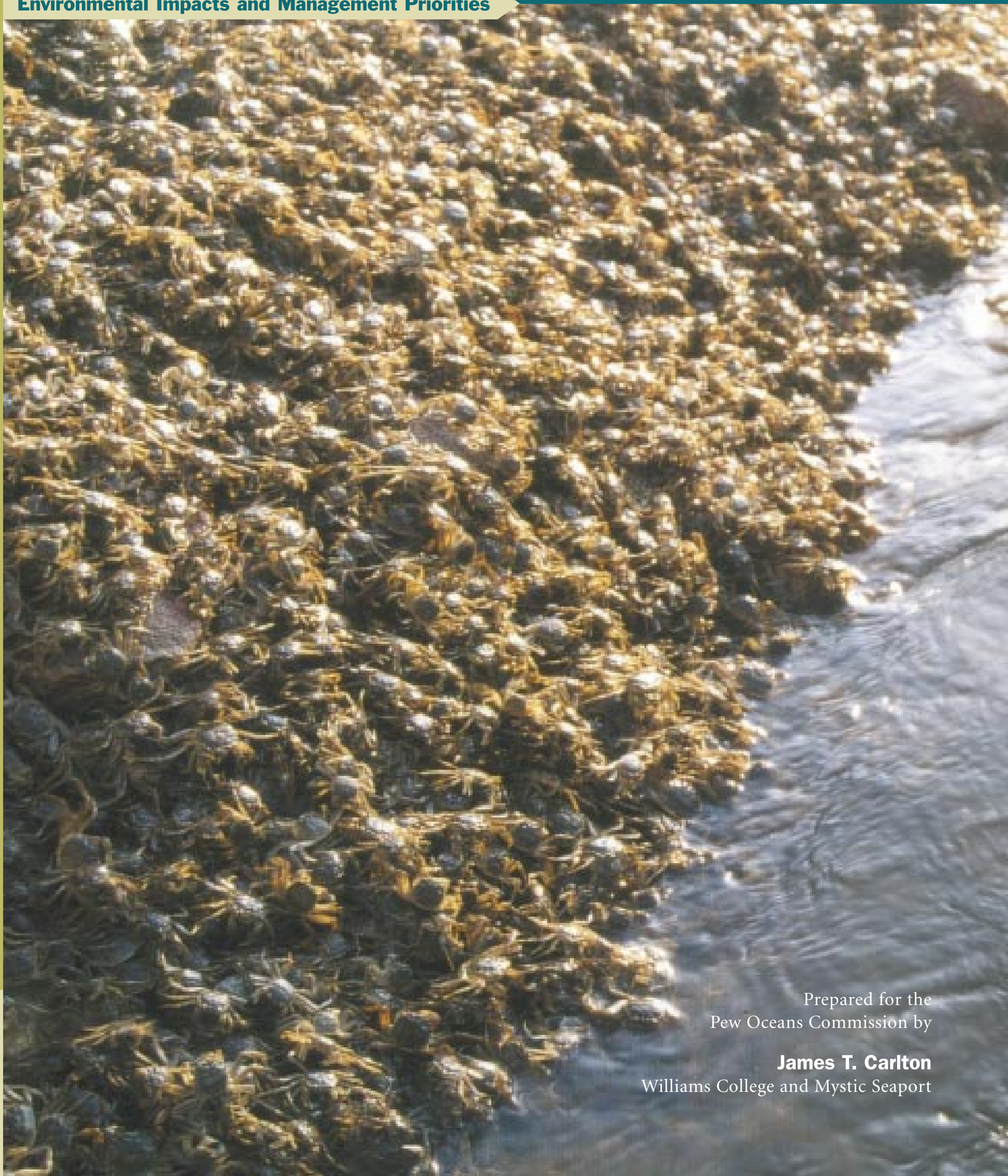
Introduced Species
IN U.S. COASTAL WATERS

Environmental Impacts and Management Priorities



Prepared for the
Pew Oceans Commission by

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PEW OCEANS COMMISSION

Front and Back Cover: *An army of juvenile Chinese mitten crabs carpets a riverbank along the Elbe near Geesthacht, Germany. Researchers believe that Chinese mitten crabs were accidentally introduced to German waters through ballast water carried on ships from China in the early 1900s. Chinese mitten crabs are born in marine and brackish waters. Juvenile crabs migrate long distances upstream to live in fresh water for two to four years and then travel back to salt water to reproduce and die. The crabs excavate burrows—some as deep as 20 inches (51 cm)—along riverbanks, causing bank erosion and levee damage. Large numbers of these crabs can damage commercial fishing nets and kill the intended catch.*

Contents

Abstract

Introduced species are a growing and imminent threat to living marine resources in the United States. Hundreds of species arrive in U.S. waters from overseas each day, playing a game of ecological roulette with ecosystem and economic stability. These species arrive by way of ships' ballast water and hull fouling, by fisheries activities, and by other means. Hundreds of introductions have occurred and non-native species now inhabit many coastal marine communities from the Hawaiian Islands to New England. Every assessment indicates that the rate of marine introductions in U.S. waters has increased exponentially over the past 200 years and there are no signs that these introductions are leveling off. New introductions are occurring regularly on all coasts, producing immediate and damaging impacts, and leading to millions of dollars in expenditures for research, control, and management efforts. In San Francisco Bay alone, for example, an average of one new introduction was established every 14 weeks between 1961 and 1995.

Prevention is the most important step in the management of introductions. For most vectors, no formal legal or regulatory management tools are in place to prevent or reduce introductions, or to control newly discovered introductions. With coastal ecosystems threatened by a broad array of human impacts, U.S. marine environments may be increasingly susceptible to introductions of nonindigenous species. There is a need for national compulsory ballast and fouling management programs, an intentional introductions management program, a national rapid-response and early-warning invasions system, a vastly expanded bioinvasions research program with regional marine bioinvasion monitoring surveys, and a greatly expanded education and public awareness campaign.

Bioinvasions Glossary

Terminology

The terminology associated with introduced species remains in flux. Introductions, or introduced species, are also known as invasive, alien, exotic, foreign, non-native, naturalized, immigrant, and nonindigenous species. Sometimes these words are treated synonymously; at other times, they each have different meanings. Some biologists around the world use terms such as "acclimatization" or "xenobiota." The term "invasive species" refers to a broadly defined group of introduced species that bring or could bring some measure of harm. For example, Executive Order 13112 (1998) defines "invasive species" as "an alien species whose introduction does or is likely to cause economic or environmental harm or harm to human health." "Invasive" is a powerful word conveying a sense of impact and urgency, and is commonly used in federal and state statutes and in the names of commissions and councils. However, "harm" is an imprecise, subjective, and unquantified concept. As a result, the use of "invasive" is avoided in this report.

Ballast water is water placed in a ship to increase the draft, change the trim, regulate the stability, or to maintain stress loads within acceptable limits; it includes the sediment that accumulates in ballast tanks and holds as well (National Research Council, 1996).

Biocontrol refers to the release of one species to control another.

Bioinvasions is a broad term that refers to both human-assisted introductions and natural range expansions; in this report, "bioinvasions" refers to the former.

Fouling organisms are animals and plants, such as barnacles, mussels, and seaweeds, that attach to human-made substrates, such as piers, navigation buoys, and the bottoms of ships.

Introduced species are those that have been transported by human activities—intentionally or unintentionally—into a region in which they did not occur in historical time and are now reproducing in the wild.

Invasional meltdown is the process by which a group of nonindigenous species facilitates one another's invasion in various ways, increasing the likelihood of survival, ecological impact, and possibly the magnitude of impact.

Pathway has been used to mean vector, purpose (the reason why a species is moved), and route (the geographic corridor from point A to point B). For clarity, "pathway" is avoided in this report.

Vector is the physical means or agent by which a species is transported. Ballast water, ships' hulls, and the movement of commercial oysters are examples of vectors. Synonyms include pathway, dispersal mechanism, and mode.

I. Marine Bioinvasions and **Their Importance**

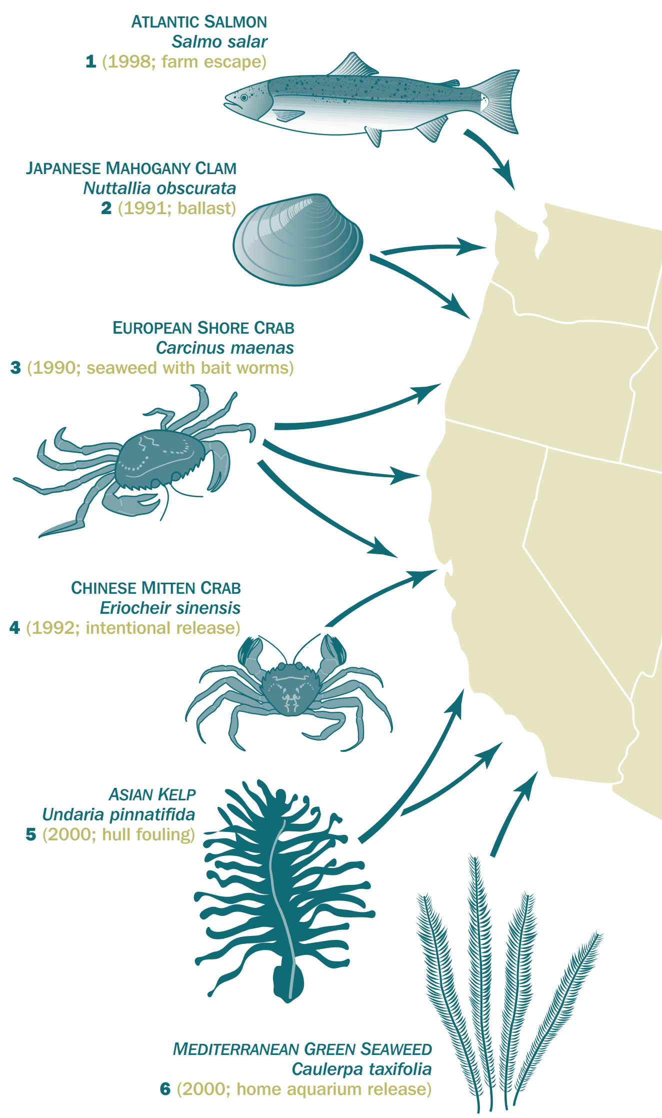
How Do Introductions Affect Our Ability to Restore, Maintain, and Protect Living Marine Resources?

Introduced species fundamentally alter the shores of the United States (Carlton et al., 1995, Carlton, 1996b, 2000a; Ruiz et al., 2000). After habitat destruction, introduced species are considered the greatest cause of the loss of biological diversity (Vitousek et al., 1997). Introductions occur when humans move species into regions where the species did not occur in historical time. This report considers the introductions that occur in marine waters and in estuarine, or brackish waters. On occasion, the report cites freshwater introductions as examples of certain patterns or processes.

Introduced species of crabs, mussels, clams, jellyfish, seagrasses, and marsh grasses dominate marine ecosystems from the Hawaiian Islands to the Pacific Northwest, south to San Francisco Bay and southern California, east to the Gulf of Mexico, and north to Chesapeake Bay and New England (Figures One and Two). These introductions have caused fundamental impacts on fisheries resources, industrial development and infrastructure, human welfare, and ecosystem resources and services (Carlton, 1989, 1999a, 2000a; Ruiz et al., 1997).

Figure One

Some Recent Bioinvasions in U.S. Coastal Waters



Notes About Recent Bioinvasions

1 Tens to hundreds of thousands of salmon regularly escape from fish farms in the Pacific Northwest; reproducing population established at least in British Columbia (Volpe et al., 2000).

2 Abundant edible clam moving south from Canada; in southern Oregon as of 2000 (Carlton, 1999b).

3 Abundant omnivore consuming shellfish and many other species; Morro Bay to the Pacific Northwest (Grosholz et al., 2000).

