2017 NOAA Marine Debris Program Report

Invasive Species

Marine Debris as a Potential Pathway for Invasive Species

Photo Credit: Oregon State University, Hatfield Marine Science Center

March 2017

National Oceanic and Atmospheric Administration
National Ocean Service

National Centers for Coastal Ocean Science – Center for Coastal Environmental Health and Biomolecular Research
219 Ft. Johnson Rd.
Charleston, South Carolina 29412

Office of Response and Restoration
Marine Debris Program
1305 East-West Hwy, SSMC4
Silver Spring, MD 20910

Cover photograph a **close-up of marine life found on a derelict dock from Japan that washed up on Agate Beach in Newport, Oregon.**
Photo Credit: Oregon State University, Hatfield Marine Science Center

For citation purposes, please use:
National Oceanic and Atmospheric Administration Marine Debris Program. (2017). Report on Marine Debris as a Potential Pathway for Invasive Species. Silver Spring, MD: National Oceanic and Atmospheric Administration Marine Debris Program.

For more information, please contact:
NOAA Marine Debris Program
Office of Response and Restoration
National Ocean Service
1305 East-West Highway
Silver Spring, Maryland 20910
301-713-2989
https://MarineDebris.noaa.gov

Acknowledgements

The National Oceanic and Atmospheric Administration (NOAA) Marine Debris Program would like to acknowledge Paul L. Pennington, Ph.D. (National Centers for Coastal Ocean Science) for conducting this research, and Courtney Arthur (Industrial Economics, Inc.) and Keith Cialino (NOAA Marine Debris Program) for providing guidance and support throughout this process. Special thanks to James T. Carlton (Williams College and Mystic Seaport) and Margaret M. Brady (NOAA National Sea Grant Program) for reviewing this paper and providing helpful comments. Thanks also to Catherine Polk (NOAA National Ocean Service, National Centers for Coastal Ocean Science) for creating the graphics, Kevin McMahon (NOAA National Ocean Service, National Centers for Coastal Ocean Science) and Krista Stegemann (NOAA Marine Debris Program) for a copy-edit review of this report, and Emma Tonge (NOAA Marine Debris Program) for design and layout. Funding for this project was provided by the NOAA Marine Debris Program.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

There is mounting concern over the increase in debris in our ocean and the potential for that debris to serve as a pathway for the introduction of non-native species. While the pathways associated with global shipping draw the greatest amount of attention regarding marine invasives, the purpose of this paper is to consider the potential role that marine debris may play in introducing non-native species that may become invasive. This paper is not a comprehensive review of either subject (marine debris or invasive species), as reviews are available in the literature for both. Rather, the objectives of this paper are to address:

- key terminology and concepts related to marine debris and invasive species,
- the major types of organisms occupying marine debris (by functional group),
- some key case studies regarding non-native species and marine debris,
- a basic framework to invasion with respect to marine debris,
- a successful invader and the role of marine debris,
- key information gaps and research needs, and
- recommendations for the mitigation of marine debris-mediated species invasions or expansions.

The intersection of marine debris and invasive species is very complex and not well understood. This is because each issue is very complex in its own right. Determining the potential risk of a non-native species invading a new range using marine debris as a pathway is not possible at the present time due to numerous confounding factors, knowledge gaps, and research hurdles. However, given what we know about the barriers to invasion presented in this paper, we can draw some broad conclusions regarding the potential circumstances that might lead to invasion success by a non-native species due to marine debris.

There are four broad potential invasion scenarios. First, marine debris may be able to extend the current range of a species to a particular coastline, fueled by factors such as the impacts of climate change. Densely-populated coastlines are of particular concern, since they are found to have increased debris loads. Second, invasive species that are already established in an area due to another pathway (such as shipping) can use local pathways (such as marine debris) to extend their range even further. Third, large debris items in the open ocean can carry large numbers of organisms and species to new locations. Fourth and finally, reoccurring arrivals of small biofouled debris items from a particular locale may be important in leading to multiple inoculations of the same species, overwhelming the local population and introducing genetic constraints, as opposed to the introduction of any one small isolated item.

BACKGROUND

Marine Debris and Invasive Species: Two Convergent Issues

Litter in the ocean is called *marine debris* and it comes in many forms, shapes, and sizes. It ranges in size from micro-debris (particles < 5mm) to macro-debris (>2.5m) (Lippiatt, Opfer, & Arthur, 2013), and can even include derelict vessels that are several hundred feet long. Marine debris is comprised of a mix of materials, including but not limited to plastic, nylon, wood, metal, and glass. Debris materials can be found free-floating at the surface of the ocean, within the water column, lying on the bottom, or littering shorelines (National Oceanic and Atmospheric Administration Marine Debris Program [NOAA MDP], 2016; United Nations Environment Programme [UNEP], 2011).

In addition to the unsightliness of marine debris, there are a host of serious and potentially damaging associated impacts. Ingestion, entanglement, ghost fishing, economic loss, habitat damage, vessel damage, and the introduction of invasive species are all potential impacts associated with marine debris (NOAA MDP, 2016). For some of these concerns, such as ghost fishing (derelict fishing traps continuing to entrap fish), marine debris is perhaps the sole causative agent. For others, marine debris is one of many potential causative agents. This is the case with invasive species; marine debris and invasive species are two separate but overlapping issues of environmental concern.

While these two environmental problems are different at many levels in terms of how we study, mitigate, prevent, or eliminate them, they do have several commonalities. First, both marine debris and invasive species are of global concern (National Invasive Species Council [NISC], 2008; UNEP, 2009; UNEP, 2011). Second, both issues are very complex in their own right and the elimination of one will not lead to the elimination of the other; each will require its own set of unique mitigation strategies. Third, human-made marine debris and the transport of species outside of their native ranges likely co-emerged and began in earnest when mankind took to the seas aboard vessels and boats several thousand years ago (Carlton, 1987; Carlton, 2011). In more modern times, shipping has increased globally (in terms of speed, size, and number of vessels) and has led to the dispersal of many non-native species (Carlton, 1987; Carlton, 2001; Lewis, Hewitt, Riddle, & McMinn, 2003; United States Environmental Protection Agency [USEPA], 2012). Concurrently, modern debris consists mostly of non-biodegradable materials such as nylon and plastics (e.g. fiberglass, polyvinyls, styrofoam, etc.). In addition, unlike ancient litter which mostly degraded and sank, modern litter has a long life at sea and can float for years, transiting vast distances (NOAA MDP, 2016).

NOAA's Role with Marine Debris

The Marine Debris Research, Prevention, and Reduction Act was signed into law in 2006; it was further amended and renamed the Marine Debris Act in 2012 (33 U.S.C. §§ 1951-1958). These pieces of legislation authorize the NOAA Marine Debris Program to "identify, determine sources of, assess, prevent, reduce, and remove marine debris and address the adverse impacts of marine debris on the economy of the United States, marine environment, and navigation safety." In this role, NOAA serves as the federal lead to address marine debris in

"While these two environmental problems are different at many levels in terms of how we study, mitigate, prevent, or eliminate them, they do have several commonalities. "

the United States and does this through research, prevention, removal, regional coordination, and emergency response.

NOAA's Role with Invasive Species

NOAA's role in addressing invasive species is primarily governed by the Nonindigenous Aquatic Nuisance Prevention and Control Act (NANPCA) of 1990, as amended by the National Invasive Species Act (NISA) of 1996. The NANPCA established the Aquatic Nuisance Species Task Force (ANSTF), which is co-chaired by the Director of the U.S. Fish and Wildlife Service and the Under Secretary of Commerce for Oceans and Atmosphere (NOAA Administrator). The NANPCA also legally defined the term "Aquatic Nuisance Species" as a "nonindigenous species that threatens the diversity or abundance of native species or the ecological stability of infested waters, or commercial, agricultural, aquacultural or recreational activities dependent on such waters."

Executive Order 13112 (1999) established the National Invasive Species Council (NISC) to ensure that federal agencies and programs carry out activities to prevent and control invasive species in a coordinated, effective, and efficient manner. The order also designated the secretaries and administrators of 13 federal departments to serve on this council. The NISC is co-chaired by the Secretaries of Commerce, Agriculture, and the Interior. The order also defined the term "invasive species" (see below) and authorized the NISC to prepare and issue a National Invasive Species Management Plan (NISC, 2008).

What is an Invasive Species?

There is a large amount of inconsistency in regard to the concept of "invasive species" and with the terminology used to describe a species that is found outside of its natural range (Carlton, 2001; Lodge *et al*., 2006; Molnar, Gamboa, Revenga, & Spalding, 2008) . While Carlton (2001) specifically avoided the use of the term "invasive," others have used it in various ways. Many have used the term in a broad sense to mean any species that exists outside of its natural range (Molnar *et al*., 2008; Richardson *et al*., 2000). In that context, the term "invasive" is essentially synonymous with the terms "alien," "exotic," "non-indigenous," "ornamental," and "non-native." It is possible to have a non-native species that does not spread prolifically and harmfully (Zenni & Nuñez, 2013), which is the case with many crop species or ornamental trees on land that require constant human intervention in order to sustain the crop or plant. However, an "invasive species" causes some amount of damage or harm to the new range that it has invaded.

