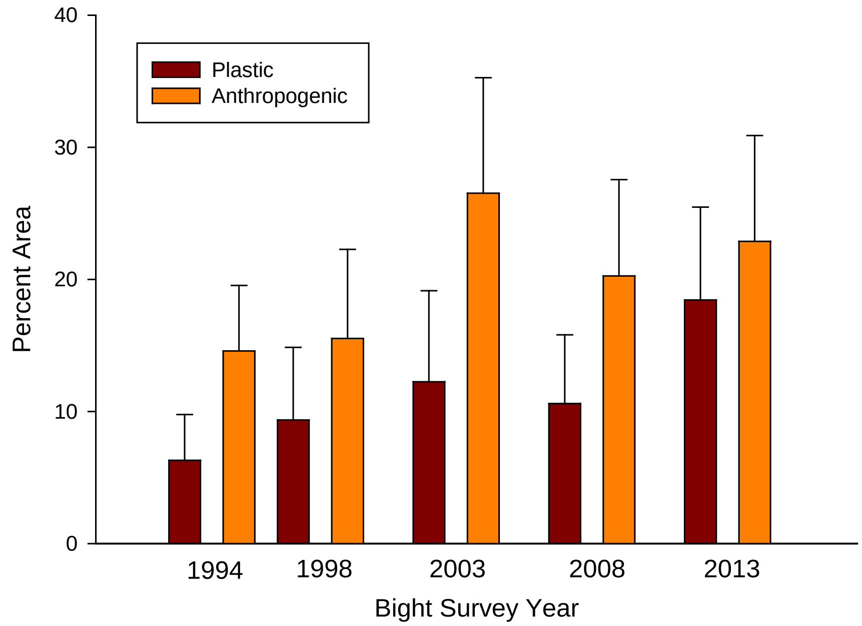


Figure 5: Trends in overall and plastic marine debris on the ocean bottom over all Bight surveys in the Southern California Bight from 1994 through 2013. Graph reflects only strata in common between all 5 surveys (inner, middle and outer shelf).

VIII. Tables

Table 1: Number of sites sampled in the Southern California Bight by stratum in 2013.

Statum	Stratum Area	Number of Sites Sampled
Bay	67	26
Inner Shelf	975	29
Mid Shelf	1528	29
Outer Shelf	438	27
Upper Slope	2857	29
MPA	137	24
Entire SCB	6003	164

Table 2: Percent of area by debris type and abundance bin in the Southern California Bight in 2013.

	No. of	Percent Area by Abundance Bin			
Debris Type	Stations	1 item	2-10 items	11-100 items	>100 items
Plastic	35	22.4	1.7	0.6	-
Other	11	10.1	1.7	0.1	-
Lumber	1	1.6	-	-	-
Metal Debris	5	2.2	-	-	-
Glass Bottles	4	3.0	-	-	-
Cans	8	3.9	2.5	-	-
TOTAL	49	29.6	5.2	0.7	-

Table 3: Occurrence of plastic by type and count in the Southern California Bight in 2013.

PlasticType*	No. of Stations	Cumulative No. of Items	Percent Area
HDPE	29	86	19.7
Nylon	18	35	12.9
PP	6	7	6.7
PET (or PC)	8	13	6.0
PS	8	9	2.6
Combo	4	8	2.1
PVC	2	2	1.7
PU	1	1	0.3
Any Plastic	76	161	23.2

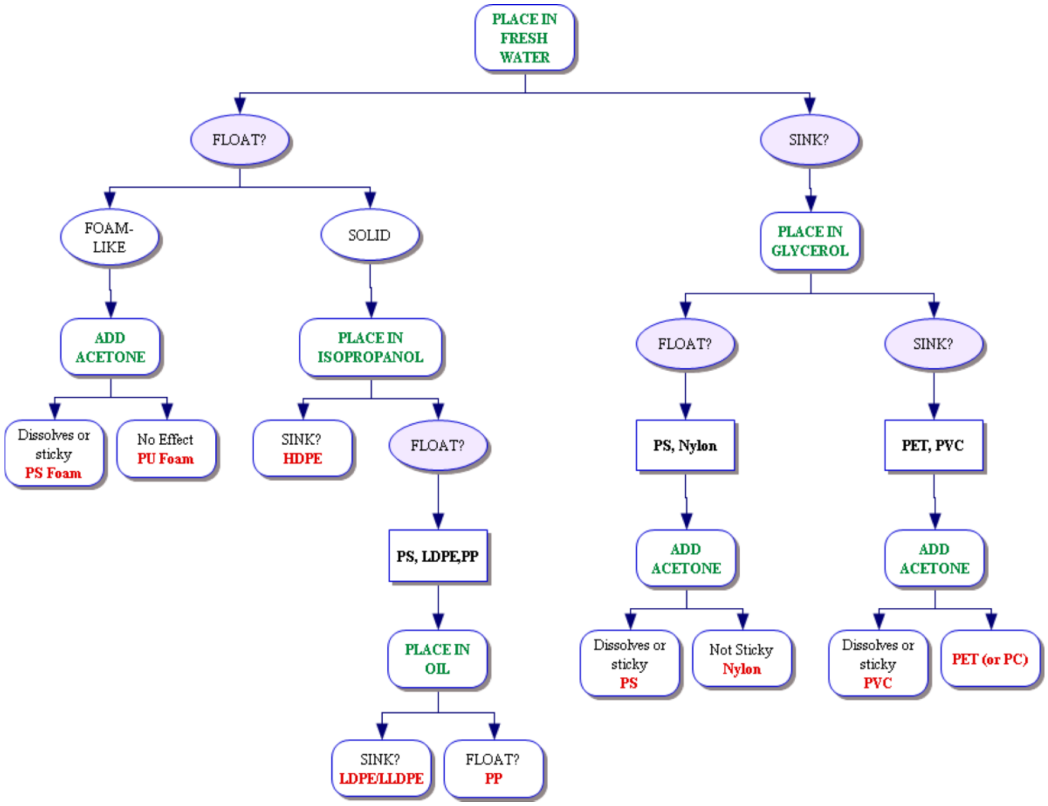
*HDPE (high-density polyethylene), PP (polypropylene),

PET (polyethylene terephthalate), PS (polystyrene),

PVC (polyvinyl chloride), PU (polyurethane),

Combo (any combination of the others)

IX. Supplemental Information



Supplemental Information 1. Flow chart showing the process for testing plastic for polymer type.