4 Abundant omnivore; downstream migrations block fish screens (see Figure Nine); digs extensive burrows in river banks and dikes (Cohen and Carlton, 1997).

5 Large—up to 3 feet (1 m)—edible kelp, or wakame, established in southern California harbors (Silva et al., In preparation).

6 Two populations established in southern California; eradication attempted during the summer of 2000 (Anderson and Keppner, 2001).

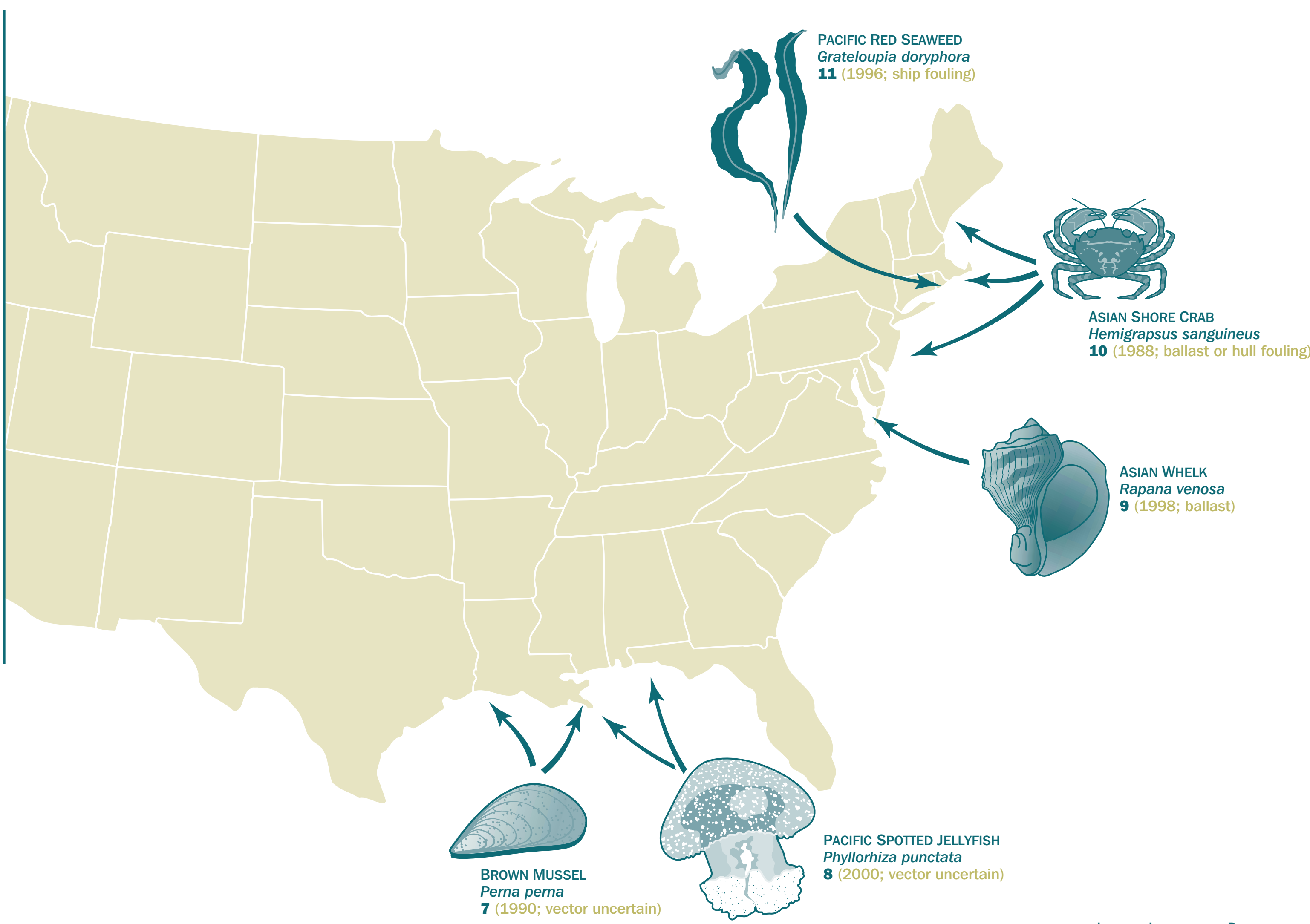
7 Abundant fouling organism from Texas to Mexico (Hicks and Tunnell, 1993).

8 Six million in an area covering 58 square miles (150 km^2) area in Gulf of Mexico in summer 2000 impacted fishery operations; vast amounts of plankton consumed with potential fishery impacts (Graham et al., 2001).

9 Well-established Chesapeake Bay population of this 6-inch (15-cm) bivalve-eating snail (Mann and Harding, 2000).

10 An omnivore; as of 2001 the most abundant tidepool crab in Long Island Sound, where it arrived in 1994 (McDermott, 1999).

11 Large—up to 3 feet (1 m)—foliose seaweed established in southern New England (Villalard-Bohnsack and Harlin, 1997).



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The rate of known introductions in U.S. waters has increased exponentially since the 18th century and shows no signs of leveling off.

The structure and biodiversity of the ecosystem itself is also affected through the introduction of new predators, competitors, disturbers, parasites, and diseases. These introductions lead to vast alterations in species interactions and changes in nutrient cycling and energy flow, which results in cascading and unpredictable effects throughout entire communities. Introduced species can foul jetties, marinas, and buoys and further stress fisheries already in trouble. In some ecosystems, the introduced species can become so dominant that finding the native species becomes an elusive task. Although no one has determined the actual economic impact, certain indicators suggest that introduced species may cost the U.S. hundreds of millions of dollars every year (Figure Three).

Hundreds of introduced species occur in U.S. coastal waters (Ruiz et al., 2000). More than 175 species of introduced marine invertebrates, fish, algae, and higher plants live in San Francisco Bay alone (Cohen and Carlton, 1995, 1998; A. Cohen and J. T. Carlton, unpublished data). Puget Sound, in Washington State, harbors at least 50 introductions; Coos Bay, in Oregon, 60 introduced species; and Chesapeake Bay, in Virginia and Maryland, at least 43 (Ruiz et al., 2000, J. T. Carlton, unpublished data).

For myriad reasons, it is difficult to pinpoint the exact number of marine introductions nationwide. Both the origin and history of many species are often uncertain. Scientists might overlook the introductions of microscopic species and many groups of organisms that are difficult to identify. Some introductions look similar to native species and require genetic identification. A decline in coastal exploration and a reduction in systematics and taxonomy training also help explain why the precise number of marine introductions remains unknown.

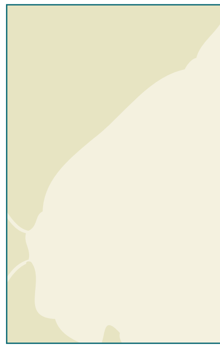
The rate of known introductions in U.S. waters has increased exponentially since the 18th century and shows no signs of leveling off (Figure Four). In San Francisco Bay alone, for example, an average of one new introduction was established every 14 weeks between 1961 and 1995 (Cohen and Carlton, 1998).

New introductions continue to occur in the United States (Figure One). Within the past two years, vast populations of the massive Pacific spotted jellyfish *(Phyllorhiza punctata)* invaded the Gulf of Mexico. In the Gulf of Maine, billions of small carnivorous European flatworms *(Convoluta convoluta)* blossomed. Populations of the large Asian whelk *(Rapana venosa)* continued to grow in the Chesapeake Bay. The Japanese mahogany clam *(Nuttallia obscurata)* reached southern Oregon. The brown mussel *(Perna perna)* invaded the Gulf of Mexico. The Asian shore crab *(Hemigrapsus sanguineus)* reached astronomical numbers in Long Island Sound. The Mediterranean green seaweed (*Caulerpa taxifolia*) and Asian kelp *(Undaria pinnatifida)* were both discovered in southern California, and in the Pacific Northwest tens of thousands of farmed Atlantic salmon (*Salmo salar*) escaped into the wild.

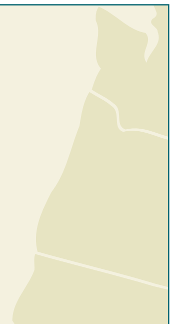
Figure Two

Regional Bioinvasions

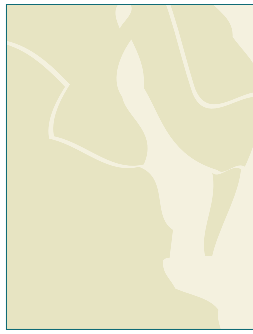
Alaska
The history of marine introductions in Alaska is not well known; recent studies indicate the presence of a number of non-native species. The Atlantic clam *(Mya arenaria)* is abundant and well established.



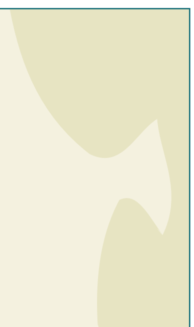
New England/Gulf of Maine
Numerous invasions occur on rocky shores, subtidal habitats, and marina floats. The European periwinkle *(Littorina littorea)*, the Asian green seaweed *(Codium fragile tomentosoides)*, the European shore crab *(Carcinus maenas)*, the Asian shore crab *(Hemigrapsus sanguineus)*, and many extraordinarily abundant sea squirts are ubiquitous, sharply changing the face of the aboriginal seascape and the distribution and abundance of native species.



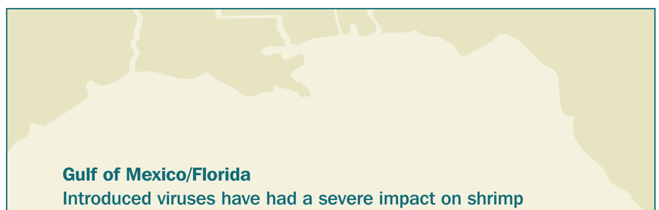
Pacific Northwest
A number of exotic species are established in many habitats. Japanese eelgrass *(Zostera japonica)*, covers large areas of former mudflats, altering the abundance and density of other species. Atlantic cordgrass *(Spartina alterniflora)* covers more than 12,000 acres of Washington State's Willapa Bay—critical habitat for shorebirds, shrimp, and oysters. The New Zealand marine pillbug [isopod] *(Sphaeroma quoyanum)* burrows in Styrofoam™, or polystyrene, in Coos Bay, Oregon, releasing millions of microscopic polystyrene particles into the water.



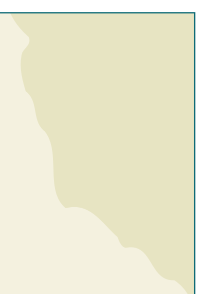
Chesapeake Bay
The introduced pathogenic "protozoan" *(Haplosporidium nelsoni)* causing MSX disease was a major factor beginning in the 1950s, leading to the decline of the native oyster *(Crassostrea virginica)* industry. As with New England, invasions commencing in the 1500s obscure the actual number of introductions that are now common throughout the Bay.



San Francisco Bay
A profoundly invaded ecosystem where no shallow-water habitat remains untouched by non-native species. In some regions, 100 percent of the species are nonindigenous, creating introduced communities through which much of the bay's food energy now flows. The New Zealand marine pillbug [isopod] *(Sphaeroma quoyanum)* erodes some regions of the bay's shoreline at an average of 3 feet (1 m) landward every year.



Gulf of Mexico/Florida
Introduced viruses have had a severe impact on shrimp mariculture industries. Introduced fouling organisms are common in many regions. Introduced brackish-water fish, such as tilapia, are abundant predators. This area is one of the least studied regions of the U.S. in terms of marine bioinvasions.



Southern California
A rich variety of invaders from around the world dominates marina floats and piers. In San Diego Bay, intertidal reefs of the Japanese mussel *(Musculista senhousia)* inhibit the growth of native species such as clams and eelgrass.

