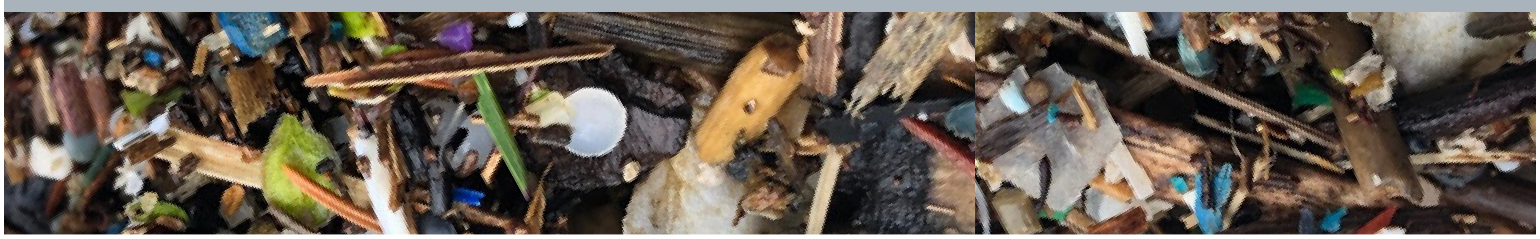
21ST ANNUAL ROGER REVELLE COMMEMORATIVE LECTURE

THE STORY OF PLASTIC POLLUTION
FROM THE DISTANT OCEAN GYRES TO THE GLOBAL POLICY STAGE

MARCH 10, 2020



Chelsea M. Rochman

We are inundated with media about ubiquitous contamination of plastic debris in our global oceans. Until recently, this was not the case. Over the last decade, the amount of research and attention regarding the topic has elevated plastic pollution to the global stage – setting priorities for research and policy. The story of plastic pollution, big and small, began in the middle of the open oceans. Today, we know that plastic debris is ubiquitous across all oceans, ecosystems, habitats and food webs – including in seafood and sea salt. In addition to understanding contamination, researchers are expanding their breadth of questioning to explore the sources, fate, and effects of plastic pollution. This has led to an expanding scientific field, which has paralleled a growing policy movement – spanning multiple levels of government from municipal to international. Over the next ten years, as we continue to conduct research to better understand plastics in our oceans, the question is not whether there is plastic pollution, but how we will use science to inform solutions and whether we are willing to do the hard work to solve the problem.

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The words “microplastic,” “single-use plastics,” and “microfiber” have become commonplace in newspaper headlines, radio programming, and policy statements. Stories about whales washing up with bellies full of plastic bags and images of turtles with plastic straws up their noses can easily be found in online media. At elementary schools parents are asked to pack zero plastic waste lunches for their children, and global conferences focused on the world’s most pressing environmental issues all discuss plastic debris along with climate change and fisheries exploitation. Today, the United Nations is considering a new international agreement focused on plastics in the environment. Twelve years ago, when I was applying for graduate school, the words plastic and pollution were not yet united to define the growing environmental issue we all know today as “plastic pollution.”

THE STORY BEGINS IN THE OPEN OCEANS

The history of research around plastic pollution begins in the middle of the oceans, thousands of miles from land, in the central gyres (Figure 1). The first scientific findings of marine plastic debris were published in the journal Science in 1972, reporting small plastic particles in the Sargasso Sea (Carpenter et al., 1972; Carpenter and Smith, 1972). More than one decade later, in 1986, undergraduate students aboard a tall ship began counting pieces of small plastic debris in surface trawls across the North Atlantic Ocean, leading to the first long-term (25 year) dataset on plastic debris (Law et al., 2010). Then, Captain Charles Moore discovered the “Great Pacific Garbage Patch” in 1996, and published the first account of large accumulations of plastic debris in the middle of the North Pacific Subtropical Gyre (Moore et al., 2001). And finally, in 2004, Richard Thompson coined the term “microplastic” to refer to the ubiquitous small plastic particles (< 5mm in size; Figure 1) he found in ocean sediments and surface waters (Thompson, 2004). In that same article, Thompson made a call for more research on this emerging contaminant, leading to an exponential rate of increasing scientific evidence measuring the contamination, fate, and effects of plastic debris in the ocean.