CHAPTER FOUR: BENTHIC MICRO-PLASTIC DEBRIS IN THE SOUTHERN CALIFORNIA BIGHT

I. Abstract

Plastic is one of the most common types of marine debris. While larger and more visible plastic debris has typically been a major concern in the ocean, virtually no data exists about the types, amounts and distribution of micro-plastic (< 5 mm) debris in subtidal, near-coastal benthic environments. The goals of this study were two-fold: (1) assess the extent and magnitude of benthic micro-plastic among different habitats in the Southern California Bight (SCB); and (2) characterize the polymer types and shapes of benthic micro-plastic debris in the SCB. Based on a probabilistic study design, 358 sediment samples were collected across 12 different habitat strata in the SCB. Benthic micro-plastic debris were found in 38% of the SCB sediments. Embayments were the strata with the greatest relative extent and abundance, specifically Ports (88% of area, mean of 63 pieces/0.1m^2), Marinas (79% of area, mean of 34 pieces/0.1m^2), Bays (71% of area, mean of 14 pieces/0.1m^2), and Estuaries (39% of area, mean of 14 pieces/0.1m^2) habitats. Continental shelf habitats had the lowest extent and abundance of benthic micro-plastic (25% of area, $\leq$2 pieces/m^2). Nylon and high-density polyethylene (HDPE) were the most common polymer types. The most common shapes of the benthic micro-plastics were fragments, line and film. This study provides important baseline information on debris of a size that is currently not monitored or regulated in California.

II. Introduction

The focus of plastic marine debris has traditionally been on larger, more visible debris affecting aesthetics, which leads to decreased visitation (Leggett *et al.* 2014) or poses a threat to wildlife through entanglement and ingestion (Anastasopoulou *et al*., 2013; Bond *et al*., 2013; Di Beneditto and Ramos, 2014). In recent years, however, smaller plastic debris has come to the forefront because it can be present in the environment in large amounts (Moore *et al.* 2001; Eriksen *et al*., 2014) and can concentrate persistent organic pollutants (POPs) via adsorption (Rios *et al*., 2007; Farrington and Takada, 2014). Others have shown that small plastics with sorbed POPs can be ingested and bioaccumulated in fish and invertebrates who eat these small plastic pieces (Boerger *et al.* 2010; Teuten *et al*., 2009). Ultimately, biomagnification of POPs may pose an additional threat to predators at higher levels of the food chain (Eriksson and Burton, 2003; Phillips *et al*., 2001; Oizumi *et al*., 2001; and Perrin, 1975). In addition, organisms that eat these small plastic particles risk incurring feelings of satiety with no nutritional value (Donnelly-Greenan *et al*., 2014).

State and federal regulators have recently promulgated policies to limit the amount of debris in southern California streams, in part to protect coastal environments downstream (CRWQCBLA 2015). These regulations, termed Total Maximum Daily Loads (TMDLs) are limited to debris sizes of >5 mm. While some studies have examined debris >5mm in southern California (Allen *et al*., 1998, 2002, 2007, 2011), few have examined micro (<5mm) debris. The studies that have focused on debris <5mm have focused almost exclusively in the water column (Moore *et al*., 2002 and Lattin *et al*., 2004).

Since 1994, benthic surveys have been conducted approximately every five years as part of the Southern California Bight (SCB) Regional Marine Monitoring Program (Allen *et al*., 1998, 2002, 2007, 2011). These surveys are an integrated, collaborative effort by both regulatory and regulated agencies to assess environmental conditions on a region-wide scale (Schiff *et al.* in press). Benthic sediment grabs for environmental monitoring are conducted to look at sediment chemistry, sediment toxicity, and infaunal communities. While marine debris has typically been part of the Bight epibenthic surveys (i.e., from trawls), debris in benthic sediment grabs has previously not been a focus. Here we report the results of the first regional survey of benthic micro-plastic debris in the Southern California Bight (SCB). The objectives of this study were to: (1) assess the extent and magnitude of benthic micro-plastic among different habitat strata in the SCB; and (2) characterize the polymer types and shapes of benthic micro-plastic debris in the SCB.

III. Methods

The SCB represents an area of 16,049 km^2 extending from Point Conception, California, to the United States-Mexico International Border, and bottom depths up to 1000 m (Figure 1, Table 1). Benthic grab surveys of the SCB utilize a probability-based study design to generate unbiased estimates of extent and magnitude (Stevens 1997; Allen *et al*., 1998, 2002, 2007, 2011). For the 2013 survey, benthic debris was sampled July through October at 358 stations in both embayment and offshore areas of the SCB (Bight 13 Contaminant Impact Assessment Workplan 2013). Sites were selected using a generalized random tessellation stratified (GRTS) procedure to ensure spatial balance among and within specific habitats of interest. The strata included: Estuaries; Bays (5-30 m); Marinas; Ports; Inner Shelf (5-30 m); Middle Shelf (31-120 m); Outer Shelf (121-200 m); Upper Slope (201-500 m); Lower Slope (501-1000m), Submarine Canyons; Channel Islands, and Marine Protected Areas (MPAs). The continental shelf zones are bathymetric life zone divisions of the continental shelf and slope along the west coast of North America (Allen and Smith 1988, Allen 2006). The MPAs are harvest refugia, recently promulgated by the State of California, in an effort to rebuild commercial fish populations and protect ecosystem function (CDFG 2008).