Hawaiian Islands
More than 100 introduced species now occur in Pearl Harbor alone. The intentionally introduced Philippine seaweed *(Kappaphycus alvarezii and K. striatum)* covers large areas of Kaneohe Bay coral reefs, reducing potential tourist value. The red mangrove *(Rhizophora mangle)*—which was introduced intentionally—now occupies more than 70 percent of Oahu's estuarine shores.

Sources: ALASKA: Carlton, 1999b; Ruiz, 2001. PACIFIC NORTHWEST: *Zostera japonica*: Posey, 1988; *Spartina*: Daehler and Strong, 1996; *Sphaeroma quoyanum* styrene particle generation: J. Carlton, A. Chang, E. Wells, unpublished. SAN FRANCISCO BAY: Cohen and Carlton, 1995; *Sphaeroma quoyanum* erosion: Talley et al., 2001. SOUTHERN CALIFORNIA: *Musculista*: Crooks, 2001. NEW ENGLAND/GULF OF MAINE: Steneck and Carlton, 2001. CHESAPEAKE BAY: Ruiz et al., 1999; MSX: Burreson et al., 2000. GULF OF MEXICO/FLORIDA: Carlton and Ruckelshaus, 1997; shrimp viruses: Goldburg et al., 2001. HAWAIIAN ISLANDS: Coles et al., 1999, J. T. Carlton and L. Eldredge, unpublished; *Kappaphycus*: Woo et al., 2000; *Rhizophora*: Demopoulis and Smith, 2001.

Figure Three

Control and Research Costs

Economic estimates of the costs of aquatic introductions are notoriously difficult (Randall and Gollamudi, 2001) and have not been made for introductions in U.S. coastal waters.[1] Negative and positive costs must be considered. Negative costs include the lost revenues associated with the destruction of fisheries or the loss of other resources due to the predatory, competitive, or disease impact of introduced species; removing introduced fouling organisms on hundreds of thousands of recreational vessels; and the costs of introduced marine wood-borers. Positive costs include the aesthetic value of introduced species—even if the public does not know which species are introduced; and the value of fisheries based upon non-native species—which is covered in part by Goldburg et al., 2001. A further challenge is the potential inclusion of the costs of possible introductions (when the organism's origin is uncertain), such as many toxic algal blooms, or "red tides," or the "killer dinoflagellate" *Pfiesteria* species. Taken as a whole, all indications are that costs to the economy of the United States from marine introductions have been vast. In addition, funds have had to be diverted away from other critical issues to research and control studies on introduced species, examples of which are given below. Since 1999, research and control costs for three Pacific coast introductions alone equaled nearly one-third of all the funds available through Sea Grant for an entire decade of research and education on introduced species.

Program	Cost
Chinese mitten crab *(Eriocher sinensis)* in California: control and research	**$1M** (2000–01) federal funds
Atlantic cordgrass *(Spartina alterniflora)* in Washington: control	**$1.17M** (1999–00) and **$718K** (2000–01) state and federal funds for eradication programs; **$200K** mowing machine; **$60K** two airboats
Atlantic cordgrass *(Spartina alterniflora)*: a multinvestigator research program on ecology and impacts on the Pacific coast	**$3.8M** (2000) National Science Foundation funds
Mediterranean green seaweed *(Caulerpa taxifolia)* in southern California: control and monitoring	**$2.33M** (2000–01) state and federal funds
Introduced freshwater and marine species: research and education	**$29.3M** (1991–2000) federal (NOAA/Sea Grant) funds

[1]The rare estimates of aquatic introduction costs are often inexact. The cost estimates of the freshwater zebra mussel (*Dreissena* spp.) introduction in the U.S. were initially $5 billion for the period 1989–2000, a number that became "urban legend," and remains the single most quoted figure to express the economic impact of an aquatic introduction in the U.S. The number, however, was based upon no study and thus no data. A more accurate number is between $750 million and $1 billion for the same period (O'Neill, 2000). In the most extensive review to date on the economic costs of introduced species in the U.S., Pimentel et al. (2000) included two major marine introductions, but both data sets require modification (a report of $44 million in annual estimated economic impact of the European shore crab *Carcinus* on the Pacific coast was based on a predicted, not an actual, value; the cost of introduced shipworm damage at $205 million/year in San Francisco Bay refers to an episode that occurred between 1919 and 1921).

Sources: *Eriocheir*: Silva, 2001. *Caulerpa*: Woodfield, 2001, Williams, 2001. *Spartina* control: Wecker, 2001. *Spartina* research: University of California, Davis, 2000. Research and Education: ANS Report, 2000. Cost data: Nicole Dobroski.

Why Do Introductions Continue to Occur?

The dispersal of introductions occurs through vectors—the physical means or agent for transporting a species (see Chapter II). Why do introductions continue to occur if dispersal vectors—such as the movement of marine life on the bottoms of ships' hulls—have existed for many decades or even centuries? A common perception is that after a vector has been transporting species from one place to another for many years, every possible species that could be introduced would be already. Although this perception is logical, it is not accurate. Zebra mussels (*Dreissena* spp.) first appeared in the Great Lakes many decades after ballast water began arriving from Europe. A European sea squirt *(Ascidiella aspersa)*, commonly found on ship-hull fouling, appeared in New England in the 1980s—after over 400 years of ship traffic between Europe and the United States.

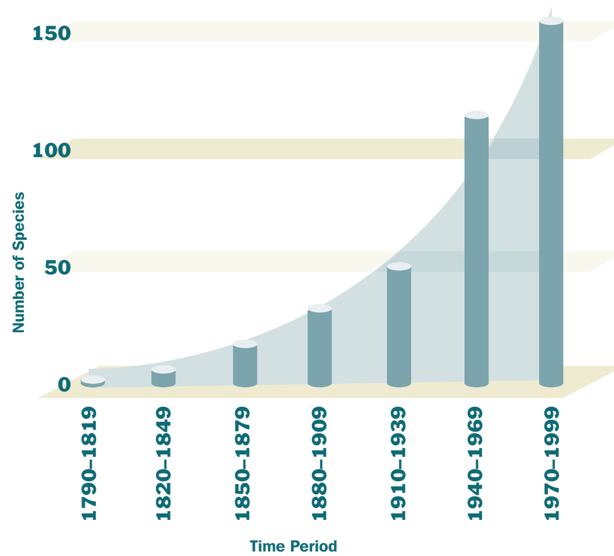
An introduction occurs when a species survives transport by a vector, is released into a new environment, and initially perseveres. The introduction is successful when the species reproduces, becomes established, and spreads in its new environment. Many factors affect the survival, spread, and proliferation of introduced species, including basic climatic factors and food resources, the nature of the reproductive biology of a species, and the presence or absence of competitors, predators, and parasites (Carlton, 1996a).

The inoculation of a species—the release of one or more species into the environment—is akin to a game of ecological roulette. A species may not travel on a vector, such as ballast water. However, if a species is entrained, it may not survive the voyage. If the species survives the voyage, its release into a new environment may fail. If the species is released, it may die. If it does not die, the species may not reproduce. Even if it reproduces, a host of existing conditions may inhibit the species from becoming established and from spreading. Predicting which species will arrive; their origin; the time of their arrival; and whether they will survive, persist, spread, and proliferate, continue to challenge scientists who study invasion biology.

Figure Four

Rate of Invasions

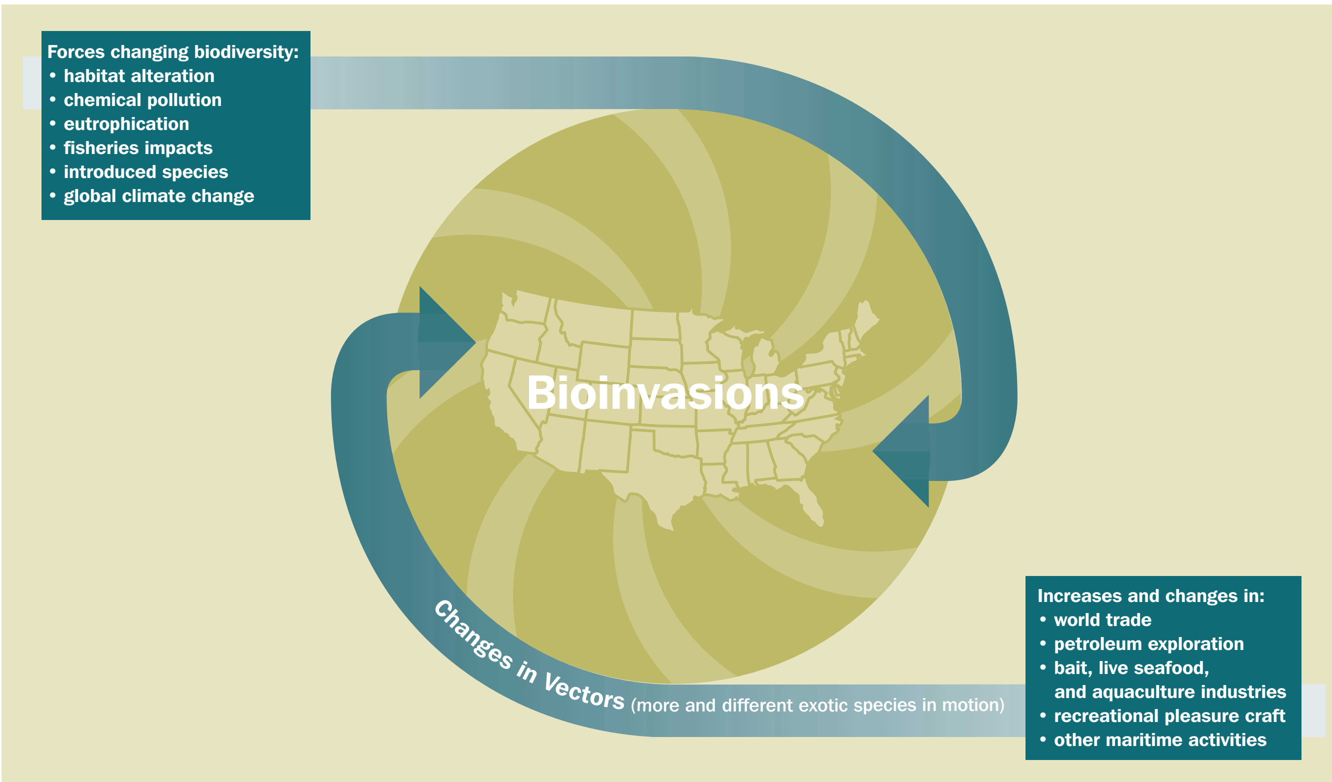
This graph shows the rate of invasions of marine invertebrates and seaweeds based upon the number of new invasions occurring in the U.S. coastal zone from 1790 to 1999. For example, there were 150 new invasions from 1970–1999. The total number of invasions plotted on this graph is 374 species.



Source: Ruiz et al, 2000.

Figure Five

Factors that Alter the Environment and the Potential for Species Transport and Introduction



The invasion picture is dynamic and ever changing. New vectors, such as oil- and gas-drilling platforms, may appear, bringing along a suite of novel species. Older vectors may increase in size and frequency. The number of donor regions—the areas from which vectors gain species—may increase as trade rules change. A new species may invade the donor area as well. Each introduction forms a new hub, radiating more spokes of dispersal. New populations may occur at the ends of these spokes and become hubs themselves.

Recipient regions—the areas that receive introduced species—may change as well. A power plant can offer warm-water effluent in a cold climate, providing a site for a southern species to establish itself. Water diverted for agriculture or other purposes may cause salinities to increase. Marinas can create new habitats for introduced species (Connell, 2000). Water chemistry may change: the majority of U.S. estuaries now exhibit nutrient enrichment due to agricultural stormwater runoff (Boesch et al., 2001). Previously abundant native species may decline, reducing potential competition with new invaders. The list of possible changes that make an environment more or less susceptible to new introductions is long.