The history of public awareness around the issue also began in the middle of the oceans. Although the “Garbage Patch” was discovered a decade prior, Ken Weiss’ Pulitzer Prize winning article in the Los Angeles Times introduced it to the world in 2006. After this introduction, the Garbage Patch was described again and again as an island of floating plastic litter twice the size of Texas. Intrigued by this idea, and with some disbelief, a group of graduate students led by Dr. Miriam Goldstein at the Scripps Institution of Oceanography (SIO) heard Thompson’s call for research and received funding for the first scientific expedition to the Great Pacific Garbage Patch in the summer of 2009.

Aboard the R/V New Horizon, the team of graduate students, a videographer, a teacher and an entrepreneur from an environmental NGO called Project Kaisei set off from San Diego to see what they could find (Figure 2a). I was just finishing up my first year of graduate school down the road at San Diego State University, and was thrilled to have a spot on the ship. Every four hours surface-skimming nets were dropped into the water to quantify small floating plastic debris and 24 hours a day observers on deck quantified and characterized any large debris. Day after day, no sign of a floating island of plastic garbage could be found. Then, on the fourth day, the observers on deck called for assistance. On the bow of the ship were two rulers being used by the observers to count debris as it passed. Up to that point, they had counted a buoy, a drink tray, and a fishing net here and there. But then, all of a sudden there were too many pieces of plastic to count and the two observers needed the eyes of many. Looking over the bow of the ship, we saw thousands of little pieces of plastic debris smaller than a pencil eraser (Figure 2b). This was not a garbage patch, this was a soup of microplastic (plastic particles <5 mm in size)

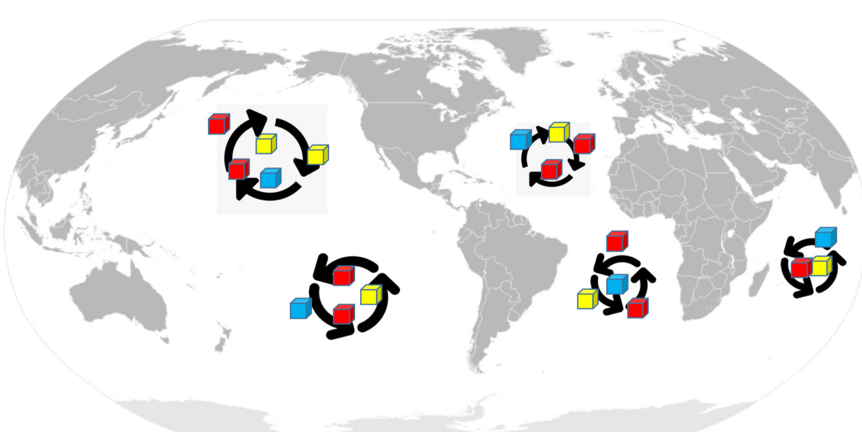

Figure 1 Representation of plastics floating in the five large subtropical gyres in the center of the North Pacific, South Pacific, North Atlantic, South Atlantic and Indian Oceans.

particles. At that moment, it was clear that the ocean plastic issue was real, but that the garbage patch was different than described. The microplastics Thompson described were numerous, and from a mitigative perspective it was clear this was not just an issue of cleanup – but one of prevention.

Coming back to land, the Scripps researchers aboard the New Horizon analyzed the samples that were collected on the expedition. They found that there was microplastic in nearly every single one (Goldstein et al., 2012). This finding, that the majority of plastic pieces were microplastics, demonstrated a need to shift the conversation from mitigation to a stronger focus on preventing plastic from entering the environment in the first place. It also demonstrated a need for more science to better quantify the magnitude of the problem, including sources, transport, and impacts of microplastics in the marine environment.