Sediment grab methods are described in detail elsewhere (Southern California Bight 2013 Regional Marine Monitoring Survey Contaminant Impact Assessment Field Operations Manual 2013). Briefly, 0.1 m^2 modified Van Veen grabs were used to collect sediment samples intended for physical, chemical, and infaunal analyses (Stubbs *et al.* 1987). The grab used for infaunal analysis was also used for micro-plastic analysis. Grab acceptance criteria included sample condition (surface disturbance, leakage, canting and washing) and depth of penetration ($\geq$5 cm). Sediment samples are washed through a 1.0 mm screen on board the vessel and all material retained on the screen was placed in a jar with 10% buffered formalin for transport to the taxonomic laboratory. At the laboratory, benthic samples were sorted under a dissecting microscope, separating organisms, plastic, and remaining debris into different containers.

Benthic plastic debris was categorized by size class (smallest size measured 1.00mm), shape type, and polymer type. Size classes were split into two: 1.00-4.75mm and >4.75mm. Shape types included Fragment, Line, Film, Pellets, Combo (more than one type of material molded together), Film and Whole Objects (e.g. plastic bottle caps, utensils, etc.). Polymer types included Nylon (polyamide), HDPE (high-density polyethylene), PET (polyethylene terephthalate), PS (polystyrene), PVC (polyvinyl chloride), PU (polyurethane), PP (polypropylene) and LDPE (low-density polyethylene).

Plastic debris was viewed under a dissecting microscope, cleaned (sediment, fouling organisms and encrusting debris was removed), sorted by size using Tyler™ Sieves and then sorted by shape type. Plastic polymer type was determined by using a dichotomous testing method developed by Anthony Andrady (pers. comm; Supplemental Information 1). This method consists of dropping the plastic into fresh water, determining if it floats, and then treating it either with Acetone, Isopropanol or Glycerol. Polymer type was determined by whether or not the piece floated, sank or dissolved in each of these media of different densities.

Data analysis focused on determining spatial extent (percentage of area) and magnitude (abundance) of benthic plastic debris in the SCB. Spatial extent was calculated using a ratio estimator (Thompson, 1992; Stevens, 1997; Allen *et al*., 1998). Relative extent was then described either by stratum or as the entire SCB. Debris abundance data were expressed as values per standard Van-Veen grab (number pieces/0.1m^2; Allen *et al*., 1998). Significant differences in abundance were evaluated using Kruskal-Wallis One Way Analysis of Variance on Ranks ($p < 0.001$) and pairwise multiple comparison procedures (Dunn's Method).

IV. Results

Thirty-eight percent of the entire SCB contained at least one piece of micro-plastic in benthic sediments (Figure 2). Embayment strata such as Ports, Marinas, and Bays had the greatest relative spatial extent of small micro-plastic debris. Micro-plastic was present in 88% of the Port area and 79% of the Marina area. The Middle and Inner Continental Shelf had the lowest relative extent of plastic presence (25% and 28% of area, respectively).

Mean abundance of benthic micro-plastic debris was greatest in Marina and Port strata, and the lowest abundance was in the Middle Shelf stratum (Figure 3). Mean abundance of benthic micro-plastic debris in the Port and Marina strata was 63 and 34 pieces/0.1m^2, respectively. Mean abundance of benthic micro-plastic debris in the Middle Shelf stratum was $\leq$2 pieces/0.1m^2. The mean abundance in Marinas and Ports was significantly higher when compared to all other strata, and the Middle Shelf had significantly lower mean counts than all other strata ($p=0.05$). Benthic micro-plastic debris in these other strata ranged from 2 - 14 pieces/0.1m^2.

Benthic micro-plastic was dominated by objects between 1–4.75mm (Figure 4). This size range extended across 33% of the SCB. In contrast, benthic micro-plastic objects >4.75mm extended across 19% of the SCB. The extent of benthic micro-plastic debris <1.0mm was not sampled.

Fragments, Line and Film had the greatest spatial extent of any plastic type, regardless of size class (Figure 4). Fragments in the 1.00 - 4.75 mm size class had greatest spatial extent of any plastic type (27% of SCB area), followed by Line and Film (approximately 10% each). Line in the > 5 mm size class had the greatest extent of any plastic type (15% of SCB area), followed by Fragments and Film (10% and 6%, respectively). Pellets and Foam were the only other measureable plastics types, but only in the smaller size class range of 1.00 to 4.75 mm. Whole objects and objects with combined plastic types were among those with extremely low coverage or were completely absent. While the spatial extent of plastic pellets was low (2% of the SCB area), the distribution of pellets was limited to the central part of the Bight and in particular off the Palos Verdes Shelf (Figure 5).

Of the eight different types of plastic polymers investigated during this study, Nylon and HDPE had the greatest spatial extent in the SCB (16% and 15%, respectively). The lowest spatial extent of the polymer type was LDPE (< 1%). In general, the spatial extent of most polymer types was $\leq$ 5% of the SCB area.