Combining these phenomena with the extraordinary fluxes now occurring in U.S. coastal waters yields a broad view of the processes that may facilitate introductions (Figure Five). The major forces driving change in coastal marine biodiversity—habitat alteration; chemical pollution; eutrophication or overenrichment; climate change; fisheries impacts; and introductions themselves (National Research Council, 1995; Steneck and Carlton, 2001)—constantly alter both donor and recipient environments, creating new opportunities for transport and introductions. Evidence indicates a shifting north of species, potentially linked to global climate change (Carlton, 2000b). Fisheries impacts remove from the sea the competitors and predators that would otherwise inhibit successful introductions (Steneck and Carlton, 2001). Introduced species themselves may facilitate other introductions in a process known as invasional meltdown—the process by which a group of nonindigenous species facilitate one another's invasion in various ways, increasing the likelihood of survival, ecological impact, and possibly the magnitude of impact (Simberloff and Von Holle, 1999).

With a world and its oceans thus in constant flux, introductions continue.

The list of possible changes that make an environment more or less susceptible to new introductions is long.

II. Dispersal of Introduced Species in U.S. Coastal Waters

Every day a large number of human-mediated vectors (Figure Six) move thousands of marine organisms around the world. Recent movements and releases span a wide variety of mechanisms (Figure Seven). These introductions underscore the need for effective education and management programs to increase awareness of the potential for human activities to result in introductions. Today, species arrive in U.S. coastal waters from virtually every region of the world, traveling across numerous trade routes that continuously change. At a given coastal site in the U.S., at any moment, there is the potential for numerous, repeated, and frequent novel inoculations of non-native species—a roulette wheel that perpetually spins new species into U.S. coastal waters.

Shipping: Ballast Water and Fouling Organisms

Today, more than 45,000 commercial cargo-carrying vessels (Lloyd's Register of Shipping, 2000) and hundreds of thousands of recreational vessels ply the world's seas. These vessels are the primary type of vector that transports marine life around the world at unprecedented rates. These vessels can carry living aquatic organisms from fresh, brackish, or marine water, across and between oceans, or along coastlines, in a variety of ways (Figure Six). An arriving vessel may be a virtual "floating biological island," with hundreds of species living both on and in the ship (Carlton, 1985, 1993, 1996b; Carlton and Geller, 1993; Carlton and Hodder, 1995; Wonham et al., 2000).

Ships carry ballast water. The ballast water is pumped or gravitated into the vessels to compensate for the lack of cargo, and for other reasons. Most ships, even those that carry cargo, have some ballast water aboard. A ship's ballast water may be taken in at port or at sea. The water is held in ballast tanks or in floodable cargo holds. A ship may discharge all or some of its ballast water when it arrives at its next port. Before water became commonly used as ballast in the 1880s, ships used rocks, sand, soil, and almost anything cheap and heavy for ballast. This movement of "dry ballast" led to the spread of thousands of species of insects and other arthropods, mollusks, and plants.

Ballast water contains four kinds of living communities (below). Each requires different sampling techniques.

- **plankton: organisms passively drifting or only modestly swimming in the water;**
- **nekton: free-swimming species in the water;**
- **fouling: attached organisms (including bacterial films) on the vertical walls and horizontal structures of the ballast compartments;**
- **benthos: bottom-dwelling, or benthic, organisms, such as mud beds of marine worms and associated species, and the encysted, or resting, stages of plant plankton (phytoplankton) and animal plankton (zooplankton).**

Figure Six

Common Marine Bioinvasion Vectors

Invasion Vectors and Types of Organisms Transported

Ships
- Planktonic and nektonic organisms in ballast water
- Attached and free-living fouling organisms on hull, on rudder, on propeller and propeller shaft, in seawater systems, seachests, in ballast tanks, and in ballasted cargo holds
- Organisms associated with anchors, anchor chains, and anchor chain lockers
- Organisms associated with cargo, such as logs that have been floated for loading

Drilling Platforms
- Attached and free-living fouling organisms
- Planktonic and nektonic organisms in ballast water

Dry Docks
- Attached and free-living fouling organisms
- Planktonic and nektonic organisms in ballast water

Navigation Buoys and Marina Floats
- Attached and free-living fouling organisms

Amphibious Planes, Seaplanes
- Attached and free-living fouling organisms
- Organisms in pontoon water

Canals
- Movement of species through sea level, lock, or irrigation canals

Public Aquaria
- Accidental or intentional release of organisms on display
- Accidental or intentional release of organisms accidentally transported with target display species

Research
- Movement and release of invertebrates, fish, seaweeds (algae) and seagrasses used in research (intentional or accidental escape)
- Organisms associated with research and sampling equipment, including SCUBA and other diving or swimming gear

Floating Marine Debris
- Transport of species on human-generated debris, such as floating nets and plastic detritus

Recreational Equipment
- Movement of small recreational craft, snorkeling and SCUBA gear, fins, wetsuits, jet skis, and similar materials

Fisheries, Including Marine Aquaculture (Mariculture)
- Transplantation or holding of shellfish, such as oysters, mussels, clams, crabs, lobsters, and other organisms; fish; or seaweed (algae) in the open sea for growth or freshening (rejuvenation); and other organisms associated with dunnage and containers
- Intentional release of shellfish, fish, and seaweed (algae) species, either as part of an official governmental introduction attempt, or as an illegal private release
- Stock enhancement, often ongoing, as well as accidentally transported associated organisms
- Movement of live seafood intended for sale but then released into the wild
- Processing of fresh or frozen seafood and subsequent discharge of waste materials to environment, which may include associated living or encysted organisms
- Movement of live bait subsequently released into the wild
- Discarding of packing materials—such as seaweed and associated organisms—used with live bait and seafood
- Movement, relocation, or drifting of fisheries gear, such as nets, floats, traps, trawls, and dredges
- Release of organisms as forage food for other species
- Organisms transported intentionally or accidentally in “live well” water, vessel scuppers, or other deck basins
- Release of transgenic stocks—genetically modified organisms (GMOs)
- Movement of algae and associated organisms as substrate for fish egg deposition

Aquarium Pet Industry
- Movement and release of invertebrates, fish, seaweeds (algae) and seagrasses used in the aquarium industry (intentional or accidental escape)

Restoration
- Movement of marsh, dune, or seagrasses as well as associated organisms
- Reestablishment of locally extinct or decimated populations of native species, and accidentally transported associated organisms

Education
- Release of species from schools, colleges, and universities following classroom use

Figure Seven

Incidences That Illustrate a Need for Effective Vector Awareness and Management Tools

Date	Incident
1989	**Seaweed with Bait.** Seaweed laden with small invertebrates and used as packing for bait worms from Maine is discarded in San Francisco Bay. As a result, the carnivorous European shore crab *(Carcinus maenas)* and the Atlantic rocky shore snail *(Littorina saxatilis)* invade the Pacific Coast.
1992	**Illegal Live Imports.** The Chinese mitten crab *(Eriocheir sinensis)* is discovered in San Francisco Bay. It proves to be an intercept at California airports—illegally imported alive from Asia.
Summer 1998	**Movement of Historic Battleship.** To soak the hull in fresh water, the *USS Missouri* is moved from Puget Sound to the Hawaiian Islands via the Columbia River. The lower hull, however, remains in salt water in the river, and as a result some fouling organisms arrive alive in Honolulu Harbor. The Mediterranean mussel *(Mytilus galloprovincialis)* from Puget Sound, on the hull of the *Missouri* reproduces in Pearl Harbor, and colonizes the ballast tanks of a nearby submarine.
September 1998	**Salmon Mariculture.** Atlantic salmon *(Salmo salar)* reproduce in the Pacific Northwest after escaping from fish farms.
March 2000	**Movement of Marina Floats.** Marina floats are towed at sea from New jersey to Massachusetts heavily encrusted with fouling organisms, including the Asian Crab *(Hemigrapsus sanguineus)*.
Early 2000	**Home Aquarium.** An apparent private home aquarium release of the Mediterranean green seaweed *(Caulerpa taxifolia)* into a lagoon near San Diego results in a well-established population of this green alga; eradication efforts follow.
Summer 2000	**Live Seafood and Sushi Bars.** A hotel sushi bar releases live Japanese freshwater crabs *(Geothelphusa dehaani)* into Lake Las Vegas, Nevada, where they are found walking around.
January 2001	**Importation of Raw Shellfish.** The state of New Jersey embargoes 6,000 cases of raw clams from China, labeled as “cooked.” Hepatitis A virus is found in the shellfish.

Sources: Seaweed with Bait: Cohen et al., 1995. Illegal Live Imports: Cohen and Carlton, 1997. Movement of Historic Battleship: Apte et al., 2000. Salmon Mariculture: Volpe et al., 2000. Home Aquarium: Anderson and Keppner, 2001.

How many and what kinds of species occur in ballast water? Studies in the U.S., Germany, Scotland, Wales, Australia, and Hong Kong, reveal a remarkable array of living marine organisms, representing all of the major and most of the smaller groups of life (Carlton, 1985; Carlton and Geller, 1993; Galil and Huelsmann, 1997; McCarthy and Crowder, 2000; Gollasch et al., 2000a, 2000b). Many species are in their larval, or dispersal, stages, becoming bottom-dwelling organisms as adults. These include sea anemones, worms, barnacles, crabs, snails, clams, mussels, oysters, bryozoans, sea urchins, sea squirts, seaweeds, and many others. Other species live permanently as adult organisms in the water. These include diatoms, dinoflagellates, copepods, jellyfish, and many others. Certain viruses and the bacteria that cause human epidemic cholera have also been detected in ballast water (Ruiz et al., 2000). Ballast organisms thus range in size from microscopic to fish 12 inches (30 cm) or longer.

At least 7,000 different species of marine life are likely transported each day around the world (Carlton, 1999a). Recent evidence suggests even greater diversity in ballast water than previously suspected within the phytoplankton and related groups (McCarthy and Crowder, 2000). Ballast water, carrying this wide array of non-native life, arrives in the U.S. at the rate of 2 million gallons per hour (Carlton et al., 1995).

Ballast, however, is not the only means by which ships carry marine life from foreign shores to the U.S. Fouling organisms attach to the outside of vessels. For the past 500 years, tens of thousands of vessels have formed a living biological conveyor belt between North America and the rest of the world, transporting species that could not survive drifting on their own across the high seas. Barnacles, mussels, hydroids, seaweeds, and an abundant variety of other marine life formed fouling assemblages that historically could be thick enough to harbor free-living species, such as crabs and fish.

Modern ships continue to carry fouling organisms on their hulls, rudders, propellers, propeller shafts, in seawater piping systems (including ballast intake screens), and in their sea chests—water compartments between the outside of ships and the ballast pumps. The latter area is known to be particularly amenable to accumulations of organisms that would not survive on the hull of the ship, and is now increasingly suspected of playing a significant role in introductions.

Antifouling paints, which are toxic to marine life, are used to discourage or prevent the attachment of fouling organisms. Decreasing uses of certain types of these paints may lead to increase in the number of fouling populations. Tributyl tin (TBT)-based paints are scheduled for international ban by 2003. In Australia, decreased use of TBT paints has already increased ship fouling (Taylor, 1998). Further studies are needed to determine if there is a correlation between decreased use of TBT-based paints and increased ship-fouling mediated introductions.

For some species of marine life, it may be difficult to determine their mode of introduction. Ballast water and the organisms in it, for example, are always discharged when a ship loads cargo. However, organisms attached to ships' hulls or sea chests must either reproduce or become dislodged or swim off the ship. Many organisms, including barnacles, mussels, hydroids, sea squirts, and seaweeds, can be transported by both mechanisms, making it difficult to distinguish between the two vectors.

At least 7,000 different species of marine life are likely transported each day around the world.