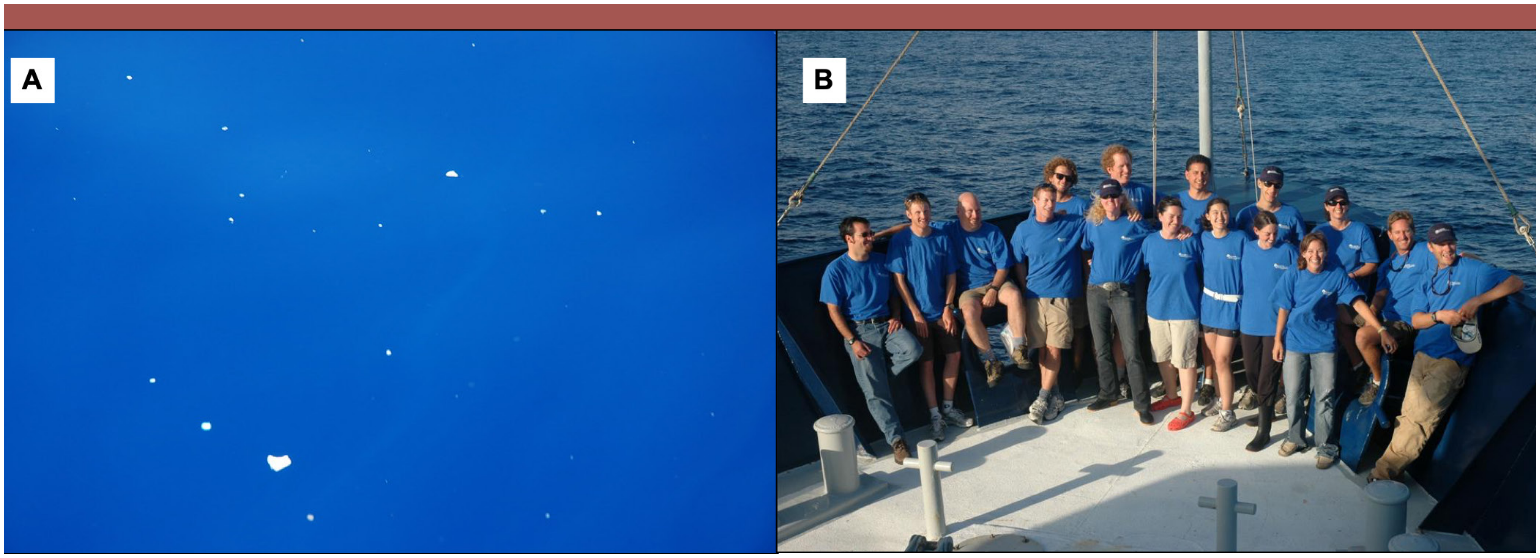

Figure 2 (A) The sight from the bow of the ship when we entered the microplastic soup of the Great Pacific Garbage Patch. (B) The group of graduate students, other researchers, educators, photographers and entrepreneurs aboard the R/V New Horizon in 2009. Pictures courtesy of Scripps Institution of Oceanography.