It is recognized that human values and public perception can complicate both the concept of "invasive species" (NISC, 2006) and the actions that are undertaken to manage that species. This produces a gray area in which the determination on whether or not a species is "invasive" is sometimes dependent upon human values. For example, salmon (*Oncorhynchus tschawytscha*) were introduced to the Great Lakes in the 1960s to rebuild a sustainable sport fishery after the collapse of trout populations, as well as to control an invasive fish called the alewife (*Alosa pseudoharengus*) (a move that would likely be very difficult to make today given the current laws). The fishery was a huge success and an economic boon for anglers and tourism along coastal regions of the Great Lakes. Today, the salmon are highly prized by anglers and are deemed beneficial, since they also feed heavily on the alewife. These salmon are non-indigenous, but are not considered to be "invasive species." After many decades now, salmon and trout are still stocked into the Great Lakes and represent a multibillion-dollar sport fishery. The alewife, while still classified as invasive, is considered one of the most

"It is recognized that human values and public perception can complicate both the concept of invasive species and the actions that are undertaken to manage that species."

"Pathways associated with global shipping are widely considered to be the most significant cause of human-mediated transoceanic dispersal of non-native marine and estuarine species."

valuable food sources supporting that fishery (Fenichel, Horan, & Bence, 2010).

Whereas no definition to date is perfect, the federal government has defined the concept of "invasive species" in two different ways. The following definition of "invasive species" was defined in Executive Order 13112 (1999).

Invasive Species: "a species that is non-native to the ecosystem under consideration and whose introduction causes or is likely to cause economic or environmental harm or harm to human health (Executive Order No. 13112, 1999; NISC, 2006)."

A white paper (NISC, 2006) produced by the National Invasive Species Council provides a non-regulatory policy interpretation of the concept of invasive species (in Executive Order No. 13122, 1999) by identifying what is meant, and just as important, what is not meant by the concept.

Prior to that, the NANPCA, as amended by the NISA, defined the concept as follows:

Aquatic Nuisance Species: "a nonindigenous species that threatens the diversity or abundance of native species or the ecological stability of infested waters, or commercial, agricultural, aquacultural, or recreational activities dependent on such waters."

For the purposes of this paper, the term "invasive species" will be used. The definition of the concept will follow that of the NANPCA (1990) and NISA (1996), since this definition is more specific regarding the harm that a non-indigenous species may cause to an ecosystem.

Pathways

Species are introduced to new ranges through pathways (National Invasive Species Information Center [NISIC], 2016; Ray, 2005; USEPA, 2012; United States Fish and Wildlife Service [USFWS], 2011) including natural processes like wind, currents, or a specific behavioral or morphological characteristic that a species might employ to disperse itself (NISIC, 2016). Species are also introduced to new ranges by a plethora of human-mediated pathways that may involve intentional or unintentional movement (as is discussed throughout this report). In the literature, the terms "pathway" and "vector" are often used interchangeably. Some authors employ the term "vector" in place of "pathway" (Barnes, Galgani, Thompson, & Barlaz, 2009; Carlton, 1999; Carlton, 2001; Carlton, 2011; Roman & Darling, 2007; Williams *et al.*, 2013), while others use the term "pathway" rather than "vector" (Carson *et al.*, 2013; Lewis, Riddle, & Smith, 2005). In keeping with the terminology employed by the NISC (established under Executive Order No. 13112, 1999) and other federal agencies (ANSTF, 1994), the term "pathway" will be used throughout this document when referring to dispersal mechanisms in a broad sense, and used to encompass all possible human-made or human-mediated mechanisms.

Known Pathways for Invasive Species

Globalization, or the integration of views, products, cultures, and ideas on an international scale, has vastly increased world travel and commerce. This process has led to an increase in the rate and magnitude of non-native species introductions through a variety of pathways (Ruiz, Carlton, Grosholz, & Hines, 1997; USEPA, 2012). In a report to the Pew Oceans Commission, Carlton (2001) identified pathways particularly susceptible to aiding marine invasions. These include ships (ballast water and hulls), drilling platforms, dry docks, aids to navigation, seaplanes, canals, public aquaria, research laboratories, marine debris, scuba and snorkeling equipment, fisheries (including aquaculture/mariculture and bait), the aquarium pet industry, habitat restoration activities, and releases from educational institutions.

Pathways associated with global shipping (e.g., ballast water and biofouling) are widely considered to be the most significant cause of human-mediated transoceanic dispersal of

Figure 1. Small vessel at Cape Disappointment (Photo Credit: Washington State Department of Ecology).

non-native marine and estuarine species (Carlton, 1987; Carlton, 2001; Lewis, Hewitt, Riddle, & McMinn, 2003; USEPA, 2012). Ballast water carried perhaps the greatest overall threat for transoceanic dispersal until recent times, as it is now controlled in part by national and international management policies (International Maritime Organization, 2016). The roles that many other pathways play in the dispersal of marine organisms are not well characterized (Williams *et al.*, 2013). Marine debris is one of the least understood anthropogenic pathways.

Historical Perspective: A Shifting Baseline?

The scale and extent of invasions by marine organisms may be greatly underestimated, seriously skewing our understanding of the history and ecology of many marine communities. Carlton (2011) suggests that many of the commonplace assumptions that we have regarding native species (crustaceans in the case of Carlton [2011]) may be erroneous. This is because global oceanic voyages for exploration, commerce, and fishing began in and have increased since the 1500s, yet the first marine biologists did not arrive on the shores of some continents to begin the process of identifying and cataloguing species until several centuries later. It is entirely possible that many of the indigenous or cosmopolitan species that we are trying to conserve are non-native species that "hitched a ride" or were purposefully introduced not more than a few hundred years ago.

"The scale and extent of invasions by marine organisms may be greatly underestimated, seriously skewing our understanding of the history and ecology of many marine communities."

MARINE DEBRIS AND INVASIONS OF MARINE SPECIES

A wide range of organisms occur on marine debris, including microbes, protists, plants, fungi, and members of many animal phyla. Which, if any, of these species are invasive? In keeping with the aforementioned definition of invasive species, we must recognize that for a species to be invasive, it needs to cause harm (or be likely to cause harm). We cannot assume that any species that attaches itself to marine debris is an invasive species, nor can we discount the possibility that it may become invasive.

The U.S. Department of Agriculture's National Invasive Species Information Center's website maintains a listing of invasive aquatic plants and animals in the United States (NISIC, 2016). The NISIC is a gateway to information about invasive species, created to meet the informational needs of the National Invasive Species Council (established under Executive Order No. 13112, 1999) and the public. Their website also contains a "watch list" of aquatic organisms that are known to be invasive on other continents, but have not made it to North American shores. In addition, the website maintains links to other global databases of introduced aquatic species.

In addition to the NISIC, the NEMESIS Database (Smithsonian Environmental Research Center, 2016) provides informational resources on non-native marine and estuarine species that occur in the coastal waters of the United States; it is maintained by the Smithsonian Institution. The United States Geological Survey (USGS) also maintains the Non-indigenous Aquatic Species (NAS) database (USGS, 2016), which contains an inventory of informational resources for introduced freshwater and marine aquatic species, with spatial references of biogeographical accounts.

It is important to note, however, that many modern-day invasions consist of species that were not on any watch list. A few examples include the Asian shore crab (*Hemigrapsus sanguineus*), now widespread along the Atlantic coast of the United States; the Chinese clam (*Corbula amurensis*), abundant in the San Francisco Bay; and the Australian green seaweed (*Caulerpa taxifolia*), which was introduced to Europe and other regions. None of these species were known to have a previous invasion history or were predicted to invade.

This paper will review the types of organisms that commonly associate with marine debris through several case studies from the literature. The goals are to describe how aquatic species associate with marine debris, provide context for understanding successful and unsuccessful invasions, and suggest knowledge gaps for further research to better understand the importance and impact of marine debris as a pathway for invasive species.

How Do Aquatic Species Associate with Marine Debris?

Aquatic species associate themselves with marine debris in a number of ways that stem directly from their natural ability to adjust and acclimate to changing conditions. On large pieces or aggregates of debris, it is likely that one would be able to document many, if not all, of the following groups. An extensive literature review by Thiel and Gutow (2005) reported over 1,200 species of sessile and motile organisms associated with natural and human-made debris from sources all over the globe. They grouped the organisms into two groups– facultative and obligate. The facultative species (959 species) were those known to live in natural benthic habitats and on debris items, whereas the obligate rafters (41 species) are known only

"We cannot assume that any species that attaches itself to marine debris is an invasive species, nor can we discount the possibility that it may become invasive."

to associate with floating debris, where they spend their entire life cycle.