Dry Docks, Drilling Platforms, and Maritime Activities

With the increase in international commerce and exploration, there has been a concomitant growth in the movement of dry docks—large structures used to float and repair ships—and of semi-submersible, self-propelled drilling and production platforms used for resource discovery and extraction. These structures have abundant subsurface space for fouling communities and they have ballast systems as well. Additional maritime activities (Figure Six) include the long-distance movement of navigation buoys, marina floats, and amphibious vessels and seaplanes, each potentially transporting a unique complement of species.

There has been a long-standing debate over the wisdom of deliberately introducing non-native species.

Fisheries Activities

The dispersal of marine life occurs through a wide range of fisheries activities (Figure Six). These activities fall into two broad categories of *intentional releases*—legal or illegal—and *accidental releases*.

An unknown number—in terms of both species and individuals—of living marine organisms are deliberately transported around the world on a daily basis. These animals are transported for direct consumption as live seafood, use as live bait for fishing, growth or "freshening" in the marine environment, with the intent or hope of starting a new fishery.

Blurring these categories are innumerable incidents in which the public intentionally or unintentionally releases living nonindigenous organisms without any particular future intent. Live Atlantic lobsters *(Homarus americanus)* purchased at the airport in Boston or New York are released in southern California waters hours later by people who would prefer to let the shellfish live rather than eat them. Fishermen may discard seaweed—in which numerous other organisms live—used as baitworm packing after a day's fishing; they may also discard leftover worms. Indeed, the use of seaweed for bait packing with worms from the U.S. Atlantic coast apparently led to the introduction of the European shore crab *(Carcinus maenas)* on the American Pacific coast. This seemingly insignificant vector illustrates a critical point: an apparently small vector may not be a minor one if it leads to major introductions. This raises the challenge of how to prioritize vector management based upon traffic volume or the number of associated transported species.

We have no data on the scale of illegal attempts to plant species to start new fisheries. However, these attempts may be a significant source of introductions, given the ease with which people carry living organisms into the U.S. in their luggage through international airports.

The role of live seafood sold in markets where it is not native is also not well understood. For example, the Chesapeake Bay blue (softshell) crab *(Callinectes sapidus)* is sold alive (and healthy) in San Francisco fish markets, and has been occasionally released by the public into California waters. While it might be impossible under California state law (Cohen and Foster, 2000) for private persons or public agencies to obtain the necessary permits to release *Callinectes* into California waters to deliberately start a fishery, seafood consumers or advocates who want to start a new fishery are unlikely to be aware of—or regulated by—such permit requirements.

There has been a long-standing debate over the wisdom of deliberately introducing non-native species. In the 19th century, many "acclimatization societies" and government agencies intentionally released non-native species into U.S. waters to "improve nature" or start new fisheries. The intentional introduction of the Atlantic striped bass *(Morone saxatilis)* to the Pacific coast in the 1870s is one of the most striking marine examples.

Today there are far fewer attempts to sprinkle exotic marine species in the wild. When there is interest in doing so, however, proposals often center on using individuals that cannot reproduce (because they are sterile or because the temperatures for reproduction are not right). Concern has remained, however, as to whether individuals could adapt to new temperature regimes and whether sterile individuals would remain sterile.

In recent decades proposals to revitalize the waning oyster industries in the Gulf of Maine and Chesapeake Bay have focused on the use of non-native species of oysters (Shatkin et al., 1997; Gottlieb and Schweighofer, 1996). These non-native oysters are resistant to the diseases that killed native Chesapeake Bay oysters.

In 2001, the state of Virginia placed sterile stocks of the Japanese oyster *(Crassostrea ariakensis)* in the Chesapeake Bay (Latané, 2001). However, there is still concern that some individuals could revert to a reproductive state and thus result in the unintentional establishment of wild populations, which could then spread to other states and jurisdictions that do not desire the establishment of nonindigenous oysters. For this reason, the state of Maryland did not participate. This incident points out the difficulties of managing these issues in interstate waters under the current regulatory system.

Aquarium Industry and the Availability of Living Marine Organisms on the Internet

The aquarium industry—with invertebrates, fish, seaweeds, and seagrasses in the "pet" or "display" category—similarly imports an unknown number of species and individuals from around the world. Primarily tropical and subtropical species are imported, but temperate species are active in the trade as well. With the exception of a few specially regulated species, such as piranhas, most such organisms are legally imported into the country—although there may be no intention to release the organisms into the wild. In the southern half of the U.S., aquarium-released subtropical and tropical fish are abundant and diverse components of wild fish communities (Courtenay and Stauffer, 1984).

In addition to marine life available for home aquaria, a long list of other marine organisms can be purchased for education and research on scores of websites. The fate of these organisms remains largely in the hands and control of a public or research sector with few, if any, regulatory constraints and often little or no information about the potential consequences of such releases.

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Other Vectors

A variety of additional vectors, such as dredge spoil disposal, beach sand transport, and the movement of recreational equipment, have been invoked at one time or another to explain the appearance of new species. These vectors may be regionally or locally significant at times, with bursts of activity related to special or focused events. Biocontrol, or the release of one species to control another, has not yet led to the release of new species in the oceans, although it is a topic of rapidly increasing discussion.

Today, more species—and more individuals of those species—are transported because of the increasing diversity of vectors.

Floating marine debris as a potential vector for introductions is also an area of increasing concern, especially in the Pacific Ocean, where large numbers of fishing nets are adrift, coming ashore covered with marine organisms in such places as the Hawaiian Islands (Godwin, 2001).

Coastal Dispersal of Introductions

Once a new species has arrived in the U.S., it may disperse along the coastline by natural means. It may float or drift as planktonic larvae. It can be attached to floating materials such as seaweeds, seagrasses, and marine debris. A new species can also be transported by human-mediated vectors (discussed above) or by a combination of the two. Most research efforts have focused on the mechanisms that could bring new, foreign species into U.S. waters. As a result, few data are available that adequately describe or quantify how a new invader subsequently moves along a coastline. These data are critical to predict both rate and direction of spread.

The Number and Diversity of Transport Vectors

In the past 200 years, the number of vectors available for the transport of marine species has steadily increased. In the year 1800, for example, only two mechanisms—ship-hull fouling and ballast rocks—were available to move the European shore crab *(Carcinus maenas)* across or between oceans. By 1900, three additional mechanisms were available: ballast water, intentional movement as food, and the importation of oysters for aquaculture. By the year 2000, there were ten human-mediated mechanisms that could move the crab around the world —all of the previous ones (except ballast rocks, which were no longer used by 2000), plus six other mechanisms: moving crab as bait, in the aquarium trade, in the school-educational market, as a research animal, accidentally with lobster shipments, and on petroleum drilling-production platforms.

The stage is constantly set and reset for new bioinvasions as a plethora of transport mechanisms fall into play on an hourly basis. Numerous ships reach U.S. coastal sites every day. Marina floats arrive from distant harbors and seaplanes land in U.S. waters. Live, non-native marine organisms are purchased for food, for use as bait, or as pets. Educational and research institutions and public aquaria are holding a large variety of living exotic marine organisms. A large seafood restaurant overlooking the water imports live Maine lobsters, wrapped in fresh invertebrate-laden seaweed. In a nearby salt marsh or estuary, restoration attempts may be underway to reestablish important plants, using stocks—along with the shipped sediments—from distant locations.

Today, more species—and more individuals of those species—are transported because of the increasing diversity of vectors. Moreover, the fact that one species can now be moved by many different means makes the prevention of introductions an even greater challenge.

III. Marine Bioinvasions
Prevention, Reduction, and Control

Pre-Introduction Management

How Are Accidental Introductions Regulated?

Accidental introductions must be prevented from occurring. The eradication of introductions once they have become widespread and abundant has been largely unsuccessful. Eradication, therefore, is a less desirable and far more costly method of managing introductions than preventing the entry of introduced species in the first place.

Ballast water is widely regarded as the leading modern-day vector of marine bioinvasions. Since 1990, a complex array of guidelines, regulations, and laws has evolved relative to the management of ballast water. In addition, existing laws relating to water pollution—the Clean Water Act of 1972 and the Rivers and Harbors Act of 1899, for example—could be applied to ballast water management (Cohen and Foster, 2000).

At the international level, the United Nations International Maritime Organization (IMO) instituted voluntary guidelines in 1991. IMO continues to consider regulations that are more binding. These and similar guidelines call for ballast water exchange (BWE): the release of coastal-derived ballast water on the high seas—far from land—followed by reballasting with mid-ocean water. BWE is based on the principle that marine organisms from the coastal zone, estuaries, and rivers will die when they are released in the open ocean, and that open-ocean organisms will not survive when they are discharged in estuaries and rivers. A number of factors, however, affect the success of BWE. Certain circumstances, such as stormy weather, prevent ships from undertaking BWE. Organisms attached to the bottom and walls of ballast tanks may remain attached after having been through the water-exchange process. In addition, design limitations on some ships prevent the complete exchange of ballast water. As a result of these limitations, a large number of suggestions for other methods of physical, chemical, and biological control of living organisms in ballast water and sediment have been proposed (Carlton et al., 1995; Carlton, 1998; National Research Council, 1996; Cohen and Foster, 2000). NOAA Sea Grant (ANS Report, 2000) and other agencies are funding research through a number of field-trial programs, including those focusing on micro-filtration, ultraviolet radiation, and hydrocyclonic technologies.

The U.S. National Invasive Species Act of 1996 (NISA), a reauthorization and expansion of a 1990 law, provided ships entering U.S. ports from outside the Exclusive Economic Zone a three-year window of opportunity to undertake a voluntary open-ocean exchange

There are no focused management plans in place for the numerous vectors that are transporting thousands of species of marine life every day.

program with a mandatory reporting requirement. The program recommends that ships exchange as close to 100 percent of their water as possible. NISA requires that the Secretary of Transportation make the program mandatory if the voluntary program is not satisfactory (an undefined term in the legislation). Implementation of the regulations was to begin by October 1997, but the regulations did not become effective until July 1, 1999. In the first 12 months of the program, only 12,170 of the 58,000 vessels arriving in U.S. ports filed a mandatory reporting form. Approximately 3,500 vessels declared an intention to discharge ballast water, but only 21 percent of these vessels reported a complete mid-ocean exchange.

Motivated largely by the lengthy international and federal management process, the states of California, Oregon, Washington, Michigan, and Maryland, have passed or are considering ballast water-control legislation encompassing a variety of approaches. California has set up a mandatory exchange program, but the efficacy of that program is unknown. An increasing number of state-by-state regulations can lead to a complex patchwork of potentially disparate regulations, leading to inherent challenges in consistency, enforceability, and workability in foreign trade. This underscores the need for an effective mandatory nationwide plan (see Chapter IV).

Reducing Non-Ballast Water Introductions

There are no focused management plans in place for the numerous vectors (Figure Six) that are transporting thousands of species of marine life every day. Regulations that date back to the 19th century technically prohibit the release of non-native species in many states (Cohen and Foster, 2000; J. T. Carlton, unpublished). In modern-day terms, these regulations—or updated versions of them—may be focused on regulating the movement of live fish and shellfish. However, there is great variability in the coverage and enforcement of these statutes from state to state.

As noted in chapter two, the public can purchase and transport numerous species of marine organisms between states without regulatory constraints. In contrast, proposals for the legal release of the same species would require extensive environmental impact statements, and authorities at the state level would likely reject them. Similarly, there is little focused management to control fouling organisms, a matter of increasing concern (Chapter II).

How Are Intentional Introductions Regulated?

As a signatory to the International Council for the Exploration of the Sea (ICES), the U.S. abides by the ICES Code of Practice on the Introduction and Transfers of Marine Organisms (Carlton and Richardson, 1995). This code requests that proposals for the intentional release of a non-indigenous marine organism into the waters of the North Atlantic Ocean for mariculture or other purposes must be submitted to ICES for comment. ICES will offer advice on the advisability and risk of such releases. In the 1990s, for example, proposals for open-ocean farming of the Japanese red seaweed *(Porphyra yezoensis)*—also known as nori—at Eastport, Maine, were reviewed by ICES and permitted by Maine.