V. Discussion

This is the first regional study of its kind investigating the extent and magnitude of micro-plastic debris in nearshore sediments. Benthic micro-plastic debris were widespread in the Southern California Bight, occurring in just over one-third of the region's sediments. While the benthic micro-plastics were found in all strata, not all strata had similar levels of benthic micro-plastics. Embayment strata such as Marinas, Ports, Estuaries and Bays had the greatest extent and magnitude of benthic micro-plastics, while offshore strata such as the Continental Shelf had much lower extent and magnitude. Although sources of marine debris can be either ocean- or land-based, either through illegal dumping, accidental loss, and by natural disasters (EPA 2008, Sheavly 2007), the increased extent and magnitude of benthic micro-plastics in Embayments indicates that land-based sources may predominate in the SCB; however, while it is apparent that there is a linkage between land-based trash and marine debris, the linkage between Bight habitats and land-based sources is poorly understood.

It was not surprising that Nylon and HDPE were the most commonly found polymer type in benthic micro-plastic pieces found in SCB sediments. Both of these plastic types are commonly used in a variety of products. Nylon is frequently used in automobile parts, tires, ropes and synthetic fibers (Kohan 1995). Polyethylene is the most abundant type of plastic produced in the world (Piringer and Baner 2008), and one of the most common types of polyethylene is HDPE. Both of these plastics can withstand large temperature ranges, which makes them ideal to use in a variety of commercial products. (Bal *et al.* 2007). Unfortunately, this also means that Nylon and HDPE are most likely to persist in the environment.

Benthic micro-plastic shape provides some insight into potential sources. The most common of plastic shapes in this study were fragments, lines and films; a finding consistent with the results of other studies (Free *et al*., 2014). There is much variation in the time it takes for plastics to breakdown, and much of this is dependent on the shape, polymer type, and environmental conditions (Andrady 2003). Plastics breakdown more quickly when dry and exposed to sunlight (Andrady *et al*., 1993). Mechanical processes such as wind-blown or stream transport will also enhance degradation. This benthic micro-plastic likely results from the fragmentation and degradation of items including plastic bags, bottles and wrappers, and perhaps fishing gear in the form of line and rope, items that were among the most abundant in epi-benthic trawls (Moore *et al*., in prep.).

The presence of plastic pellets supports that the source of micro-plastic debris in the SCB are predominantly land-based. Plastic pellets are the pre-production material used for manufacturing. In the SCB, these plastic manufacturing facilities are concentrated in the Los Angeles and Orange Counties. While the extent of plastic pellets in the SCB was not large, their occurrence was constrained to the areas directly offshore (and down current of) the watersheds that drain these manufacturing facilities. This is also consistent with the primary locations plastic pellets are found on SCB beaches (SCCWRP, unpublished data). Moreover, runoff from land-based sources in the SCB has been shown to be a source of pellets being transported to the marine environment (Moore *et al.*, 2011).

The information generated by this study will contribute to the baseline information for regulated and regulatory agencies charged with implementing the trash TMDLs in southern California. One challenge facing these environmental managers is their focus on trash larger than 5mm; however, the results of this study indicate that marine debris smaller than 5 mm is important to consider. At this time, it is unclear how much of the micro-plastic pieces that are found in the Bight sediments were transported as pieces < 5 mm versus how much was broken down from larger pieces, once delivered to the seafloor. Reducing macro-plastic, as current policies aim to do, will clearly help address micro-plastic as larger pieces breakdown or fragment. One other consideration is that the biological effects of micro-plastic ingestion is not well studied, but potential effects include hormone disruption, reproductive impairment, immune system impairment, and disease development (Wright *et al.*, 2013). Additionally, this study did not investigate micro-plastics less than 1 mm, but recent attention to microbeads typically used in the production of human bath products (i.e., scrubs, toothpaste, etc.) could pose an even greater threat to smaller organisms (Browne *et al.*, 2011).