BIOFILMS

Microorganisms (bacteria, microalgae, and fungi) have the ability to colonize various surfaces (Decho, 2000) of both organic (animals, plants [e.g. wood], protists, and fungi) and inorganic (sediments and rocks) origin. As part of the colonization process, microbes form a consortium and secrete a matrix of extracellular polymers (EPS) to create a "microbial biofilm" (Decho, 2000). In addition to serving as protection, this mucilaginous biofilm allows the various species of microbes within the matrix to mutually share nutrients, extracellular enzymes, and other essential compounds. Biofilms are also known to sequester metal contaminants and attract pathogens (Decho, 2000) and harmful algal bloom (HAB) species (Maso, Garces, Pages, & Camp, 2003).

It is widely accepted that microbes will colonize any surface in the marine environment (Lobelle & Cunliffe, 2011). To that end, biofilms are common on marine debris, yet only a few studies have addressed the issue (Lobelle & Cunliffe, 2011; Maso *et al*., 2003; Saldanha *et al*., 2003; Webb, Crawford, Sawabe, & Ivanova, 2009; Ye & Andrady, 1991). Thiel and Gutow (2005) reported 72 microbial species found on marine debris in their extensive literature review, including cyanobacteria (11 species), fungi (32 species), and microalgae (29 species). A study by Zettler, Minceer, and Amaral-Zettler (2013) revealed that there is an incredible host of microbes associated with small plastic marine debris (approximately less than 5mm), some of which may harbor pathogens, such as some members of the genus *Vibrio*.

Figure 2. Wakame kelp (Undaria pinnatifida), native to Japan and a known invasive species, was found in Oregon attached to debris that resulted from the Japan tsunami in 2011 (Photo Credit: Oregon State University, Hatfield Marine Science Center).

SESSILE ORGANISMS: ENCRUSTERS/ BIOFOULERS

The encrusting or biofouling community is perhaps the most recognized group of organisms on floating and beached marine debris. The encrusters consist of a variety of sessile organisms (i.e., those that do not move) including, but not limited to, bryozoans, barnacles, ascidians, hydroids, macroalgae, encrusting species of foraminiferans, and some mollusks and polychaetes (Winston, Gregory, & Stevens, 1997). Like biofilms, encrusters will attach to nearly any surface in the marine environment. Much attention has been particularly paid to fouling on boat hulls. In fact, hull fouling has been an impediment to marine transportation since humans first took to the ocean in boats. Encrusters significantly reduce hull speed and efficiency (Schultz, Bendick, Holm, & Hertel, 2010), so a great amount of effort and money is spent on preventing the fouling of ship hulls. For example, Schultz *et al.* (2010) estimated the overall cost associated with hull cleaning, hull coating, and fuel loss due to fouling to be approximately $56 million per year for the United States Navy's mid-size destroyer fleet (Arleigh Burke class destroyer DDG-51) of about 60 ships. When this cost is extrapolated to all of the commercial, military, and private vessels around the world, the enormity of the cost to control biofouling becomes highly apparent.

Knowledge of fouling on marine debris pales in comparison to that associated with the fouling of ships, but the impact of marine debris and its potential as a pathway for invasive species cannot be discounted. A variety of studies have observed encrusting organisms on marine debris, with some studies documenting non-native organisms present on beach- or shoreline-stranded debris (Barnes & Fraser, 2003; Barnes & Milner, 2005; Winston *et al*., 1997), and others focusing on floating debris (Astudillo, Bravo, Dumont, & Thiel, 2009; Bravo *et al*., 2011; Goldstein, Carson, & Eriksen, 2014). Thiel and Gutow (2005) reported that the vast majority of the species reported (of more than 1,200 species) on marine debris were from the phyla Cnidaria (Hydrozoa), Crustacea (Amphipoda), and Bryozoa.

To date, no studies document marine debris as being the sole pathway responsible for an invasion of encrusting organisms into a particular area. Given the multitude of potential pathways for the introduction of invasive species, the degree to which marine debris plays a role in the invasion of encrusting communities remains unclear.

"The impact of marine debris and its potential as a pathway for invasive species cannot be discounted."

MOBILE ORGANISMS: HITCH-HIKERS/ HANGERS-ON/AQUATIC RAFTERS

Gregory (2009) noted the possibility that mobile organisms may be associated with marine debris. In a recent study (Goldstein *et al*., 2014), a variety of plastic-associated rafting organisms were observed during Eastern and Western Pacific Ocean cruises from 2009 to 2012, with various sessile and mobile species reported. Ninety-five different taxa (largely arthropods, mollusks, and cnidarians) in 11 phyla were found on the debris, with an approximately equal distribution of mobile and sessile species. The taxa included many mobile grazers and predators, and were found on debris objects that were varied in size and diverse in composition. Many of the taxa found on the debris were known invaders (Goldstein *et al*., 2014). Previously, Thiel and Gutow (2005) reviewed this topic and found 410 arthropod species were associated with debris, with more than 100 mobile arthropod species. In another study (Astudillo *et al*., 2009), mobile species were identified as a major functional group found on floating detached aquaculture buoys off the coast of Chile.

TERRESTRIAL RAFTERS

Perhaps the earliest documented case of terrestrial organisms rafting on floating objects is an account of ants rafting on a floating log (Wheeler, 1916). There are few other reported cases of terrestrial flora or fauna rafting

Figure 3. A small derelict boat washed ashore on the remote Spring Island, British Columbia, Canada, and was positively identified as a vessel lost during the 2011 Japan tsunami (Photo Credit: Kevin Head).

"There are great impediments to survival of terrestrial organisms rafting great distances, including lack of shelter, exposure to salt water, wave action, lack of food, and lack of potable water, which likely explains why we do not see many documented cases of these organisms traveling great distances."

on floating items. In the case of the ants, they had reportedly floated a short distance from the mainland of Brazil to San Sebastian Island. There are great impediments to survival of terrestrial organisms rafting great distances, including lack of shelter, exposure to salt water, wave action, lack of food, and lack of potable water, which likely explains why we do not see many documented cases of these organisms traveling great distances. In the review by Thiel and Gutow (2005), a small number of non-marine or terrestrial species associated with mostly natural floating material was reported, but most were found in relatively close proximity to their native ranges. These included 12 species of non-marine arthropods, three species of amphibians, 17 species of reptiles, and two small mammal species.

While these occurrences are rare, it is believed that terrestrial species arrived and were established on many islands and distant shores by rafting on natural material over the millennia. A paper by Eldredge and Gould (1972) offered a controversial view on this topic when it was released, but is now considered a landmark paper. They suggested that speciation occurred not gradually over the course of millennia, but through punctuated events not unlike the Japan tsunami in 2011. There is geologic evidence for giant tsunamis, earthquakes, volcanic eruptions, and even meteor strikes, which likely ejected a great amount of natural drifting material (rafts) into the ocean that may have carried terrestrial species to distant shores.

Case Studies

REGIONAL STUDY: PLASTIC BEACH DEBRIS; EAST COAST OF FLORIDA

Three studies conducted in 1980, 1988, and 1994 along the East Coast of Florida surveyed beach-stranded debris items and associated biota (Winston *et al*., 1997). The studies primarily focused on plastic items that were largely colonized by encrusting organisms. Over 64 taxa were observed from nine phyla, and the dominant groups were foraminiferans, bryozoans, hydroids, algae, tube-building polychaetes, and barnacles. Four of the five dominant species were native species. These encrusters and benthic species appeared to have originated from Caribbean or Floridian coasts and islands. There was possibly one exotic bryozoan species reported, perhaps originating from the coast of Brazil. These studies also noted seasonal differences in the diversity of organisms and evidence of reproduction by the encrusters.

The plastic debris that was surveyed was predominantly of U.S. origin and probably originated from within 500 miles of the study site (Winston *et al*., 1997). To a lesser extent, some items originating from the Caribbean were noted, which agrees with prevailing current patterns in the region. Items manufactured in Portugal, Greece, and Scandinavia were observed, but the debris point of origin (i.e. where they were discarded) was not known. Since the majority of the debris and the associated species on the debris originated from within the region, range expansion of current inhabitants is more likely than new invasions by non-natives. There was no evidence found to suggest possible establishment or invasion by transoceanic, non-native species.

REGIONAL STUDY: AQUACULTURE BUOYS; SOUTHEASTERN PACIFIC, COAST OF CHILE

Astudillo *et al*. (2009) studied organisms associated with detached aquaculture buoys in the Southeastern Pacific off the coast of Chile from 2001 to 2005. Thirty-four detached buoys were surveyed and contained a total of 134 species representing 14 phyla. About 54% of the species were common across all buoys, and the overwhelming majority of them were indigenous to the region. The most common species were mobile species and suspension feeders, of which the majority had sexual reproduction strategies such as separate sexes, internal fertilization, and direct or very short larval development. Encrusting communities were found to be very mature and well-established.