Exceptions to state-level control of introductions occur under certain federal statutes. Under the Lacey Act of 1900, no one can import the Chinese mitten crab *(Eriocheir sinensis)* to the United States or transport the species within the U.S. (Cohen and Foster, 2000). The mitten crab, however, is already established in San Francisco Bay. The green seaweed *(Caulerpa taxifolia)* was listed in 1999 under the Federal Noxious Weed Act (FNWA) of 1974, making its importation and interstate transport illegal. The Mediterranean clone of *Caulerpa taxifolia* became established in southern California in the summer of 2000.

For most other vectors, management efforts have concentrated on education and information flow to the public and industry. Efforts have focused on increasing awareness and on reducing and preventing introductions. President William Clinton's 1999 Executive Order 13112 resulted in the establishment of the National Invasive Species Council (NISC). In January 2001, NISC released a management plan entitled "Meeting the Invasive Species Challenge." NISC has served to increase attention and focus on both the scale of introductions and the need for management at the federal level. However, the release of the NISC Management Plan coincided with the arrival of a new administration that did not create NISC. It is premature, therefore, to judge either the current or the future effectiveness of NISC.

Figure Eight

Physical Control of Introduced Populations

In 1951 a reproducing population of more than 60 adult **Japanese oyster drills** *(Thais clavigera)* were discovered in Ladysmith Harbor, on the east coast of Vancouver Island, British Columbia, three years after they had been introduced with importations of Japanese oysters. The snails and their egg capsules were removed by hand, and the oyster drills did not become established.

Between 1973 and 1976, volunteers made more than 1000 trips to remove over 475 tons of the **Japanese seaweed** *(Sargassum muticum)* from the shores of the Solent region of southern England. The algae persisted, and remains an abundant species.

In 1993, volunteer SCUBA divers—known as starbusters—removed 30,000 **Japanese sea stars** *(Asterias amurensis)*—weighing four tons—from shallow waters around Hobart in southern Tasmania. In 2001, the population of *Asterias* at Hobart was estimated at 140,000,000 individuals.

In 1996, the mechanical removal of the **Atlantic cordgrass** *(Spartina alterniflora)* in Willapa Bay began. With more than 12,000 acres of *Spartina* established in the bay, control costs in 1999–2000 included an expenditure of $200,000 for a mowing machine (Figure Three).

In 1997, in Cayucos, southern California, 1,600,000 native **turban snails** (*Tegula funebralis*) potentially or actually infected with an introduced South African worm (initially imported to California with infected abalones, and having major impacts in California abalone mariculture facilities) were removed by hand from the intertidal rocky shore. Screens were also installed at the outflow of the nearby abalone facility, which had initially led to the infestation of the turban snails in the wild. As of 2000, no further infestations in the wild had been detected.

Sources: *Thais* in British Columbia: Carl and Guiguet, 1958; Quayle, 1964. *Sargassum* in England: Gray et al., 1977. *Asterias* in Tasmania: Morrice, 1995; R. Thresher, personal communication. *Spartina* in Willapa Bay: Major and Grue, 1997. Abalone worms: Culver and Kuris, 2000.

Figure Nine

Crabzilla

Crabzilla—a monstrous 8-foot-wide by 18-foot-high traveling fish screen—now straddles the conveyance channel at the Tracy Fish Collection Facility, located in Alameda County, California. It scoops up crabs on a giant revolving wheel while allowing fish to slip through tiny mesh openings. Although the wheel usually spins at speeds of about 2 feet per minute, it can be sped up to around 20 feet per minute if lots of crabs are entering the channel. While the salvaged fish are trucked back to the Delta far from the pumps, the crabs are brushed and pressure-hosed off the screen onto a conveyor belt that dumps them into a container. From there they are hauled to Modesto and ground into fertilizer.

—from ABAG, 2000

Note: This is a description of a $600,000 screen in operation in the summer of 2000 to trap Chinese mitten crabs at a water-pumping station in the San Francisco Bay estuary. The Chinese mitten crab was first discovered in the bay in 1992. Today several million Chinese mitten crabs live in San Francisco Bay.

Post-Introduction Management

As with pre-introduction management, there are no legal or regulatory frameworks in place to eradicate or reduce newly discovered marine introductions or to prevent the subsequent spread of the introductions.

For more than 50 years, researchers have attempted to remove new populations of marine introduced species with varied degrees of success (Figure Eight). Removal attempts have included handpicking sea stars off the seafloor, mowing down introduced salt marsh grasses, and removing infected turban snails from a rocky shore. Efforts to combat individual animals at specific sites of concern—areas in which the animals foul pipes or block screens, for instance—are an immediate option, but they are generally not designed to eradicate an introduced species (Figure Nine).

Physical removal also includes converting an introduction into a commercial fishery (Thomas et al., 2001). Potential extraction fisheries include the introduced European crab *(Carcinus maenas)* in New England (Walton, 2001) and the Asian whelk, *(Rapana venos)* in the Chesapeake Bay (Mann, 2001). Proposals to create a fishery for the Chinese mitten crab *(Eriocheir sinensis)* in San Francisco Bay were rejected out of concern that such fisheries might encourage the deliberate introduction of the crab elsewhere.

Chemical control is the only other option that is readily available and in use (see page 20), although there is increasing scrutiny over the negative effects of chemical treatment. Other options (Figure Ten) are either not yet available or not yet sanctioned for use in the marine environment. Deciding when, where, and whether to attempt eradication is a complex process (Myers et al., 2000). Eradication efforts could potentially lead to other environmental damages.

While the debate about chemical control continues, pressures to quickly eliminate newly discovered inoculations of exotic species are mounting. There is an increasing desire to demonstrate the ability to "knock out" initial populations, accompanied by an awareness of the later challenges to remove a species once it has established multiple or continuous populations over a broad area. As a result, two recent major attempts to control the initial discoveries of marine introductions involved the use of chemicals.

In March 1999, an Asian fouling mussel *(Mytilopsis sallei)* was discovered in large densities—more than 27,700 individuals per square yard—in three marinas controlled by locks in Darwin, the largest port on the tropical northern Australian coast. Researchers treated the marinas with liquid chlorine—sodium hypochlorite—and copper sulphate, killing the mussels and a considerable amount of other marine life. The program appears to have been successful (Willan et al., 2000).

In the summer of 2000, researchers discov-

Figure Ten

Strategies for the Post-Invasion Control of Marine Introductions

1. Mechanical Control

Mechanical removal of individuals (rationale may include the harvesting of the species for some use), or mechanical in-situ destruction of individuals (regenerative powers of target species from pieces must be determined).

2. Chemical Control

Toxic chemical release, including the potential development of species-specific chemicals. Method may extend beyond treatment area, unless chemicals are of short duration.

3. Physiological Control (Autocidal)

Development of a species-specific chemical metabolic inhibitor or disrupter, impacting feeding, locomotion, reproduction, or other processes.

4. Genetic Control

Genetic engineering of introduced species to alter environmental tolerances, reproduction, or other processes.

5. Ecological Control by Habitat Modification (Environment Manipulation)

Environment is modified in some physical or chemical manner so that either the target species is affected and/or a natural or introduced biocontrol species is enhanced.

6. Ecological Control By Species Introduction Or Enhancement (Biocontrol)

Introduction of one or more non-native species or enhancement of one or more native species. Method has potential to extend beyond treatment area.

Non-native or native taxa include host-specific:

(a) parasites and parasitic castrators;
(b) parasitoids;
(c) pathogens (disease agents);
(d) predators.

Source: Modified from J. T. Carlton, Table 7, in GESAMP, 1997.

ered the Mediterranean green seaweed *(Caulerpa taxifolia)* in a lagoon in southern California. They treated the algal beds with liquid chlorine. Although high mortality followed, individual plants did survive (Woodfield, 2001).

Researchers have not yet attempted to use biocontrol—the release of one species to control another species—in the ocean.

In each of these cases, researchers used the chemicals in a restricted site and they decided to sacrifice all resident organisms—native and introduced—in an effort to remove the new introduction. Both sites are monitored to determine the success of treatment. It is unlikely that these will be the last such attempts to apply chemicals to control newly discovered populations of exotic species. Therefore, it would be worthwhile to develop criteria and rationales based on previous experiences in an effort to improve the success of future attempts. Over the long term, it may be difficult to distinguish residual populations from new introductions without genetic identification.

Researchers have not yet attempted to use biocontrol—the release of one species to control another species—in the ocean. However, after a long and mixed history on land, biocontrol is an option receiving increasing scrutiny for marine application. As with land attempts, concerns center on the potential for a biocontrol species to impact organisms other than the original target host. Researchers are actively discussing and debating the introduction of parasites or predators to control bioinvasions. Targets for biocontrol include introductions of the European shore crab *(Carcinus maenas)* in California and Australia, the Japanese sea star *(Asterias amurensis)* in Australia, green seaweed *(Caulerpa taxifolia)* in the Mediterranean, and the American comb jellyfish *(Mnemiopsis leidyi)* in the Black and Caspian Seas (Lafferty and Kuris, 1996; Simberloff and Stiling, 1996; Kuris et al., 1996; Carlton, 1997; Goddard et al., 2001; Thresher and Bax, 2001; Thibaut and Meinesz, 2001).

IV. Recommendations for **Action**

The needs to reduce and prevent accidental introductions and to regulate intentional releases of non-native species in U.S. coastal marine waters differ little from that of classical quarantine or management science for exotic species on land and in fresh water. It is important that we understand the human vectors that transport marine species as well as their variation in space and time. Then we must interrupt the vectors.

The management of introductions should be tackled from the point of origin to the point of arrival. The goal is to minimize the opportunities for the successful transport and survival of species on a given vector. Options that reduce most or all of the living organisms associated with a vector are more likely to meet that goal successfully. History has taught us that selecting target species, identifying key potential invaders, or using a black, or dirty, list may only prevent or slow the arrival of previously known pests from entering the United States. In contrast, it is impossible to predict how an introduced species, with no previous pest history, will affect the environment when it arrives in a new region that has a complex web of novel resources, competitors, predators, or parasites.

If we want to successfully combat bioinvasions, we need to consider more significant and aggressive action. We need to do more, and we need to do it now. We must prevent and reduce invasions; coordinate response to newly discovered introductions; expand research to understand the why, where, and numbers of introduced species as well as their impact on the environment; and improve and enrich education and public awareness.

The National Invasive Species Act (NISA) of 1996 is up for reauthorization and revision. The reauthorization should include significantly strengthened federal measures for research, prevention, and response, as discussed below. Two major obstacles have limited the success of NISA: the lack of adequate funding and a strong programmatic structure.

The recommendations in this chapter strike at the heart of long-term management needs and transcend any particular legislation. The recommendations should be incorporated into the general regulatory framework for bioinvasions in the United States.

Management Priorities

National Compulsory Ballast Management Program

An improved program for compulsory ballast management should provide (a) expanded funding for the United States Coast Guard for the enforcement of mandatory ballast water exchange, and (b) advanced research and development to explore and implement ballast water treatment methods, other than open-ocean ballast exchange.

Eradication of new populations of non-native species may succeed with the development of a national early-warning invasions system.

National Compulsory Fouling Management Program

An improved program should seek to significantly reduce the transport of fouling organisms by ships, (e.g., through the development of environmentally benign antifouling treatments and regular hull cleaning.) The United States Coast Guard should lead this program.