VI. References

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VII. Figures

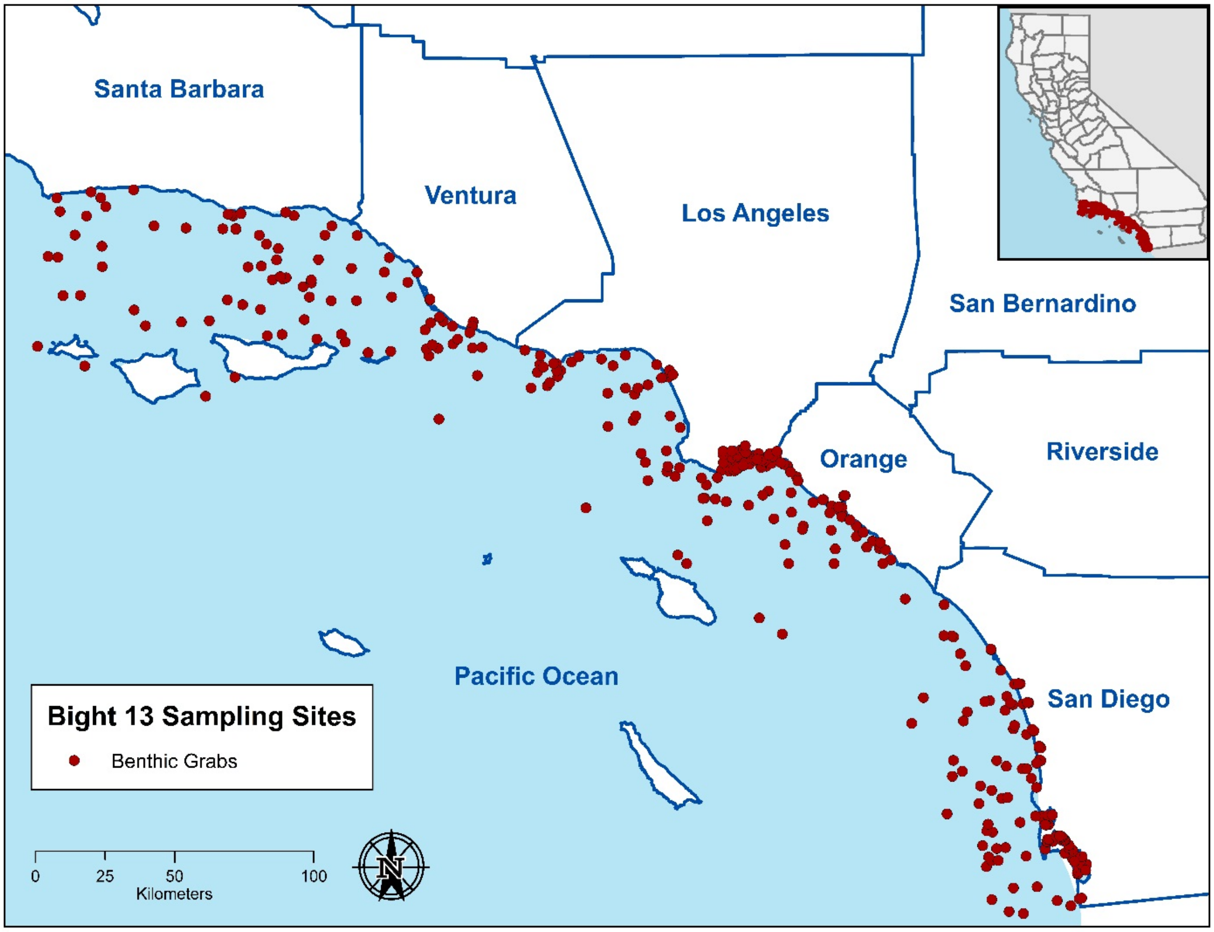


Figure 1: Stations sampled by benthic grab in the Southern California Bight at depths of 10-1000 m, July-October 2013.

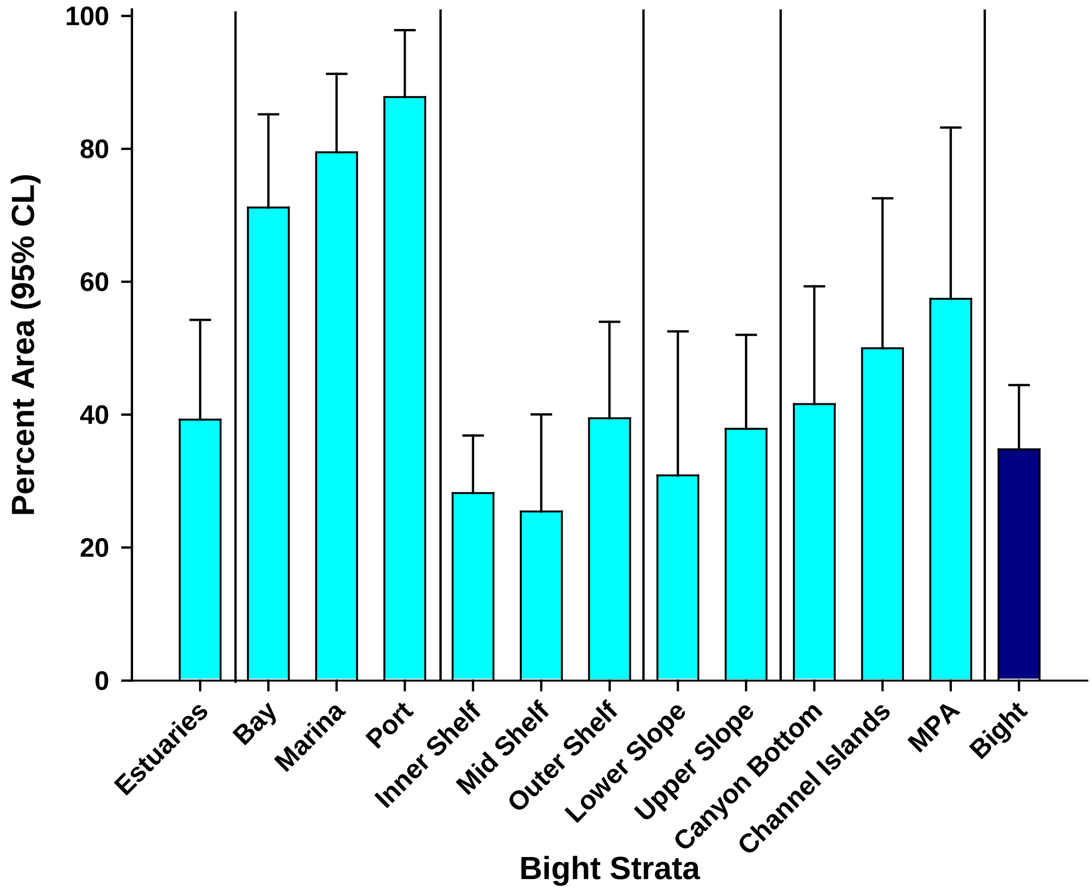


Figure 2: Extent of benthic plastic debris occurrence (% of area ±95% Confidence Intervals) in 2013 for the entire Southern California Bight and by stratum.