These plastic buoys were found to originate from a common aquaculture operation in the Bay System of Coquimbo, Chile. Plastic buoys float higher out of the water, resulting in high windage which can cause them to be transported farther distances (Astudillo *et al*., 2009), as opposed to other types of plastic debris.

GLOBAL STUDY: OPEN OCEAN AND COASTAL DEBRIS; ATLANTIC OCEAN

In 2002, Atlantic Ocean shipboard surveys were conducted between hemispheres (from 68°S to 78°N) to compare floating open-ocean marine debris to debris stranded on beaches (Barnes & Milner, 2005). The Eastern North Atlantic (off of Europe) had the greatest amount of floating debris, and debris stranding densities were greatest in equatorial regions. Plastic pieces were the dominant debris type found in both the open ocean and stranded on beaches. While sampling was limited compared to the scale of the study, there was no change detected in the amount of debris collected when compared to a survey conducted ten years earlier.

During this study, organisms were only documented from beach-stranded debris and were predominately encrusters, such as balanomorph barnacles, pedunculate barnacles, byrozoans, hydroids, and polychaetes from sites across both hemispheres (Barnes & Milner, 2005). One exotic species (the invasive barnacle, *Elminius modestus*, now known as *Austrominius modestus*) was found attached to plastic debris in the Shetland Islands, United Kingdom. The barnacle is native to Australia, but was introduced to Britain in the 1940s during World War II (Crisp, 1958), presumably via biofouling from ships. In a prior survey, Harms (1990) found ten plastic debris items during a benthic survey in the Elbe Estuary (Germany Bight,

"Hurricanes, tsunamis, landslides, and floods can destroy property and can generate an extreme amount of debris in a very short period of time."

North Sea), of which eight had *A. modestus* attached. In total, 104 individuals of *A. modestus* were found (Harms, 1990). Barnes and Milner (2005) discussed that the impacts of marine debris on animal introductions are difficult to measure and that future oceanic surveys are warranted for a more inclusive picture.

GLOBAL STUDY: OPEN OCEAN DEBRIS; NORTH PACIFIC OCEAN

A study conducted in the North Pacific (Goldstein *et al.*, 2014) documented the taxa associated with floating debris in the open ocean between 2009 and 2012. Eighty-seven percent of the 242 debris items collected were rigid plastic fragments, and approximately 25% of those were larger than 2 cm in diameter. Ninety-five taxa from 11 phyla were observed associated with the debris, the majority of which were suspension feeders, with arthropods being the most dominant group. Ominvores, grazers, and predators were also present in significant numbers. Most of the taxa found were those commonly associated with rafting and fouling on debris, although about a quarter were not previously documented as being part of rafting assemblages. Goldstein *et al.* (2014) indicated that some of the observed taxa were known invaders, but they did not determine whether the populations that were encountered originated from their home range or from a new or expanded range.

NATURAL DISASTERS AND MARINE DEBRIS

Natural disasters can cause severe damage to property, loss of life, economic losses, and extreme environmental damage. Hurricanes, tsunamis, landslides, and floods can destroy property and can generate an extreme amount of debris in a very short period of time. This debris can be scattered in many directions and deposited in upland areas, on coasts and shorelines, or washed out to sea. In recent years, there have been a number of natural disasters that have generated a great deal of marine debris. One of the more serious events in recent years was the March 11, 2011 earthquake (9.0 magnitude) in Japan that triggered a tsunami, with waves up to 40 meters (NOAA, 2013b; Figure 4). The event devastated over 200 miles of coastline and resulted in great loss to human life and property. The debris generated from this event consisted of nearly any item imaginable, ranging from small plastics to derelict fishing vessels tens of meters long. Items began showing up along the West Coast of the United States about a year later in 2012.

Debris from a natural disaster can be different than other debris discarded into the ocean. Items such as floating docks, anchored buoys, and watercraft can get ripped loose or dislodged from moorings and washed out to sea. These items typically have mature, well-colonized communities of marine organisms. In addition, a great amount of debris from terrestrial sources can be injected into the ocean, and subsequently become colonized by marine life. Such disaster-generated debris is capable of floating across the ocean and stranding on foreign shores, resulting in a number of potential introductions (NOAA MDP, 2016). For example, four docks from the Port of Misawa, Japan were dislodged from their moorings during the Japan tsunami (Barnea *et al.*, 2014). Two of these docks drifted across the Pacific Ocean and stranded on the West Coast of the United States: one in Oregon (June 2012) and one in Washington (December 2012), while the third dock resurfaced in Hawai'i, but was not recovered. The dock that washed ashore in Oregon was covered in growth and contained numerous non-native species., while the dock that washed ashore in Washington had less coverage of biota. This could possibly be due to scouring in the surf zone, but more than 400 pounds of biota were removed from the dock, representing more than 60 species from coastal Japan (NOAA, 2013a). Both docks, which spent more than a year

Figure 4. Disaster-generated debris is capable of floating across oceans and stranding on foreign shores, resulting in a number of potential invasive species introductions. This figure shows the possible introductions resulting from marine debris generated by the March 11, 2011 earthquake (9.0 magnitude) and resulting tsunami in Japan.

at sea, contained significant and thriving communities of organisms at the time of their stranding on the West Coast of the United States.

Framework for Invasion

Numerous frameworks or models have been proposed for the invasion process (Richardson *et al*., 2000; Shea & Chesson, 2002; Williamson & Fitter, 1996; Williamson, 1996). Blackburn *et al*. (2011) developed a unified framework that combined many of the concepts and ideas of previous models, outlining four stages for an organism to become an invasive species in a new range. First, the species must be *transported* to the foreign range via a pathway. Second, the species must be *introduced* to the foreign range. Third, the species must become *established* in the foreign range, which includes survival and reproduction. Finally, the species must spread in that range to become invasive.

The reality is that there are far more *failed* invasions as a result of species introductions than successful invasions (Blackburn *et al*., 2011; Lockwood, Cassey, & Blackburn, 2005; Zenni & Nuñez, 2013). This is due to the numerous barriers in each stage of the invasion framework. In order to understand the likelihood that an introduced species will successfully invade a new range, it is important to gain an understanding of past failed invasions and the reasons for those failures (Zenni & Nuñez, 2013).

Zenni and Nuñez (2013) found five main factors that contribute to the failure of a species invasion. These include poor propagule pressure, abiotic resistance, biotic resistance, genetic constraints, and mutualist release. As a pathway for invasive species introduction, marine debris adds additional complexity and barriers to the *transportation* stage of the framework. These barriers include distance and transit hurdles, harsh environments, and complications for reproduction such as dispersal issues associated with differing developmental strategies.

One of the first and most obvious barriers to invasion for a species utilizing marine debris as a pathway is that it first must establish itself on the debris. Encrusting organisms, for example, are particularly well-adapted to colonizing human-made surfaces, including the hulls of ships, marine debris, docks, buoys, jetties, and platforms. There is also the case of coastal structures and vessels (such as docks, barges, derelict watercraft, lost/adrift buoys, etc.) that are often completely colonized with biota at the point of origin or release. Debris cast off of ships can then become colonized by organisms as it drifts into various regions or ecosystems. Non-encrusting organisms are often embedded into the encrusting communities on marine debris.

For short or regional transits, the species may survive without the need for extensive habitat resources. For longer transits, a species or community of species will require all of the necessary resources to survive the transit. In many respects, they must first become established on the debris. Many of the barriers associated with the introduction of a species to a new range also exist with respect to an organism being associated with the marine debris.

PROPAGULE PRESSURE

The issue of propagule pressure is not unique to organisms using marine debris as a pathway of introduction. Propagule pressure is defined as the composite number of viable, non-native individual organisms introduced into a new range (Lockwood *et al*., 2005; Roman & Darling, 2007; Zenni & Nuñez, 2013). There are two components to propagule pressure— size and number, which

Figure 5. A worker uses a 30% bleach spray to decontaminate and reduce the spread of possible marine invasive species on the Japanese dock which made landfall on Washington's Olympic Peninsula in December 2012 (right; Photo Credit: Allen Pleus, Washington Department of Fish & Wildlife).