A DIVERSE SIZE SPECTRUM
Macro- Vs Micro- Plastic

Before diving deeper into the scientific body of work, it is important to spend some time getting to know the subject: plastic. Plastic debris comes in diverse sizes, shapes, colors and chemistries (Figure 3). By weight, large plastic debris such as fishing nets, make up the largest percentage of plastic floating in our oceans (Lebreton et al., 2018). However, microplastics make up the most by count. Researchers estimate that there are between 15 and 51 trillion microplastic particles floating at the surface of the oceans (van Sebille et al., 2015), reaching from the poles to the equator. Note that this is just at the surface, researchers have uncovered microplastics in the deepest parts of the ocean (Jamieson et al., 2019) and in Arctic sea ice (Obbard et al., 2014). Although some think of microbeads (the tiny pieces of plastics banned from facewash) when we think of microplastics, the term microplastic incorporates a large diversity of plastic types (Rochman et al., 2019), including those that were produced as microplastics (e.g., microbeads, pre-production pellets often referred to as "nurdles") and those that are literally degraded bits of larger plastic products (e.g., tire dust, microfibers and fragments of bottles, bags, and film). The former is called primary microplastics and the latter is referred to as secondary microplastics. Secondary microplastics are the most common type of microplastic waste found at sea. Still, we must not forget the primary sources of microplastics as well as the sources that emit secondary microplastics into the oceans (e.g., microfibers, tire and roadwear particles). These particles, specifically microfibers, are some of the most common microplastic types found in global ecosystems (Barrows et al., 2018). This diversity of plastics in the environment, coming from hundreds of different products with diverse polymer backbones and chemical additives, make this type of pollution complex – different from its chemical counterparts such as pesticides or trace metals. To better understand this complex emerging contaminant, a growing number of researchers have entered the field of plastic pollution leading to an expanded and more diverse body of knowledge.

A GROWING FIELD SPREADS ACROSS THE OCEANS AND TOWARDS DRY LAND

The R/V New Horizon returned from the middle of the North Pacific Ocean to dry land just over one decade ago. Since that time, the field has grown tremendously and the number of scientific papers about plastic pollution have increased at an exponential pace (Figure 4). The bulk of the research on plastic pollution is no longer unique to the open ocean, and much of the work now takes place in coastal waters, shallow bays and estuaries, and on beaches – closer to the source of the pollution.

A growing scientific field has led to an expansion of knowledge which in turn leads to further scientific questions. Today there is no doubt that plastic pollution contaminates the surface of every ocean (van Sebille et al., 2015), the deep sea (Fischer et al., 2015), sea ice (Obbard et al., 2014), and every level of the food web (Gall & Thompson, 2015). Now, researchers are working to gain a better understanding of the sources of the contamination, their fate once they end up in the ocean, and their effects to aquatic ecosystems.

The sources of plastic pollution are many, and the pathways by which they enter the oceans equally diverse. An estimated 80% of plastic pollution in the ocean comes from land (Jambeck et al., 2015), and the rest are thought to enter via maritime activities (e.g., fishing vessels, cruise ships). Plastics enter the oceans via mismanaged waste from households, wastewater, and industry (e.g., agriculture, plastic manufacturing). Such mismanaged waste may enter the oceans via littering, wind-blown from landfills or overflowing garbage bins, natural disasters, accidental spills, or sewage overflows. Mismanaged waste does not have to be directly littered into an ocean to become marine debris; rivers are one of the dominant pathways for plastics to reach the oceans (Lebreton et al., 2017). Thus, plastic debris entering any part of a watershed via stormwater runoff, wastewater effluent, agricultural runoff, industrial runoff, or wind has a chance of reaching the oceans.

Once in the environment, researchers are trying to wrap their heads around the fate of plastic pollution. Plastic floating in the middle of the subtropical gyres demonstrates long-range transport via ocean currents (van Sebille et al., 2015). Microplastics in Arctic snow (Bergmann et al., 2019) suggest long-range atmospheric transport. As a result of long-range oceanic and atmospheric transport, plastics, including microplastics, are found in large concentrations in Arctic sea ice (Obbard et al., 2014) and are also present in sediments (Browne et al., 2011) and wildlife from the deepest parts of the ocean (Woodall et al., 2014). Consequently, this widespread contamination has led to the contamination of hundreds of species of wildlife across all trophic levels (Gall & Thompson, 2015) – leading to questions about effects.

When it comes to large plastic debris, there is no doubt that plastic pollution can have an impact

Figure 3 Microplastics (left) sampled from surface water in San Francisco Bay, CA, USA and mounted on double-sided tape (Picture taken by C. Brookson). Macroplastics (right) in the riparian zone of the Tijuana River Valley in San Diego, CA, USA.