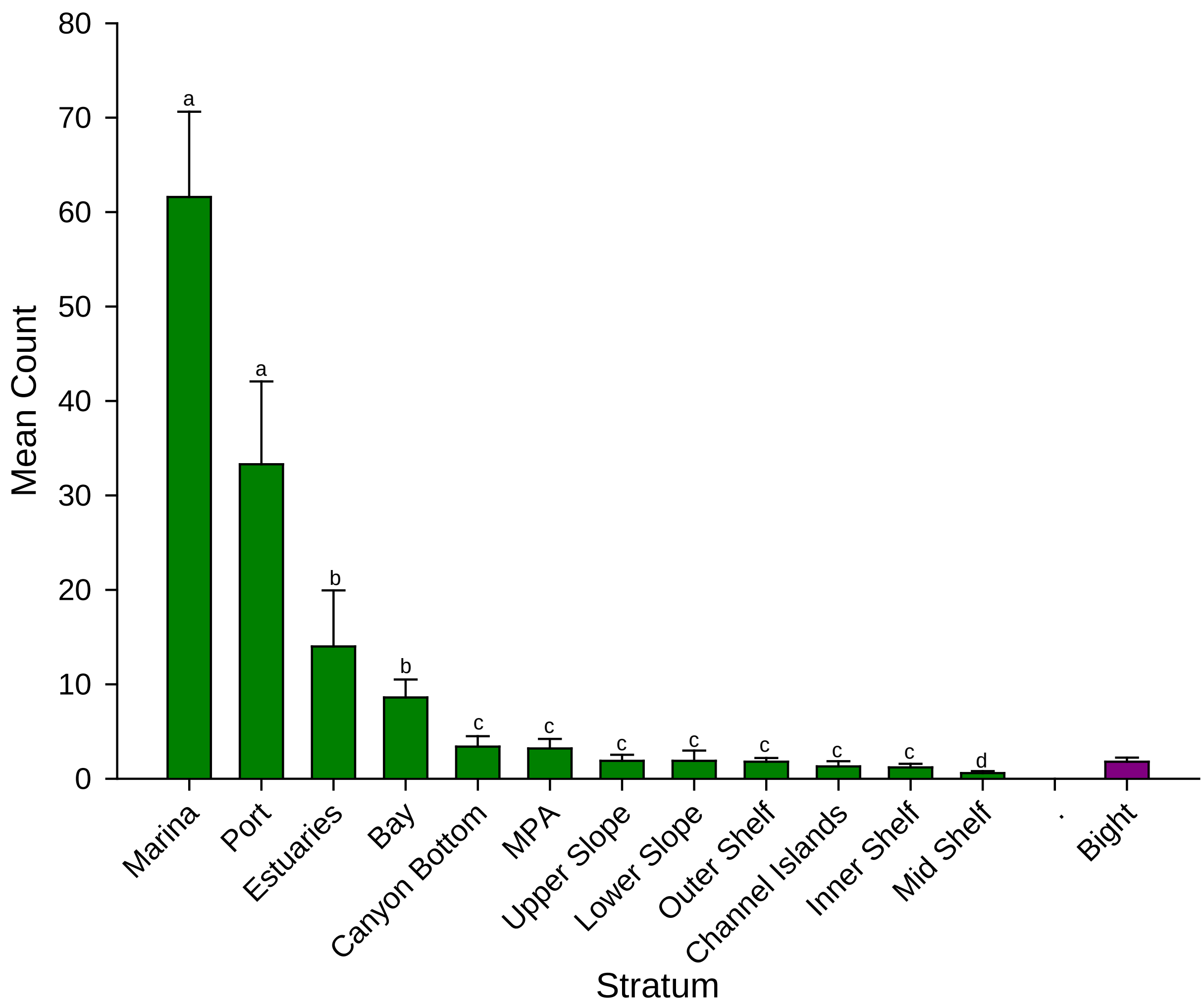


Figure 3: Mean count (+95% Confidence Limits) of benthic micro-plastic debris in the Southern California Bight by stratum in 2013. Letters indicate statistical similarities (same letter) or significant differences (different letter).