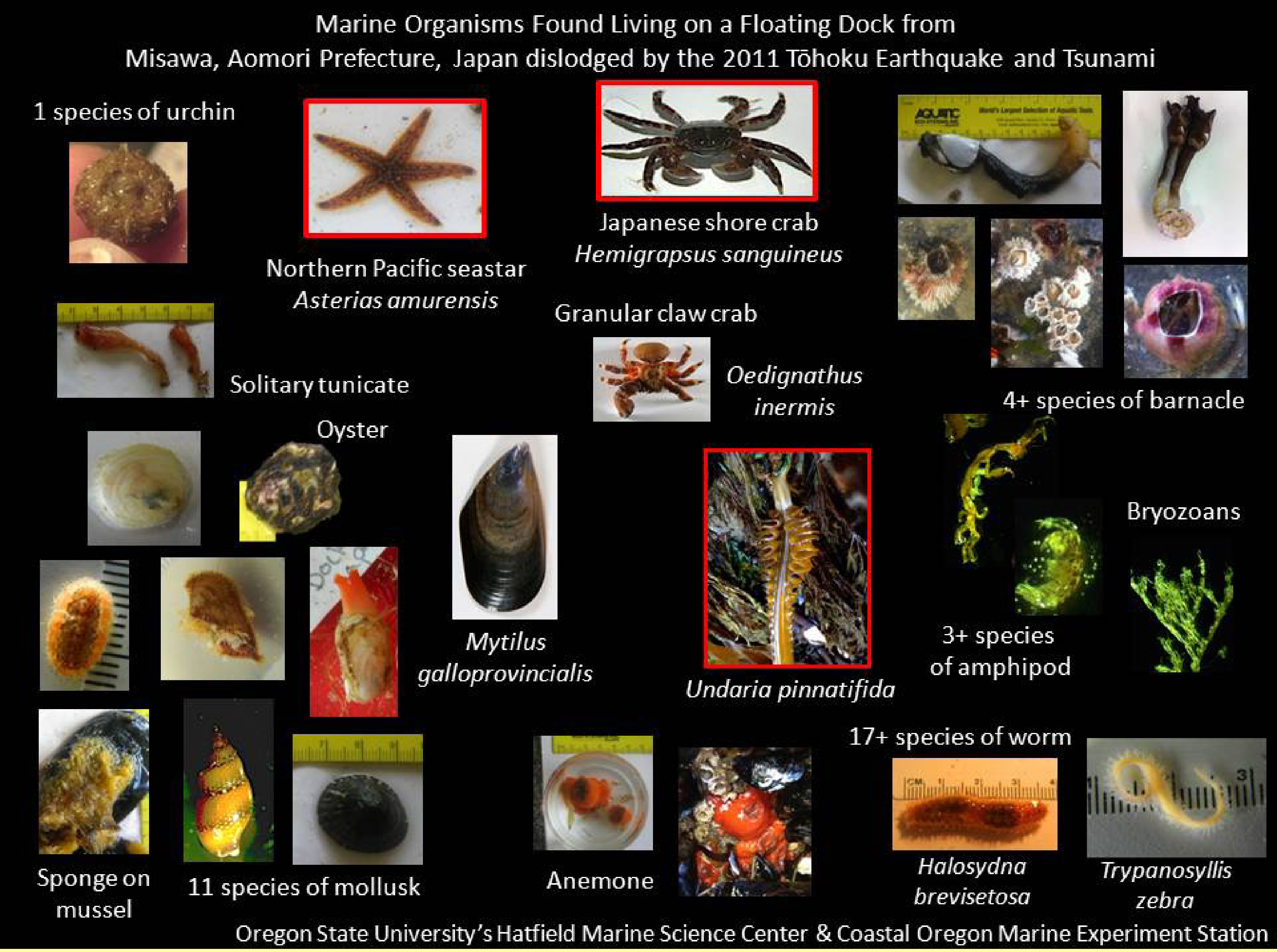


Figure 6. The marine organisms that were found on the derelict Misawa floating dock that washed ashore on Agate Beach in Newport, Oregon (Photo Credit: Oregon State University, Hatfield Marine Science Center).

refer to the number of individuals in a single release and the number of release events. The size of a piece of marine debris is directly proportional to its potential propagule size since the larger the debris, the more individuals it can carry. Goldstein *et al.* (2014) found the size of the debris is positively correlated with the number of taxa found on the debris. The number of pieces of debris originating from a particular locale is a contributor to propagule number. The concept of propagule quality has also been introduced (National Research Council [NRC], 2011), which relates to the viability of the organisms and/or their capacity to reproduce.

The significance of small, isolated pieces of marine debris with minimal associated biota remains unclear. Given the extremely poor propagule pressure attributed to a small, isolated piece of debris, we can speculate that the risk for invasion is decreased. Conversely, large pieces of marine debris, such as the Misawa docks (Barnea *et al.*, 2014), have significantly increased propagule pressure and, in turn, the risk of invasion success is increased. Many small pieces of debris originating from the same area, such as the aquaculture buoys off of Chile (discussed on page 14; Astudillo *et al.*, 2009), can also have a significantly increased risk of invasion success. While the propagule size for an individual detached buoy is small, the numerous buoy losses over time from Chilean aquaculture facilities constitute a significantly increased invasion risk due to the high propagule number (multiple releases).

CONCLUSION

A Successful Invasion via Marine Debris

The early thinking was that a successful invasion could include one male and one female, or a single fertilized female, to cause the establishment of a species in a new range (Wheeler, 1916). However, given the many barriers to transportation, introduction, establishment, and spread, we see the process is much more complicated.

Currently there are no reported invasions solely due to marine debris as a pathway (J.T. Carlton, personal communication). This is, in part, because teasing out which of many pathways brought a species to a new region has often proved challenging (Carlton & Ruiz, 2005). Molecular genetic techniques may assist in ferreting out probable source populations and thus may be useful in helping to identify possible pathways of introduction. Despite these challenges, we cannot dismiss marine debris as a potential pathway in invasion biology. There are several scenarios whereby marine debris may play a role in species invasions.

REGIONAL INVASIONS AND RANGE EXPANSIONS:

In any given region, the majority of marine debris likely originates from the region itself or nearby locations (Winston *et al*., 1997) and in populated coastal areas, increased debris loads have been observed (Barnes & Milner, 2005; Ribic, Sheavly, Rugg, & Erdmann, 2012; Wei, Rowe, Nunnally, & Wicksten, 2012; Winston *et al*., 1997). Marine debris, in concert with other pathways, may play a role in the range expansion of native and introduced species when coupled with climate change impacts (Mainka & Howard, 2010; Figure 7). Climate change impacts that may drive range expansions and new invasions include changing temperatures, changing precipitation patterns, changing air and ocean chemistry, and changing ocean circulation (Mainka & Howard, 2010).

Regional dispersal via marine debris could foster the range expansion of organisms that reproduce sexually or asexually. Due to the sheer amount of debris that can be present, propagule pressure is greatly increased, allowing the organism to overcome genetic constraints and have increased mate encounters. Organisms that have larval developmental strategies are at an advantage in regional dispersal scenarios. If adult forms of organisms are able to associate with debris or other pathways and reproduce, then they can potentially extend the maximum 'reach' of their larvae's dispersal limits (Mainka & Howard, 2010).

TRANSOCEANIC INVASIONS:

For global or transoceanic introductions via marine debris, barriers to invasion are numerous and thus the potential for invasion is more limited. Like regional dispersal mechanisms, species encrusted on oceanic pieces of marine debris must have sufficient propagule pressure. However, large debris items (such as Japanese tsunami debris—the Misawa docks) with mature communities of organisms are of particular concern. These communities have greatly increased propagule size and quality, containing many individuals of many different species at various life-history stages. While there are a number of variables at play, the communities of organisms on this large debris can have reduced founder effects and increased mate encounters once they reach a foreign range. Increased debris loads in the ocean

"For global or transoceanic introductions via marine debris, barriers to invasion are numerous and thus the potential for invasion is more limited."