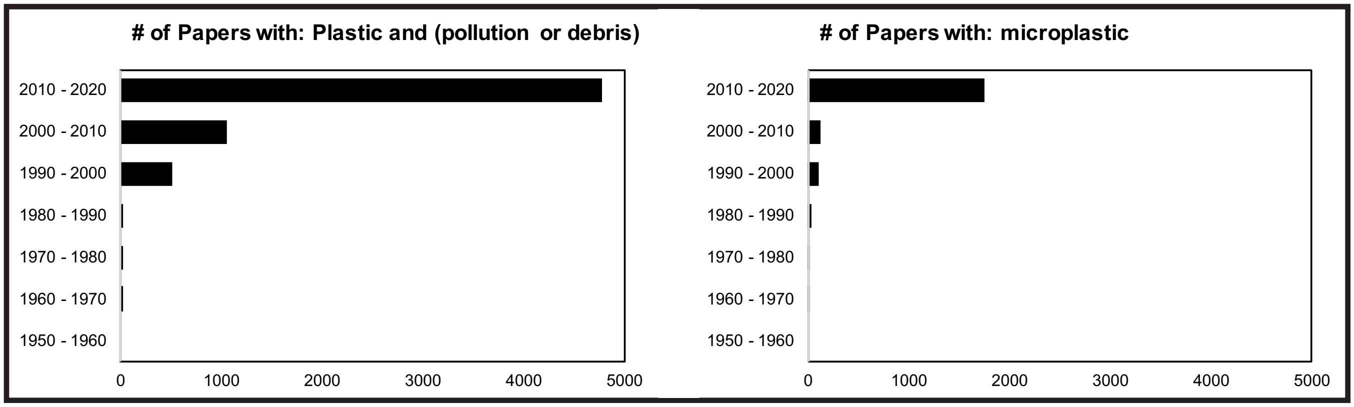

Figure 4 The number of papers that appear in Web of Science Core Collection using search terms Plastic AND (pollution or debris) (left) and Microplastic (right).

on wildlife, and there is compelling evidence suggesting macroplastics are already impacting marine populations, species, and ecosystems (Rochman et al., 2016; Bucci et al., 2019). Studies have reported contamination via entanglement or ingestion in hundreds of species of wildlife. This contamination can lead to laceration of the tissues, mortality of an individual organism, declines in population size, and/or changes in the assemblages of species. A recent study published in the journal Science found that plastic debris was correlated with disease in coral reefs (Lamb et al., 2018). A recent systematic review reports evidence of adverse effects in 23 species of marine mammals, 4 species of turtles, 11 species of birds, 4 species of fish, many species of invertebrates, and one species of algae (Bucci et al., 2019).

When it comes to microplastics, the story is more complicated. There have been many studies testing the effects of microplastics on organisms. Although the results are variable, there is irrefutable evidence that microplastics can impact organisms. In laboratory studies, microplastics have been shown to cause a variety of biological effects including: changes in gene expression (e.g., Paul-Pont et al., 2016), inflammation (e.g., von Moos et al., 2012), disruption of feeding behaviour (e.g., Cole et al., 2015), decreases in growth (Au et al., 2015), decreases in reproductive success (e.g., Au et al., 2015; Sussarellu et al., 2016), changes in larval development (e.g., Nobre et al., 2015), reduced filtration and respiration rates (e.g., Paul-Pont et al., 2016), and decreased survival (e.g., Au et al., 2015; Cui et al., 2017). Still, while many laboratory experiments find that microplastics can affect the gene expression, growth, reproduction, or survival of an animal, others do not detect any effects and conclude that microplastics have no negative effects (Bucci et al., 2019). Thus, the clear consensus around macroplastics inform a need for policies to mitigate plastic pollution in general, but the lack of clear consensus around microplastics has led to decision-makers suggesting further research is necessary to inform mitigation strategies specific to microplastics.

HOW DID WE GET HERE?