National Intentional Introductions Management Program

This program should include mandatory procedures to regulate (a) the intentional release of live non-native marine organisms, and (b) the interstate transport of live marine organisms. There is some chaos as individual states attempt to regulate intentional introductions in the open marine waters they share with adjacent states and nations. This situation dictates a new cooperative federal role for the United States Fish and Wildlife Service and the National Marine Fisheries Service to regulate introductions in all marine waters, including those in which states have dominion.

National Rapid-Response Program

A well-structured national program must be developed to focus on the eradication of new populations of marine introductions (GAO, 2001). This program should include alternatives to chemical treatment. Congress should require NMFS and FWS to mount a strike force in close cooperation with individual states. Eradication of new populations of non-native species may succeed with the development of a national early-warning invasions system. A workable system will require a sufficient number of experts—trained in systematics and taxonomy—to recognize and correctly identify new introductions.

National Marine Bioinvasions Research Program

An improved program would include a national research effort to focus on the current pulse of introductions. The National Science Foundation and NOAA Sea Grant should administer the program cooperatively. The program should:

- **provide a national comparative database against which the success of vector management strategies can be measured;**
- **assess economic and other societal impacts;**
- **determine ecological impacts; and**
- **implement a permanent national marine bioinvasion survey based upon standardized measures of patterns and rates of introductions at a consortium of different sites. These sites should represent a variety of types and strengths of vectors. To make these surveys possible, we will need to spend significantly more on training and support for marine systematics and taxonomy. Without this training, many new introductions simply cannot be correctly recognized.**

As part of this research program, we must improve our ability to better understand the regulatory importance of the drivers of coastal change—habitat destruction, fisheries overextraction, global climate change, chemical pollution, eutrophication, and the introductions themselves— if we are to better understand the fundamental processes that may regulate bioinvasions.

National Education and Public Awareness Program

One of the primary challenges facing marine education and public awareness programs is the fact that the ocean world is alien to most of the public. However, new technologies and innovative educational programs allow more and more members of the public to experience the ocean and to develop an appreciation for its importance, as well as a desire to protect it. Government and industry must take the lead in helping people understand the harm marine bioinvasions can cause. With an increasing number of diverse outreach and public awareness campaigns about introductions, there is a striking need to develop one unified national program—under the leadership of NOAA Sea Grant—that will focus on the prevention of bioinvasions.

Federal Funding

Spend More to Achieve Goals

Significantly more funding must be appropriated for the prevention, control, and study of bioinvasions. The current level of federal funding is grossly inadequate to reduce the scale and impacts of marine bioinvasions. Despite the clear recognition of many specific actions now needed (described on pages 22–24), the minuscule funding now available for research and management actions leaves many fundamental gaps in the national effort to address this problem. If we hope to substantially alter the rates and impacts of bioinvasions, increased federal funding for aquatic introduction research and education is required. At a minimum, federal appropriations should be increased 50 million dollars annually. Industries that play a fundamental role as vectors transporting non-native species should bear more of the costs of prevention, control, and research. Congress should establish a national bioinvasions reparation fee, which will significantly help to recoup federal-funding costs for management, research, and development programs.

One of the primary challenges facing marine education and public awareness programs is the fact that the ocean world is alien to most of the public.

Failing early enactment of the measures recommended above, it is likely that courts will be asked to invoke laws that already make it illegal to release living organisms in waters to which they are not native (Cohen and Foster, 2000). The invocation of these laws will become a primary agenda item should federal and international regulation continue at the pace that characterizes the usual politics of environmental oversight, and a business-as-usual approach will bring a steady stream of new bioinvasions producing profound impacts on the marine environment in the United States.

Works Cited

ABAG. 2000. Association of Bay Area Governments. Estuary Newsletter, Dec. 2000. 21 Aug. 2001. <http://www.abag.ca.gov/bayarea/sfep/news/newsletter/est0012.html>.

Anderson, L. W. J. and S. Keppner. 2001. *Caulerpa taxifolia*: marine algal invader provokes quick response in U.S. Waters. ANS Digest, 4:2, 21–23.

ANS Report. 2000. Aquatic Nuisance Species. An update on Sea Grant research and outreach projects 2000. Ohio Sea Grant College Program, Columbus, Ohio, OSHU-TB-046.

Apte, S., B. S. Holland, L. S. Godwin, and J. P. A. Gardner. 2000. Jumping ship: a stepping stone event mediating transfer of a non-indigenous species via a potentially unsuitable environment. *Biological Invasions* 2:75–79.

Boesch, D. F., R. H. Burroughs, J. E. Baker, R. P. Mason, C. L. Rowe, and R. L. Siefert. 2001. Marine pollution in the United States. Significant Accomplishments, Future Challenges. Pew Oceans Commission, Arlington, Virginia.

Burreson, E. M., N. A. Stokes, and C. S. Friedman. 2000. Increased virulence in an introduced pathogen: *Haplosporidium nelsoni* (MSX) in the eastern oyster *Crassostrea virginica. Journal of Aquatic Animal Health* 12:1–8.

Carl, G. C., and C. J. Guiguet. 1958. *Alien animals in British Columbia*. British Columbia Provincial Museum Handbook 14.

Carlton, J. T. 1985. Transoceanic and interoceanic dispersal of coastal marine organisms: the biology of ballast water. *Oceanography and Marine Biology, An Annual Review* 23:313–371.

Carlton, J. T. 1989. Man's role in changing the face of the ocean: biological invasions and implications for conservation of near-shore environments. *Conservation Biology* 3:265–273.

Carlton, J. T. 1992. Dispersal of living organisms into aquatic ecosystems as mediated by aquaculture and fisheries activities. *In Dispersal of Living Organisms into Aquatic Ecosystems*. A. Rosenfield and R. Mann, eds. Maryland Sea Grant Publication, College Park, Maryland. 13–15.

Carlton, J. T. 1993. Dispersal mechanisms of the zebra mussel (*Dreissena polymorpha*). In *Zebra Mussels: Biology, Impacts, and Control*. T. F. Nalepa and D. W. Schloesser, eds. CRC Press, Inc., Boca Raton, Florida. 677–697.

Carlton, J. T. 1996a. Pattern, process, and prediction in marine invasion ecology. *Biological Conservation* 78:97–106.

Carlton, J. T. 1996b. Marine bioinvasions: the alteration of marine ecosystems by nonindigenous species. Oceanography 9:36–43.

Carlton, J. T., ed. 1997. Report of the Study Group on Marine Biocontrol of Invasive Species. International Council for the Exploration of the Sea, Copenhagen, Denmark. Document CM 1997/Env:10.

Carlton, J. T. 1998. Ballast Water: Ecological and Fisheries Implications. International Council for the Exploration of the Sea, ICES Cooperative Research Report No. 224.

Carlton, J. T. 1999a. The scale and ecological consequences of biological invasions in the world's oceans. In Invasive Species and Biodiversity Management. O. T. Sandlund, P. J. Schei, and Å. Viken, eds. Kluwer Academic Publishers, Dordrecht, Netherlands. 195–212.

Carlton, J. T. 1999b. Molluscan invasions in marine and estuarine communities. *Malacologia* 41:439–454.

Carlton, J. T. 2000a. Quo Vadimus Exotica Oceanica? Marine Bioinvasion Ecology in the Twenty-First Century. In *Marine Bioinvasions: Proceedings of the First National Conference*. J. Pederson, ed. Massachusetts Institute of Technology, MIT Sea Grant College Program, MITSG 00-2, Cambridge, Massachusetts. 6–23.

Carlton, J. T. 2000b. Global change and biological invasions in the oceans. In *Invasive Species in a Changing World*, H. A. Mooney and R. J. Hobbs, eds. Island Press, Covelo, California. 31–53.

Carlton, J. T., and J. B. Geller. 1993. Ecological roulette: The global transport of nonindigenous marine organisms. *Science* 261:78–82.

Carlton, J. T., and J. Hodder. 1995. Biogeography and dispersal of coastal marine organisms: experimental studies on a replica of a 16th-century sailing vessel. *Marine Biology* 121:721–730.

Carlton, J. T., D. M. Reid, and H. van Leeuwen. 1995. Shipping Study. The role of shipping in the introduction of nonindigenous aquatic organisms to the coastal waters of the United States (other than the Great Lakes) and an analysis of control options. The National Sea Grant College Program/Connecticut Sea Grant Project R/ES-6. Department of Transportation, United States Coast Guard, Washington, D.C. and Groton, Connecticut. Report Number CG-D-11-95. Government Accession Number AD-A294809.

Carlton, J. T., and K. Richardson. 1995. International Council for the Exploration of the Sea. Code of Practice on the Introductions and Transfers of Marine Organisms, 1994. Preamble and a Brief Outline of the ICES Code of Practice, 1994. International Council for the Exploration of the Sea, Copenhagen, Denmark.

Carlton, J. T., and M. H. Ruckelshaus. 1997. Nonindigenous marine invertebrates and algae. In *Strangers in Paradise. Impact and Management of Non-Indigenous Species in Florida*. D. Simberloff, D. C. Schmitz, and T. C. Brown, eds. Island Press, Washington, D.C. and Covelo, California.187–201.

Cohen, A. N., and J. T. Carlton. 1995. Biological Study. Nonindigenous aquatic species in a United States estuary: a case study of the biological invasions of the San Francisco Bay and Delta. A Report for the United States Fish and Wildlife Service, Washington, D.C., and the National Sea Grant College Program, Connecticut Sea Grant, NTIS Report Number PB96-166525.

Cohen, A. N., and J. T. Carlton. 1997. Transoceanic transport mechanisms: introduction of the Chinese mitten crab, *Eriocheir sinensis*, to California. *Pacific Science* 51:1–11.

Cohen, A. N., and J. T. Carlton. 1998. Accelerating invasion rate in a highly invaded estuary. *Science* 279:555–558.

Cohen, A. N., J. T. Carlton, and M. C. Fountain. 1995. Introduction, dispersal and potential impacts of the green crab *Carcinus maenas* in San Francisco Bay, California. *Marine Biology* 122:225–237.

Cohen, A. N., and B. Foster. 2000. The regulation of biological pollution: preventing exotic species invasions from ballast water discharged into California coastal waters. *Golden Gate University Law Review* 30:787–883.

Coles, S. L., R. C. DeFelice, L. G. Eldredge, and J. T. Carlton. 1999. Historical and recent introductions of nonindigenous marine species into Pearl Harbor, Oahu, Hawaiian Islands. *Marine Biology* 135:147–158.

Connell, S. D. 2000. Floating pontoons create novel habitats for subtidal epibiota. *Journal of Experimental Marine Ecology and Biology* 247:183–194.

Courtenay, W. R., and J. R. Stauffer, eds. 1984. *Distribution, biology, and management of exotic fishes*. Johns Hopkins University Press, Baltimore, Maryland.

Crooks, J. A. 2001. Assessing invader roles within changing ecosystems: historical and experimental perspectives on an exotic mussel in an urbanized lagoon. *Biological Invasions* 3:23–36.

Culver, C. S., and A. M. Kuris. 2000. The apparent eradication of a locally established introduced marine pest. *Biological Invasions* 2:245–253.

Daehler, C. C., and D. R. Strong. 1996. Status, prediction and prevention of introduced cordgrass *Spartina* spp. invasions in Pacific estuaries, USA. *Biological Conservation* 78:1–58.

Demopoulos, A. W. J., and C. R. Smith. 2001. Impact of invading mangroves on Hawaiian soft-sediment communities. In *International Conference on Marine Bioinvasions*, New Orleans, Louisiana. Louisiana Sea Grant. 30–31.

Galil, B. S., and N. Huelsmann. 1997. Protist transport via ballast water—biological classification of ballast tanks by food web interactions. *European Journal of Protistology* 33:44–253.

GAO. 2001. General Accounting Office. Invasive species. Obstacles hinder federal rapid response to growing threat. United States General Accounting Office, GAO-01-724. 22 Aug. 2001. <http://www.gao.gov/new.items/d01724.pdf>.