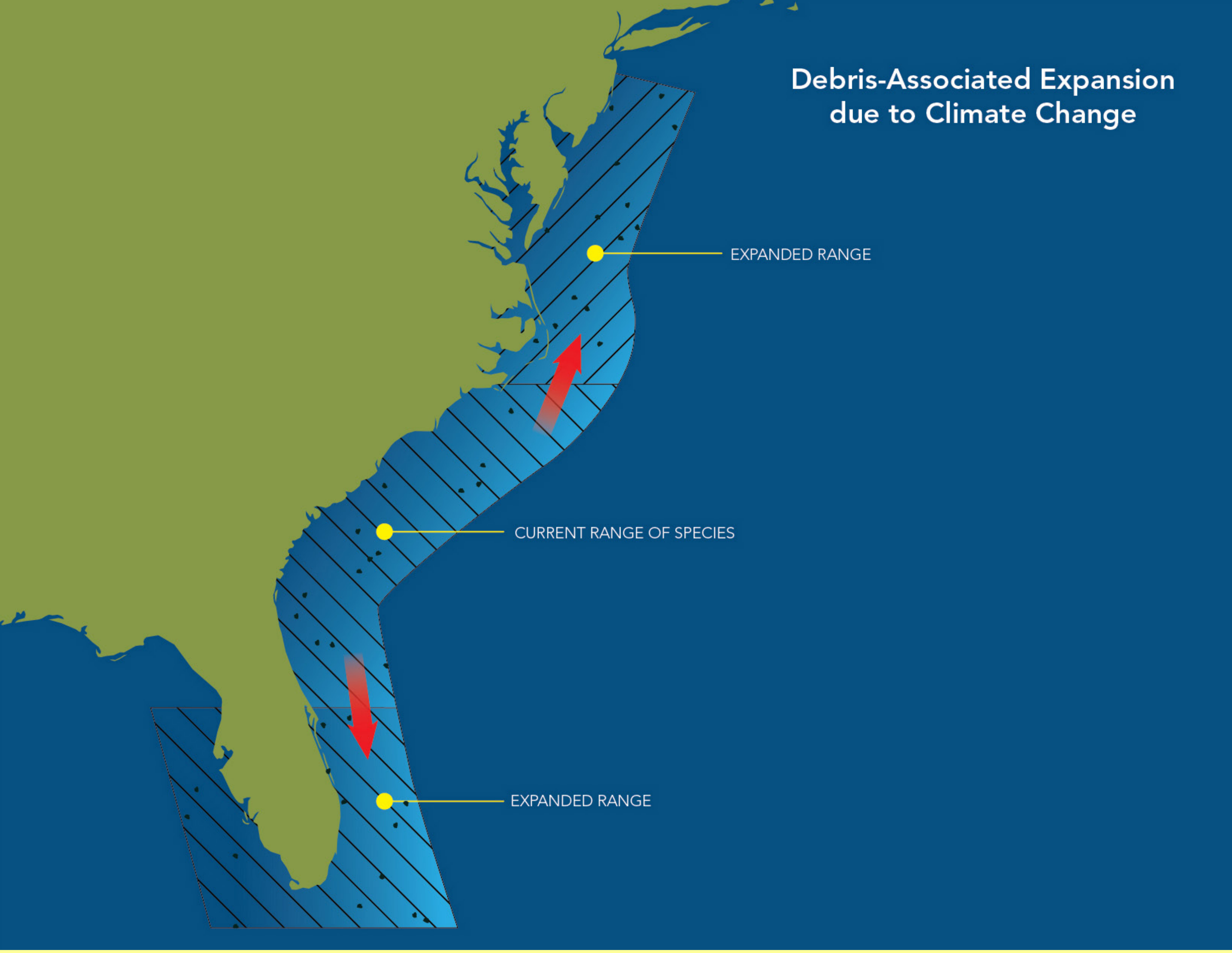


Figure 7. Regionally, marine debris, in concert with other pathways, may play a role in range expansion of native and introduced species when coupled with climate change impacts.

resulting from extreme events may increase the chance of transoceanic species introductions.

Assisted Invasion by Marine Debris

While much attention is given to marine debris' potential to start prolific and damaging invasions by non-native species, marine debris-assisted invasion of established invasive species (Winston *et al.*, 1997) is also a concern, although this has not been well documented (Figure 8). A possible scenario could be an invading organism arriving to a new range as larvae via ballast water or hull biofouling from a home range thousands of miles away. Through high propagule pressure, the organism may settle, become established, and reproduce in the new range. A variety of local or regional pathways, including marine debris, may then assist in the continued spread of the invasion.

As an example, the invading Australian barnacle *A. modestus* (as discussed on page 14) was introduced via ballast water to the United Kingdom during World War II (Crisp, 1958). Since that time, the barnacle has spread throughout the U.K. and Europe, predominantly by larval dispersal on coastal currents. Barnes and Milner (2005) observed high densities of floating debris in those waters off of Europe and the U.K. and found *A. modestus* attached to plastic debris on the shores of the Shetland Islands. In another study, newly-settled individuals of *A. modestus* were found on plastic debris from a benthic trawl in the Elbe Estuary

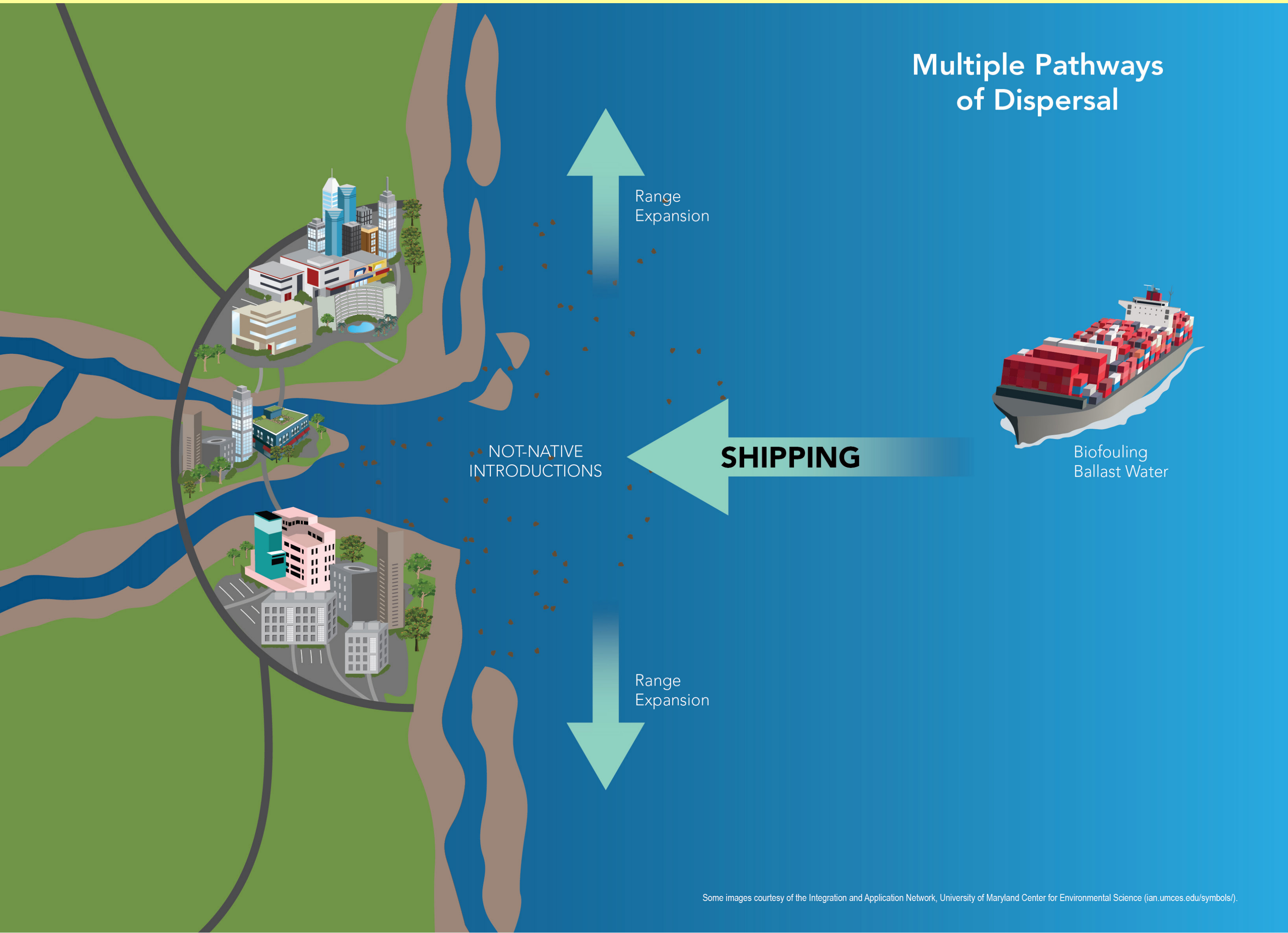
> **"The debris was not serving as a transport mechanism, but rather as a mechanism that serves to increase the number of individuals in a given area by providing more habitat."**

near Germany (Harms, 1990). In that case, the debris was not serving as a transport mechanism, but rather as a mechanism that serves to increase the number of individuals in a given area by providing more habitat. This may lead to increased larval dispersal, which is the primary mechanism for dispersal of *A. modestus*. While the role of marine debris is perhaps very minimal in this case, it may assist in the proliferation of the established invasive species by providing additional pathways or increased habitat areas.

Summary and Knowledge Gaps

The issues surrounding marine debris as a pathway for invasive species are complex and not well understood. What we do know is that while there are numerous barriers for a species to overcome, thousands of aquatic and terrestrial invasions have been successful through a variety of pathways. On one hand, we might predict that invasion risk is very low with regard to marine debris as a pathway given these barriers. On the other hand, invasion risk may

Figure 8. A variety of local or regional pathways, including marine debris, can assist in the continued spread of established invasive species introduced to the area through other pathways, such as shipping.



be high under certain situations and scenarios. We must also consider the fact that debris loads are still increasing (Jambeck *et al*., 2015). This suggests that the overall risk for impacts due to marine debris is increasing. While definitive examples of invasion via marine debris elude scientists, there is a potential risk of invasion based on the weight of evidence. Here is what we know:

- The amount of debris in the ocean is increasing.
- Organisms from distant shores are found attached to or associated with marine debris.
- Some of the organisms associated with debris are known invaders.
- Debris loads are heaviest in populated areas.
- Large pieces of debris can harbor more organisms and can float long distances.
- Extreme events such as cyclonic storms, earthquakes, and tsunamis can produce enormous amounts of debris.
- During the introduction of a non-native species, increased numbers of individuals may increase the chances of invasion success.