In 1955 the cover of Life Magazine celebrated a new lifestyle they called “Throwaway Living.” The article celebrated the rise of single-use products, which included plastic cutlery, plastic straws, plastic plates, and plastic cups (Figure 5). Since this time, annual plastic production has increased from 2 million tonnes (Mt) in 1950 to 380 Mt in 2015 (Geyer et al. 2017). Today, it continues to rise and is expected to increase by 40% over the next decade. Of course, there are many positive attributes of plastics – they are inexpensive, light-weight, durable, and their diversity enables a large number of products. Still, some of these positive attributes have also led to a less sustainable usage of these materials (roughly 40% of production is single-use items) and the mismanagement we see today. Of all plastics produced to date, an estimated 9% have been recycled, 12% incinerated, and 79% sent to landfills or littered in the natural environment (Geyer et al., 2017). Jambeck et al. (2015) estimate that of the 275 Mt of plastic waste generated in 2010 alone, roughly 8 Mt entered the ocean, becoming plastic pollution. If we continue under business-as-usual, annual plastic emissions to the oceans are predicted to increase to 28 Mt by 2025 (Jambeck et al. 2015). This prediction sparked a global movement with politicians, journalists, and environmental activists agreeing on the need to reduce plastic emissions into the ocean to well below today’s levels.

STEMMING THE TIDE: THE POLICY LANDSCAPE

Today, there is no doubt that anthropogenic debris of all shapes and sizes litters our oceans. This debris is found in hundreds of species of wildlife, including in the species we consider seafood (Santillo et al., 2017). It is also found in our drinking water (Pivokonsky et al., 2018). We know that plastic pollution harms individual organisms, wildlife populations, and communities (Bucci et al., 2019). These impacts, combined with evidence for accelerating plastic production and leakage into the environment, suggest governments should come together to limit future plastic emissions now, before they transform ecosystems irreparably (Borrelle et al., 2018).

For plastic pollution, there is no simple solution – and certainly no one-size-fits-all strategy. Unlike CFCs, we cannot simply ban all plastics from production. Diverse policies are necessary at every level of governance. Thus far, we have seen policies enacted at the local level, with single-use product bans such as bag bans, straw bans, and microbead bans. Some cities or states have adopted stormwater and/or sewage bylaws to prevent plastics from entering the water via runoff. Some countries and regions are considering plastic strategies, such as at the country level in Canada or at the regional level with the G7 Ocean Plastics Charter.

Similar to trends in research, international policies relevant to plastic pollution also began in the oceans with MARPOL Annex V, entering into force in 1988. A major part of this Annex was a complete ban on dumping plastic from ships. The second international level document was the US National Oceanographic and Atmospheric Administration (NOAA) and UNEP Honolulu Strategy in 2011. The Honolulu Strategy is a planning tool to reduce plastic pollution and its impacts. Then, in February 2017, UNEP announced the Clean Seas global campaign on marine litter. This campaign encourages individuals, industries, and member states to voluntarily commit to an action of their choice, big or small, to reduce plastic pollution. Most recently, in 2019, 187 countries adopted a change to the Basel Convention, aimed at restricting the trade of plastic waste overseas. Today, UNEP is considering an international agreement aimed at reducing plastic pollution well below today's levels.

Diverse policies that work in tandem to reduce plastic pollution are necessary. An international agreement that provides enabling policies to proceed with diverse solutions to reduce emissions would be a useful way forward. I envision an agreement where countries sign on as signatories with a defined reduction target. For example, one country might agree to reduce 25% of their emissions by 2025. To meet reduction targets, each country needs to come up with strategies to do it. Because there is no one-size-fits-all solution, each country may take on its own set of unique solutions to reach its target. For example, we may adopt container deposit schemes to improve recycling rates, eliminate the use of some single-use plastic items that are unnecessary (e.g., straws) and not practically recyclable, improve waste collection and management infrastructure, and agree to market only plastics that are recyclable and/or reusable in their region. Although policies that mitigate large plastic debris also reduce microplastic debris, we need to make sure we consider microplastics when we consid-