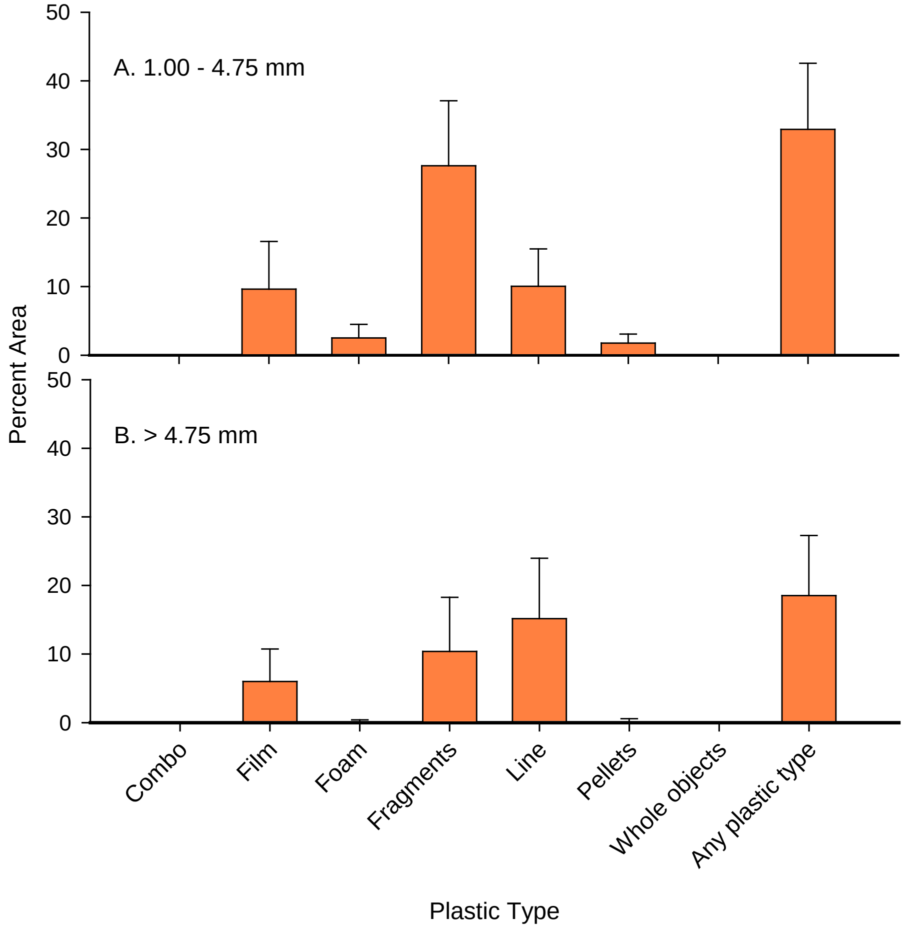


Figure 4: Extent (% area ± 95% Confidence Limits) of benthic plastic debris in the Southern California Bight in 2013 by plastic type for size class 1.00-4.75 mm (A) and >4.75 mm (B).

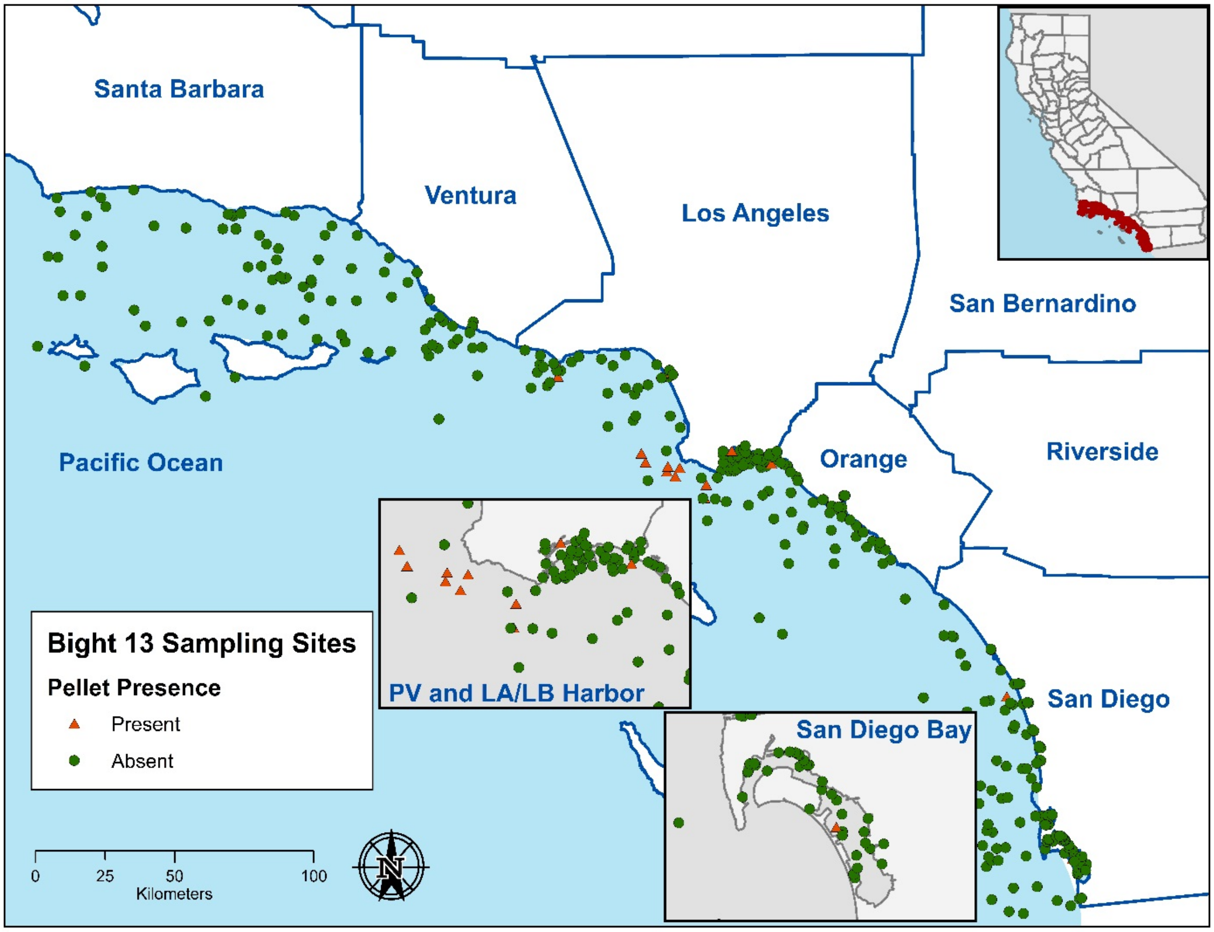


Figure 5: Presence or absence of plastic pellets in the benthic sediments of the Southern California Bight in 2013.