GESAMP. 1997. The United Nations Group of Experts on Scientific Aspects of Marine Pollution. Opportunistic settlers and the problem of the ctenophore *Mnemiopsis leidyi* invasion in the Black Sea. GESAMP Reports and Studies 58.

Goddard, J. H. R., M. E. Torchin, K. D. Lafferty, and A. M. Kuris. 2001. Experimental infection of native California crabs by *Sacculina carcini*, a potential biocontrol agent of introduced European green crabs. In *International Conference on Marine Bioinvasions*, New Orleans, Louisiana. Louisiana Sea Grant. 54–55.

Godwin, S. 2001. B. P. Bishop Museum, Honolulu, Hawaii, Personal communication. 18 May 2001.

Goldburg, R. J., M. S. Elliott, and R. L. Naylor. 2001. Marine Aquaculture in the United States: Environmental Impacts and Policy Options. Pew Oceans Commission, Arlington, Virginia.

Gollasch, S., J. Lenz, M. Dammer, and H-G. Andres. 2000a. Survival of tropical ballast water organisms during a cruise from the Indian Ocean to the North Sea. *Journal of Plankton Research* 22:23–937.

Gollasch, S., H. Rosenthal, H. Botnen, J. Hamer, I. Laing, E. Leppäkoski, E. Macdonald, D. Minchin, M. Nauke, S. Olenin, S. Utting, M. Voigt, and I. Wallentinus. 2000b. Fluctuations of zooplankton taxa in ballast water during short-term and long-term ocean-going voyages. *Internationale Revue der Hydrobiologie* 85:597–608.

Gottlieb, S. J., and M. E. Schweighofer. 1996. Oysters and the Chesapeake Bay ecosystem: A case for exotic species introduction to improve environmental quality? *Estuaries* 19:639–650.

Graham, W., H. M. Perry, and D. L. Felder. 2001. Ecological and economic implications of the trophic jellyfish, *Phyllorhiza punctata*, in the northern Gulf of Mexico during the summer of 2000. In *International Conference on Marine Bioinvasions*, New Orleans, Louisiana. Louisiana Sea Grant. 59.

Gray, P. W. G., and E. B. Gareth Jones. 1977. The attempted clearance of *Sargassum muticum* from Britain. *Environmental Conservation* 4:303–308.

Grosholz, E. D., G. M. Ruiz, C. A. Dean, K. A. Shirley, J. L. Maron, and P. G. Connors. 2000. The impacts of a non-indigenous marine predator in a California bay. *Ecology* 81:1206–1224.

Hicks, D. W., and J. W. Tunnell, Jr. 1993. Invasion of the south Texas coast by the edible brown mussel *Perna perna* (Linnaeus, 1758). *The Veliger* 36:92–94.

Kuris, A. M., K. D. Lafferty, and M. J. Grygier. 1996. Detection and preliminary evaluation of natural enemies for possible biological control of the northern Pacific seastar, *Asterias amurensis*. CSIRO Centre for Research on Introduced Marine Pests, Technical Report 3.

Lafferty, K. D., and A. M. Kuris. 1996. Biological control of marine pests. *Ecology* 77:1989–2000.

Latané, L. 2001. Test oyster buoys hope for revival. *Richmond Times-Dispatch*, Richmond, Virginia, B2. May 23, 2001.

Lloyd's Register of Shipping. 2000. Lloyds World Fleet Statistics 1999. Lloyd's Register of Shipping, London, United Kingdom.

Major, W., and C. E. Grue. 1997. Control of *Spartina alterniflora* in Willapa Bay, Washington: efficacy of mechanical and chemical control techniques, and their off target impacts on eelgrass *(Z. japonica)*. In *Second International Spartina Conference. Proceedings*. K. Patten, ed. Washington State University, Long Beach, Washington. 76–81.

Mann, R. Virginia Institute of Marine Science, Gloucester Point, Virginia. 2001. Personal communication. 5 June 2001.

Mann, R., and J. M. Harding. 2000. Invasion of the North American Atlantic coast by a large predatory Asian mollusc. *Biological Invasions* 2:7–22.

McCarthy, H. P., and L. B. Crowder. 2000. An overlooked scale of global transport: phytoplankton species richness in ships' ballast water. *Biological Invasions* 2:321–322.

McDermott, J. J. 1999. The Western Pacific brachyuran *Hemigrapsus sanguineus (Grapsidae)* in its new habitat along the Atlantic coast of the United States: feeding, cheliped morphology and growth, pp. 425–444. In *Crustaceans and the Biodiversity Crisis. Proceedings of the Fourth International Crustacean Congress.* Koninklijke Brill NV, Leiden.

Morrice, M. G. 1995. The introduced northern Pacific seastar, *Asterias amurensis* (Lutken), in Tasmania. In *The Introduced Northern Pacific Seastar, Asterias amurensis (Lutken) in Tasmania*. Australian Nature Conservation Agency, Canberra, Australia.

Myers, J. H., D. Simberloff, A. M. Kuris, and J. R. Carey. 2000. Eradication revisited: dealing with exotic species. *Trends in Ecology and Evolution* 15:316–320.

National Research Council. 1995. *Understanding Marine Biodiversity*. National Academy Press, Washington, D.C.

National Research Council. 1996. *Stemming the Tide. Controlling Introductions of Nonindigenous Species by Ships' Ballast Water*. National Academy Press, Washington, D.C.

O'Neill, C. R. 2000. National Aquatic Nuisances Species Clearinghouse, New York Sea Grant Extension, Brockport NY, Personal Communication, 22 Dec. 2000.

Pimentel, D., L. Lach, R. Zuniga, and D. Morrison. 2000. Environmental and economic costs of nonindigenous species in the United States. *BioScience* 50:53–65.

Posey, M. H. 1988. Community changes associated with the spread of an introduced seagrass, *Zostera japonica. Ecology* 69:974–983.

Quayle, D. B. 1964. Distribution of introduced marine Mollusca in British Columbia waters. Journal of the Fisheries Research Board of Canada 21:1155–1181.

Randall, A., and H. Gollamudi. 2001. Dealing with the analytical challenges of valuation: aquatic nuisance species control. In *Revealing the Economic Value of Protecting the Great Lakes*. A. Cangelosi, ed. Northeast-Midwest Institute and National Oceanic and Atmospheric Administration, Washington, D.C.

Ruiz, G. M. Smithsonian Environmental Research Center, Edgewater, Maryland. Personal Communication. 10 Mar. 2001.

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

Ruiz, G. M., P. W. Fofonoff, J. T. Carlton, M. J. Wonham, and A. H. Hines. 2000. Invasion of coastal marine communities in North America: apparent patterns, processes, and biases. *Annual Review of Ecology and Systematics* 31:481–531.

Ruiz, G. M., P. Fofonoff, and A. H. Hines. 1999. Non-indigenous species as stressors in estuarine and marine communities: assessing invasion impacts and interactions. *Limnology and Oceanography* 44(3 part 2):950–972.

Ruiz, G. M., T. K. Rawlings, F. C. Dobbs, L. A. Drake, T. Mullady, A. Huq, and R. R. Colwell. 2000. Global spread of microorganisms by ships. *Nature* 408:49–50.

Shatkin, G., S. E. Shumway, and R. Hawes. 1997. Considerations regarding the possible introduction of the Pacific oyster (*Crassostrea gigas*) to the Gulf of Maine: a review of global experience. *Journal of Shellfish Research* 16:463–477.

Silva, P. C., R. A. Woodfield, A. N. Cohen, L. H. Harris, and J. H. R. Goddard. In preparation. A large Asian kelp arrives in the Eastern Pacific Ocean. *Biological Invasions* 3.

Silva, R. G. 2001. Chief, Fish Facility Branch, United States Bureau of Reclamation, Tracy Office, Tracy, California. Personal communication, 30 Mar. 2001.

Simberloff, D., and B. Von Holle. 1999. Positive interactions of nonindigenous species: invasional meltdown? *Biological Invasions* 1:21–32.

Simberloff, D., and P. Stiling. 1996. How risky is biological control? *Ecology* 77:1965–1974.

Steneck, R. S., and J. T. Carlton. 2001. Human alterations of marine communities: students beware! In *Marine Community Ecology*. M. D. Bertness, S. D. Gaines, and M. E. Hay. Sinauer Associates, Inc., Publishers, Sunderland, Massachusetts.

Talley, T. S., J. A. Crooks, and L. A. Levin. 2001. Habitat utilization and alteration by the invasive burrowing isopod, *Sphaeroma quoyanum*, in California salt marshes. *Marine Biology* 138:561–573.

Taylor, A. 1998. BHP, Inc. Personal communication. 23 Mar. 1998.

Thibaut, T., and A. Meinesz. 2001. Biological control of the invasive *Caulerpa taxifolia* in the Mediterranean Sea. In *International Conference on Marine Bioinvasions*, New Orleans, Louisiana. Louisiana Sea Grant.

Thomas, M., N. Benjamin, and Z. Grader. 2001. The utilization of fishing effort in controlling and/or containing certain marine invasive species. In *International Conference on Marine Bioinvasions*, New Orleans, Louisiana. Louisiana Sea Grant.

Thresher, R. E., and N. J. Bax. 2001. Classical biological control of the northern Pacific seastar and the European shore crab: prospects for success based on five years of background work. In *International Conference on Marine Bioinvasions*, New Orleans, Louisiana. Louisiana Sea Grant.

University of California, Davis. 2000. 7 Sept. 2001. <http://www.dateline.ucdavis.edu/110300/DL_newgrant.html>.

Villalard-Bohnsack, M., and M. M. Harlin. 1997. The appearance of *Grateloupia doryphora (Halymeniaceae, Rhodophyta)* on the northeast coast of North America. *Phycologia* 36:324–328.

Vitousek, P. M., H. A. Mooney, J. Lubchenco, and J. M. Melillo. 1997. Human domination of Earth's ecosystems. *Science* 277:494–499.

Volpe, J. P., E. B. Taylor, D. W. Rimmer, and B. W. Glickman. 2000. Evidence of natural reproduction of aquaculture-escaped Atlantic salmon in a coastal British Columbia river. *Conservation Biology* 14:899–903.

Walton, W. University of Maryland, College Park, Maryland. 2001. Personal communication. 5 Apr. 2001.

Wecker, M. Olympic Natural Resources Center, University of Washington. Personal communication. 18 Mar. 2001.

Willan, R. C., B. C. Russell, N. B. Murfet, K. L. Moore, F. R. McEnnulty, S. K. Horner, C. L. Hewitt, G. M. Dally, M. L. Campbell, and S. T. Bourke. 2000. Outbreak of *Mytilopsis sallei* (Récluz, 1849) (Bivalvia: *Dreissenidae*) in Australia. *Molluscan Research* 20(2):25–30.

Williams, S. 2001. Bodega Marine Laboratory. Personal communication, 10 Mar. 2001.

Wonham, M. J., J. T. Carlton, G. M. Ruiz, and L. D. Smith. 2000. Fish and ships: relating dispersal frequency to success in biological invasions. *Marine Biology* 136:1111–1121.

Woo, M., C. Smith, and W. Smith. 2000. Ecological interactions and impacts of invasive *Kappaphycus striatum* in Kane'ohe Bay, a tropical reef. In *Marine Bioinvasions: Proceedings of the First National Conference*, J. Pederson, ed. Massachusetts Institute of Technology, MIT Sea Grant College Program, MITSG 00-2, Cambridge, Massachusetts.

Woodfield, R. 2001. Merkel Inc. Personal communication, 10 Mar. 2001.

Pew Oceans Commission

Connecting People and Science to Sustain Marine Life

The Pew Oceans Commission is an independent group of American leaders conducting a national dialogue on the policies needed to restore and protect living marine resources in U.S. waters. After reviewing the best scientific information available, the Commission will make its formal recommendations in a report to Congress and the nation in 2002.

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