Figure 5 The cover of LIFE magazine in 1955 celebrating "Throwaway Living".

er all of the policy options for plastic pollution. Policies specific to microplastics may include, but are not limited to, leakage standards for microplastics (e.g., from washing machine effluent, wastewater, stormwater, etc.), filters on washing machines to trap microfibers, bioretention cells (or rain gardens) on stormdrains, increasing industry participation in the voluntary initiative to reduce pellet loss (Operation Clean Sweep) and extend this model to textiles, material innovation, and banning microbeads. For some countries, particularly in the developing world, aid is necessary to build new infrastructure for waste. These countries need access to a global fund, similar to the UNFCCC's climate fund. To build this fund, an extended producer responsibility program can be implemented. If the fund pulled in one penny for every pound of plastic produced, the fund would build by over $6.8 billion per year. Finally, each year countries would report on their success measuring the reduction of plastic emissions globally over time and ensuring signatories reached their goal.

A PATH FORWARD

Today, scientists estimate more than 8 million Mt of plastics enter the oceans each year (Jambeck et al., 2015). It will not be simple to reduce emissions well below this value. This issue is complex. The sources of plastics into the environment are diverse. The types of plastics we produce, sell, and find in nature are diverse. The ecosystems and organisms this pollution contaminates are diverse. As a consequence, the solutions need to be diverse. We need a toolbox of solutions that include plastic reduction, the building of a circular economy, improved waste management systems, innovation of new materials and technologies for prevention, cleanup, and improved outreach and education. We also need everyone working together, including the plastic industry, waste managers, the public, scientists and all levels of government from all over the world. The first decade of my scientific career has been rewarding in that I have had the opportunity to grow with a burgeoning field of research. In parallel, I've witnessed our science be used to inform policy-makers planning for positive change. The second decade of my career will be filled with deeper scientific questioning to better understand this diverse contaminant. Still, we have learned a lot, and my hope for this next decade is that we also use the knowledge from the decade past to realize global goals for reduced inputs of plastics into the ocean to protect our oceans for people, wildlife, and the planet and in recognition of the many heroes of our oceans past, including Dr. Roger Revelle.

ROGER REVELLE

For almost half a century, Roger Revelle was a leader in the field of oceanography. Revelle trained as a geologist at Pomona College and the University of California, Berkeley. In 1936, he received his Ph.D. in oceanography from the Scripps Institution of Oceanography. As a young naval officer, he helped persuade the Navy to create the Office of Naval Research to support basic research in oceanography. He served for 12 years as the Director of Scripps where he built up a fleet of research ships and initiated a decade of expeditions to the deep Pacific that challenged existing geological theory.

Revelle's early work on the carbon cycle suggested that the sea could not absorb all the carbon dioxide released from burning fossil fuels. He organized the first continual measurement of atmospheric carbon dioxide, an effort led by Charles Keeling, resulting in a long-term record that has been essential to current research on global climate change.

In 1957, Revelle became a member of the National Academy of Sciences to which he devoted many hours of volunteer service. He served as a member of the Ocean Studies Board, the Board on Atmospheric Sciences and Climate, and many committees.

***Dr. Chelsea Rochman** is an Assistant Professor in Ecology at the University of Toronto and a scientific advisor to Ocean Conservancy. Chelsea received her PhD in Ecology from a joint program between University of California, Davis and San Diego State University in 2013. She then was a Smith Postdoctoral Fellow in Conservation Biology. She was hired as an Assistant Professor at the University of Toronto in the Department of Ecology and Evolutionary Biology in 2016. Chelsea has been researching the sources, sinks and ecological implications of plastic debris in marine and freshwater habitats for more than a decade. She has published dozens of scientific papers in respected journals and has led international working groups about plastic pollution. In addition to her research, Chelsea works to translate her science beyond academia. For example, Chelsea presented her work to the United Nations General Assembly and at the US State Department. For more information visit www.rochmanlab.com*

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