Concerns regarding invasions of organisms have prompted many studies in both terrestrial and aquatic systems. Awareness of marine debris and the various issues associated with it are beginning to gain national and global attention. Despite a number of studies documenting the association of various species with marine debris, there are significant gaps in the knowledge base and a multitude of questions persist. While this list of questions is by no means comprehensive, it serves as a starting point to begin the dialog to understand the problem:

- As a pathway of introduction, how large of a role does marine debris play in species invasions when compared with other pathways, such as shipping?
- What are the settlement densities of organisms on marine debris?
  –By debris type/composition/size?
  –By point of origin?
  –For debris discarded in the open sea versus debris discarded in estuaries that then float out to sea?
- Are microplastics in the ocean pathways for the introduction of microorganisms? Do microplastics harbor pathogens?
- How do communities of organisms change over time (ecological succession) on large debris pieces in the open ocean? Do some organisms out-compete others on the debris?
- Do species assemblages on floating marine debris differ significantly from species assemblages on beach-stranded items within the same region?

Recommendations

Based on the information discussed in the body of this report, the following recommendations are meant to assist in the further study and reduction of the potential for marine debris to act as a pathway for invasive species.

- Work with the National Invasive Species Council to integrate marine debris into the National Invasive Species Management Plan.
- Develop targeted approaches to reduce the potential spread of invasive species via marine debris.

  –Regionally:

  - Identify major debris generation points.
    –Work with regional agencies to engage the responsible parties to reduce and eliminate debris at its source.
    –Identify operations or generation points that consistently release the same type of debris (i.e. aquaculture or fishing operations).
  - Identify new types of gear or new practices that will reduce or eliminate the release of the debris.
  - Conduct beach and river sweeps; network with beach cleanups to gather data on encrusters and growth rates on debris and

provide debris to the scientific community for analysis.

–Globally:

- Identify large pieces of debris in the ocean.
  –Explore international efforts to mark and track (GPS) the large items.
  –Remove large items if feasible.

–Disaster Debris:

- As part of an overall emergency response plan/standard operating procedure:
  –Compile a listing of large resources, facilities, vessels, docks, etc. that are unaccounted for in the aftermath of the event.
  –Use models and remote sensing technologies to find and/or predict the location of large floating debris.
  –Explore international efforts to mark and track (GPS) the large items.
  –Remove large items if feasible.

REFERENCES

Aquatic Nuisance Species Task Force. (1994). Aquatic Nuisance Species Program. Washington, D.C.: Aquatic Nuisance Species Task Force.

Astudillo, J. C., Bravo, M., Dumont, C. P., & Thiel, M. (2009). Detached aquaculture buoys in the SE Pacific: Potential dispersal vehicles for associated organisms. *Aquatic Biology*, 5, 219-231.

Barnea, N., Albins, A., Cialino, K., Koyanagi, K., Lippiatt, S., Murphy, P., & Parker, D. (2014). *Proceedings of the Japan Tsunami Marine Debris Summary Meeting*. (NOAA Technical Memorandum NOS-OR&R-50). NOAA Marine Debris Program.

Barnes, D. K. A., & Fraser, K. P. P. (2003). Rafting by five phyla on man-made flotsam in the Southern Ocean. *Marine Ecology Progress Series*, 262, 289-291.

Barnes, D. K. A., Galgani, F., Thompson, R. C., & Barlaz, M. (2009). Accumulation and fragmentation of plastic debris in global environments. *Philosophical Transactions of The Royal Society B*, 364, 1985-1998.

Barnes, D. K. A., & Milner, P. (2005). Drifting plastic and its consequences for sessile organism dispersal in the Atlantic Ocean. *Marine Biology*, 146, 815-825.

Blackburn, T. M., Pyšek, P., Bacher, S., Carlton, J. T., Duncan, R. P., Jarošík, V., … & Richardson, D. M. (2011). A proposed unified framework for biological invasions. *Trends in Ecology & Evolution*, 26, 333-339.

Bravo, M., Astudillo, J. C., Lancellotti, D., Luna-Jorquera, G., Valdivia, N., & Thiel, M. (2011). Rafting on abiotic substrata: Properties of floating items and their influence on community succession. *Marine Ecology Progress Series*, 439, 1-17.

Carlton, J. T. (1987). Patterns of transoceanic marine biological invasions in the Pacific Ocean. *Bulletin of Marine Science*, 41, 452-465.

Carlton, J. T. (1999). Molluscan invasions in marine and estuarine communities. *Malacologia*, 41, 439-454.

Carlton, J. T., (2001). *Introduced species in US coastal waters: Environmental impacts and management priorities*. Arlington, Virginia: Pew Oceans Commission.

Carlton, J. T. (2011). The global dispersal of marine and estuarine crustaceans. In: Galil, B. S., P. F. Clark, & J. T. Carlton (Eds.), *In the wrong place—Alien marine crustaceans: Distribution, biology and impacts* (pp. 3-23). Netherlands: Springer.

Carlton, J. T., & Ruiz, G. M. (2005). Vector science and integrated vector management in bioinvasion ecology: Conceptual frameworks. In Mooney, H. A., R. N. Mack, J. A. McNeely, L. E. Neville, P. J. Schei, & J. K. Waage (Eds.), I*nvasive alien species* (pp. 36-53). Washington D. C.: SCOPE – Scientific Committee on Problems of the Environment Council of Scientific Unions, Island Press.

Carson, H. S., Lamson, M. R., Nakashima, D., Toloumu, D., Hafner, J., Maximenko, N., & McDermid, K. J. (2013). Tracking the sources and sinks of local marine debris in Hawai'i. *Marine Environmental Research*, 84, 76-83.

Coast Guard and Maritime Transportation Act of 2012, Pub. L. No. 112-213.

Crisp, D. J. (1958). The spread of Elminius modestus Darwin in North-West Europe. *Journal of the Marine Biological Association of the United Kingdom*, 37, 483-520.

Decho, A. W. (2000). Microbial biofilms in intertidal systems: An overview. *Continental Shelf Research*, 20, 1257-1273.

Eldredge, N., & Gould, S. J. (1972). Punctuated equilibria: An alternative to phyletic gradualism. In Schopf, T. (Ed.), *Models in paleobiology* (pp. 82-115). San Francisco: Freeman, Cooper & Co.

Exec. Order No. 13,112, 3 C.F.R. 6183-6186 (1999).

Fenichel, E. P., Horan, R. D., & Bence, J. R. (2010). Indirect management of invasive species through bio-controls: A bioeconomic model of salmon and alewife in Lake Michigan. *Resource and Energy Economics*, 32, 500-518.

Goldstein, M. C., Carson, H. S., & Eriksen, M. (2014). Relationship of diversity and habitat area in North Pacific plastic-associated rafting communities. *Marine Biology*, 161(6), 1441-1453.

Gregory, M. R. (2009). Environmental implications of plastic debris in marine settings - entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. *Philosophical Transactions of The Royal Society B*, 364, 2013-2025.

Harms, J. (1990). Marine plastic litter as an artificial hard bottom fouling ground. *Helgoländer Meeresuntersuchungen*, 44, 503-506.

International Maritime Organization. (2016). *Ballast water management*. Retrieved from: http://www.imo.org/en/OurWork/Environment/BallastWaterManagement/Pages/Default.aspx

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A.,…Law, K. L. (2015). Plastic waste inputs from land into the ocean. *Science*, 347(6223), 768-771.

Lewis, P. N., Hewitt, C. L., Riddle, M., & McMinn, A. (2003). Marine introductions in the Southern Ocean: an unrecognised hazard to biodiversity. *Marine Pollution Bulletin*, 46, 213-223.

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

Lippiatt, S., Opfer, S., & Arthur, C. (2013). *Marine debris monitoring and assessment: Recommendations for monitoring debris trends in the marine environment* (NOAA Technical Memorandum NOS-OR&R-46). NOAA Marine Debris Program.

Lobelle, D., & Cunliffe, M. (2011). Early microbial biofilm formation on marine plastic debris. *Marine Pollution Bulletin*, 62, 197-200.

Lockwood, J. L., Cassey, P., & Blackburn, T. (2005). The role of propagule pressure in explaining species invasions. *Trends in Ecology & Evolution*, 20, 223-228.

Lodge, D. M., Williams, S., MacIsaac, H. J., Hayes, K. R., Leung, B., Reichard, S., … McMichael, A. (2006). Biological invasions: Recommendations for U.S. policy and management. *Ecological Applications*, 16, 2035-2054.

Mainka, S. A., & Howard, G. W. (2010). Climate change and invasive species: Double jeopardy. *Integrative Zoology*, 5, 102-111.

Marine Debris Act, 33 U.S.C. §§ 1951-1958.

Maso, M., Garces, E., Pages, F., & Camp, J. (2003). Drifting plastic debris as a potential vector for dispersing Harmful Algal Bloom (HAB) species. *Scientia Marina*, 67, 107-110.