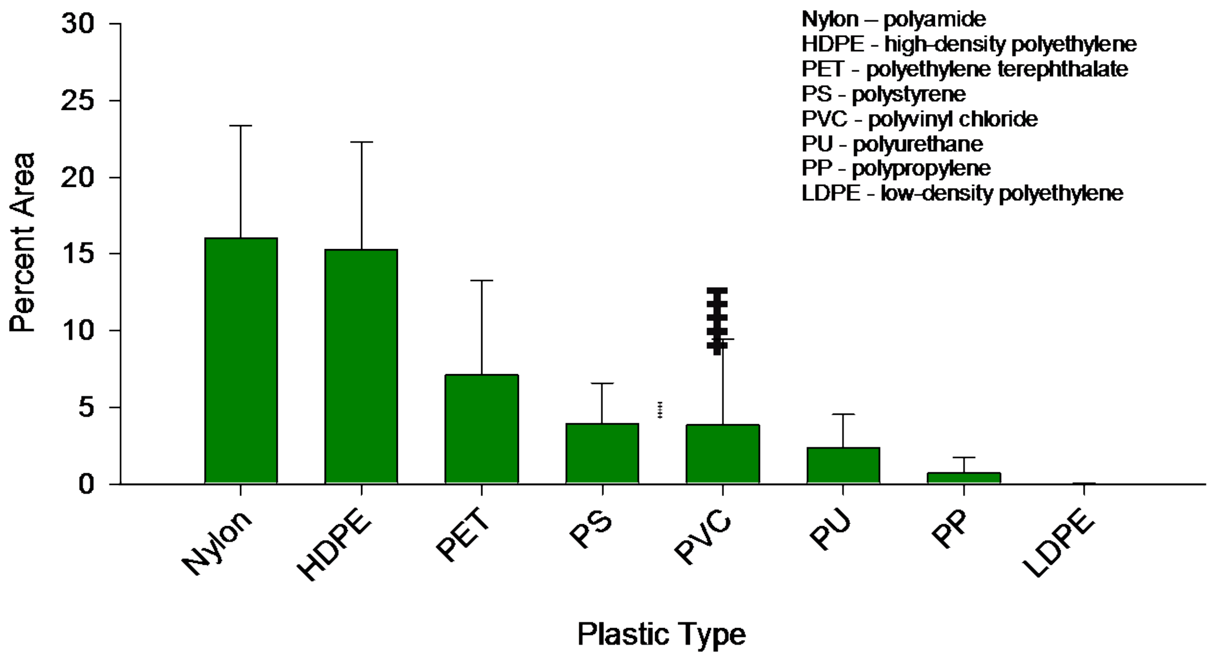


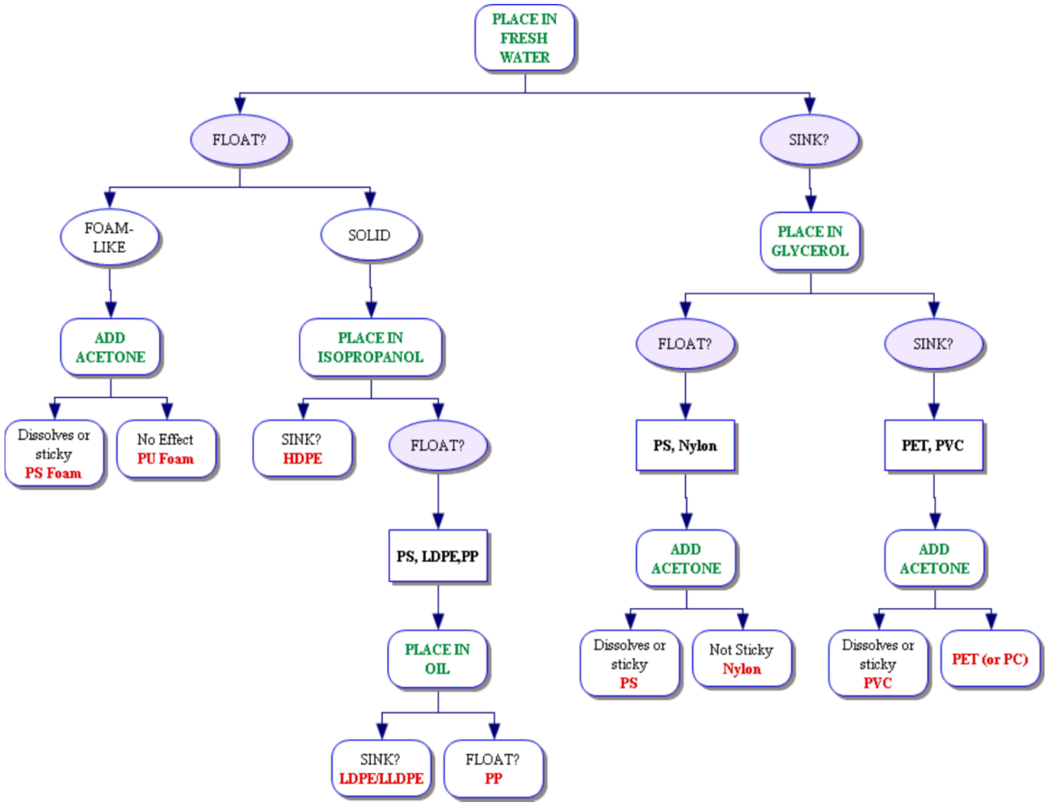
Figure 6: Percent of area (+ 95% confidence limits) by plastic polymer type in the Southern California Bight in 2013.

VIII. Tables

Table 1: Number of sites sampled by trawl in the Southern California Bight by stratum in 2013.

Coarse Stratum	Strata	Number of Stations	Areal Extent (km^2)
Embayments	Bay	31	71
	Estuaries	41	10
	Marina	34	15
	Port	30	26
Shelf	Channel Islands	14	1946
	Inner Shelf	30	1011
	Mid Shelf	30	1828
	Outer Shelf	30	536
Slope	Upper Slope	40	2754
	Lower Slope	21	7418
Canyons	Canyon Bottom	30	140
MPA	MPA	27	296
Total		358	16049

IX. Supplemental Information



Supplemental Information 1: Flow chart showing the process for testing plastic for polymer type.