Molnar, J. L., Gamboa, R. L., Revenga, C., & Spalding, M. D. (2008). Assessing the global threat of invasive species to marine biodiversity. *Frontiers in Ecology and the Environment*, 6, 485-492.

National Invasive Species Act, Pub. Law No. 104-332.

National Invasive Species Council. (2006). Invasive Species Definition Clarification and Guidance White Paper. Retrieved from: https://www.invasivespeciesinfo.gov/docs/council/isacdef.pdf

National Invasive Species Council. (2008). 2008-2012 National Invasive Species Management Plan. Washington, D.C.: National Invasive Species Council.

National Invasive Species Information Center. (2016). *USDA National Invasive Species Information Center*. Retrieved from: https://www.invasivespeciesinfo.gov/index.shtml

National Oceanic and Atmospheric Administration. (2013a). The response to the Misawa dock on the Washington coast: Summary report and lessons learned. Silver Spring, MD: National Oceanic and Atmospheric Administration.

National Oceanic and Atmospheric Administration. (2013b). Severe marine debris event report: Japan tsunami marine debris. Silver Spring, MD: National Oceanic and Atmospheric Administration.

National Oceanic and Atmospheric Administration Marine Debris Program. (2016). https://marinedebris.noaa.gov

National Research Council. (2011). Assessing the relationship between propagule pressure and invasion risk in ballast water. In Carlton, J., G. Ruiz, J. Byers, A. Cangelosi, F. Dobbs, E. Grosholz, B. Leung *et al*., (Eds.), Washington, D.C.: National Research Council.

Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990, 16 U.S.C. §§ 4701-4751.

Ray, G. L. (2005). Invasive animal species in marine and estuarine environments: Biology and ecology (DTIC Document).

Ribic, C. A., Sheavly, S. B., Rugg, D. J., & Erdmann, E. S. (2012). Trends in marine debris along the U.S. Pacific Coast and Hawai'i 1998–2007. *Marine Pollution Bulletin*, 64, 994-1004.

Richardson, D. M., Pyšek, P., Rejmánek, M., Barbour, M. G., Panetta, F. D., & West, C. J. (2000). Naturalization and invasion of alien plants: Concepts and definitions. *Diversity and Distributions*, 6, 93-107

Roman, J., & Darling, J. A. (2007). Paradox lost: genetic diversity and the success of aquatic invasions. *Trends in Ecology & Evolution*, 22, 454-464.

Ruiz, G. M., Carlton, J. T., Grosholz, E. D., & Hines, A. H. (1997). Global invasions of marine and estuarine habitats by non-indigenous species: Mechanisms, extent, and consequences. *American Zoologist*, 37, 621-632.

Saldanha, H. J., Sancho, G., Santos, M. N., Puente, E., Gaspar, M. B., Bilbao, A., ... Arregi, L. (2003). The use of biofouling for ageing lost nets: A case study. *Fisheries Research*, 64, 141-150.

Schultz, M. P., Bendick, J. A., Holm, E. R., & Hertel, W. M. (2010). Economic impact of biofouling on a naval surface ship. *Biofouling*, 27, 87-98.

Shea, K., & Chesson, P. (2002). Community ecology theory as a framework for biological invasions. *Trends in Ecology & Evolution*, 17, 170-176.

Smithsonian Environmental Research Center. (2016). *National exotic marine and estuarine species information system (NEMESIS)*. Retrieved from: http://invasions.si.edu/nemesis/

Smits, J., & Moser, F. (2009). Rapid response planning for aquatic invasive species: A Maryland example. In Smits, J. & F. Moser (Eds.), *Mid-Atlantic Panel on Aquatic Invasive Species*. Maryland: Maryland Sea Grant College, University System of Maryland.

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

United Nations Environment Programme. (2009). Marine Litter: A Global Challenge. Nairobi: UNEP.

United Nations Environment Programme. (2011). Marine debris as a global environmental problem: Introducing a solutions based framework focused on plastic. In Thompson, B. E. L. R., H. Bouwman, L. Neretin (Eds.).

United States Environmental Protection Agency. (2012). Pathways for Invasive Species Introduction. U.S. Environmenatl Protection Agency.

United States Fish and Wildlife Service. (2011). Pathways. U.S. Fish and Wildlife Service, Department of Interior.

United States Geological Survey. (2016). *Nonindigenous aquatic species*. Retrieved from: https://nas.er.usgs.gov/Default.aspx

Webb, H. K., Crawford, R. J., Sawabe, T., & Ivanova, E. P. (2009). Poly(ethylene terephthalate) polymer surfaces as a substrate for bacterial attachment and biofilm formation. *Microbes and Environments*, 24, 39-42.

Wei, C. L., Rowe, G. T., Nunnally, C. C., & Wicksten, M. K. (2012). Anthropogenic "litter" and macrophyte detritus in the deep Northern Gulf of Mexico. *Marine Pollution Bulletin*, 64, 966-973.

Wheeler, W. M. (1916). Ants carried in a floating log from the Brazilian mainland to San Sebastian Island. *Psyche*, 23, 180-183.

Williams, S. L., Davidson, I. C., Pasari, J. R., Ashton, G. V., Carlton, J. T., Crafton, …Zabin, C. J. (2013). Managing Multiple Vectors for Marine Invasions in an Increasingly Connected World. *BioScience*, 63, 952-966.

Williamson, M., & Fitter, A. (1996). The Varying Success of Invaders. *Ecology*, 77, 1661-1666.

Williamson, M. H. (1996). *Biological invasions: Population and community biology series* (15). London: New York Chapman & Hall.

Winston, J. E., Gregory, M. R., & Stevens, L. M. (1997). Encrusters, epibionts, and other biota associated with pelagic plastics: A review of biogeographical, environmental, and conservation issues. In Coe, J., & D. Rogers (Eds.), *Marine Debris* (pp. 81-97). New York: Springer Series on Environmental Management, Springer New York.

Ye, S., & Andrady, A. L. (1991). Fouling of floating plastic debris under Biscayne Bay exposure conditions. *Marine Pollution Bulletin*, 22, 608-613.

Zenni, R. D., & Nuñez M. A. (2013). The elephant in the room: the role of failed invasions in understanding invasion biology. *Oikos*, 122, 801-815.

Zettler, E. R., Mincer, T. J., & Amaral-Zettler, L. A. (2013). Life in the "plastisphere": Microbial communities on plastic marine debris. *Environmental Science & Technology*, 47, 7137-7146.

GLOSSARY

Abiotic resistance – Physical or chemical factors that inhibit the introduction and establishment of a non-native species to a new range, such as temperature, light availability, sediment/substrate type, or flow dynamics.

Aquatic invasive species (AIS) – Refers specifically to invasive species that reside in aquatic environments (Smits & Moser, 2009).

Aquatic Nuisance Species – A nonindigenous species that threatens the diversity or abundance of native species or the ecological stability of infested waters, or commercial, agricultural, aquacultural or recreational activities dependent on such waters (NANPCA, 16 U.S.C. §§ 4701-4751).

Biofilm – A consortium of microorganisms living in a matrix of extracellular polymers on surfaces.

Biotic resistance – Biological factors that inhibit the introduction and establishment of a non-native species to a new range, such as competition or predation.

Dispersal – Any movement of a species that ultimately results in increased gene flow (Ronce, 2007).

Founder effect – A loss in genetic diversity in a population that was established by a small number of individuals.

Genetic bottleneck – An extreme reduction in the demographic size of a population.

Introduced species – Refers to a species that is transported by humans or human activities into areas outside of their natural ranges. The means of introduction may be intentional or unintentional escape, release, dissemination, or placement (Executive Order No. 13122, 1999).

Invasive – Tending to spread prolifically and undesirably or harmfully.

Invasion success – The successful introduction, reproduction, and invasion by a non-native species to a new range.

Invasive species – A species that is non-native to the ecosystem under consideration and whose introduction causes, or is likely to cause, economic or environmental harm or harm to human health (Clinton, 1999; NISC, 2006).

Mutualism – A symbiotic relationship between two species when both partners benefit from the association.

Native species – Refers to a species in a particular ecosystem that historically occurred or currently occurs in that ecosystem and was not introduced (Executive Order No. 13122, 1999); a species in its natural range.

Non-native species (synonyms: alien, exotic, non-indigenous, ornamental) – Refers to any species residing outside of its currently-reported natural range.

Pathway – A dispersal mechanism that encompasses all possible human-made or man-mediated mechanisms.

Phenotypic plasticity – The ability of an organism to change its physical characteristics or traits in response to changes in the environment.

Polyphagous – Able to eat many different types of food.

Propagule pressure – The composite number of viable, non-native individual organisms introduced into a new range (Lockwood *et al*., 2005; Roman & Darling, 2007; Zenni & Nuñez, 2013).

United States Secretary of Commerce

Benjamin P. Friedman
Acting Under Secretary of Commerce for Oceans and Atmosphere

Dr. Russell Callender
Assistant Administrator, National Ocean Service