

INVASIONS *in the sea*

By Andrew N. Cohen

Worm attack

Needing a base on the Pacific Coast in 1852, the U.S. Navy went searching for a site that was “safe from attack by wind, wave, enemy, and marine worms” (Lott 1954). The attack worm that worried the Navy was the native Pacific shipworm, *Bankia setacea*. Shipworms bore tunnels in wood, severely damaging wooden pilings and ship hulls.

The Navy built its base in the northern part of San Francisco Bay, where the water is too fresh for the Pacific shipworm. No enemies attacked until an Atlantic shipworm, *Teredo navalis*, which tolerates fresher water than its Pacific cousin, arrived in the bay. The Atlantic shipworm multiplied rapidly and proceeded in 1919 to bore its way through the available habitat, dropping wharves, piers, ferry slips, and other maritime facilities into the water at an average rate of one major structure every two weeks for a period of two years (fig. 1). In current dollars, the worm caused between \$2 billion and \$20 billion in damage.

Marine invaders

Many recent biological invasions have interfered with human uses of the sea or dramatically altered marine ecosystems.

- The western Atlantic comb jelly *Mnemiopsis leidyi*, a small, gelatinous, planktonic predator, became phenomenally abundant in the Black Sea in the 1990s. It contributed to the collapse of the sea’s fisheries by eating up the crustacean zooplankton, a key link in the food web.
- Within a year of its appearance, the Asian clam *Potamocorbula amurensis* was the most abundant clam



Figure 1. The collapse of the Benicia wharf and customs house in San Francisco Bay on October 7, 1920, was caused by the Atlantic shipworm, *Teredo navalis*. FROM R. M. NEILY, HISTORICAL DEVELOPMENT OF MARINE STRUCTURES IN SAN FRANCISCO BAY, IN “FINAL REPORT OF THE SAN FRANCISCO BAY PILING COMMITTEE” (1927).



Figure 2. Introduced from Asia in ballast water, *Potamocorbula amurensis* had become the most abundant clam in northern San Francisco Bay nine months after it was noticed. ANDREW N. COHEN

in the northern part of San Francisco Bay (fig. 2). Researchers estimated that virtually the entire water column was filtered by these clams between once and twice a day, essentially vacuuming the food out of the water. The clams also concentrate selenium in their tissues, so that fish and birds that eat them are accumulating selenium at levels that are known in experimental studies to cause reproductive defects.



- Dinoflagellates are microscopic plankton that sometimes become so abundant that they color the sea as “red tides.” These outbreaks can kill invertebrates, fish, and seabirds. Some dinoflagellates produce neurotoxins that accumulate in mussels or clams consumed by humans, causing paralytic shellfish poisoning (PSP). In recent decades, red tides and PSP outbreaks have been reported more frequently around the world and in areas where they were previously unknown. At least some of these (in mainland Australia and Tasmania, France, and probably also New Zealand and Chile) apparently resulted from exotic dinoflagellates discharged in ships’ ballast water.



Seaweeds, sponges, barnacles, clams, worms, and other organisms can travel as “hull fouling,” attached or clinging to the hulls of vessels, or, like shipworms, burrowed inside wooden hulls.

San Francisco Bay demonstrates the extent to which invasions can transform an ecosystem. More than 175 exotic marine and estuarine species have been identified, including the most common worms, clams, snails, amphipods (a type of small crustacean), and foraminifers (amoeba-like microorganisms) on the bottom of the bay. Japanese zooplankton and European jellyfish have taken over in brackish waters. An Atlantic cordgrass is spreading through the bay’s salt marshes, dramatically altering habitat, threatening the existence of native cordgrass, and altering the distribution and populations of marsh-nesting birds. Chinese mitten crabs have colonized the bay, with hundreds of thousands crawling up the rivers in boom years (fig. 3). Exotic species now dominate many of the estuary’s biotic communities where they typically account for 40%–100% of the common species, up to 97% of the total number of organisms, and up to 99% of the biomass. And in recent decades they have been coming in faster than ever, with about four new species becoming established each year (Cohen and Carlton 1998).

On the move

Marine invaders are moved around the world by a variety of mechanisms. Seaweeds, sponges, barnacles, clams, worms, and other organisms can travel as “hull fouling,” attached or clinging to the hulls of vessels, or, like shipworms, burrowed inside wooden hulls (figs. 4 and 5). Many marine organisms are microscopic plank-



Although many marine invaders have been found primarily in disturbed areas in harbors, bays, and estuaries, ... specific invasion threats to open coastal and offshore areas have been documented, indicating that even these relatively pristine waters [of the National Park System] may be at risk.

ton that can be carried in a ship's ballast water. Much marine aquaculture is based on exotic species; some of these are intentionally planted in the environment, while others often escape from the facilities in which they are held, sometimes carrying exotic parasites or diseases. Saltwater species are a small but rapidly growing sector of the aquarium industry, and these organisms sometimes escape from commercial facilities or are released into the ocean by their owners when no longer wanted. Several species of marine fish, shellfish, and algae have been released by government agencies into new parts of the world to establish or support fisheries, and some agencies have considered releasing exotic marine organisms as biocontrol agents. Other vectors include the international transport and sale of live marine bait, live seafood, and live organisms for research and education (fig. 6).

Marine invasions and the National Park System

The National Park System includes more than 3 million acres (1.2 million ha) of submerged ocean floor and about 4,500 miles (7,241 km) of ocean coastline. Although many marine invaders have been found primarily in disturbed areas in harbors, bays, and estuaries, and thus may not affect most of the Park Service holdings, within each region specific invasion threats to open coastal and offshore areas have been documented, indicating that even these relatively pristine waters may be at risk.

In the Southeast, individuals and small groups of Pacific lionfish (*Pterois volitans*) have been sighted, photographed, or collected from Florida to North Carolina, with additional records in Bermuda and New York (Whitfield et al. 2002). These probably result from aquarium releases, and the evidence suggests that the lionfish is established and reproducing there. In its native range the lionfish is found on rock and coral reefs down to depths of 164 feet (50 m). Its venomous spines protect it from predators and may pose a risk to divers.

Figure 3, top left. A truckload of Chinese mitten crabs, *Eriocheir sinensis*, being hauled away from the intake screens of the Central Valley Project water diversion in central California.

Figure 4, bottom left. Several species of exotic sea squirts, sponges, and bryozoans are shown growing on a boat hull in San Francisco Bay.

Figure 5, top right. The tubes of a subtropical, hull-fouling and reef-forming polychaete worm, *Ficopomatus enigmaticus*, in San Francisco Bay.

Figure 6, bottom right. The Atlantic periwinkle, *Littorina saxatilis*, arrived in San Francisco Bay with shipments of Maine baitworms. ANDREW N. COHEN (4)



Another notorious aquarium release is the tropical green seaweed *Caulerpa taxifolia* (fig. 7). An aquarium-bred clone of this species became established in the Mediterranean Sea in the 1980s, and now covers about 10,000 acres (4,050 ha). It grows over seagrass beds, rocky reefs, and corals alike, ranging from quiet waters to wave-pounded capes, and from near-surface waters to 295-foot (90-m) depths. Fishing and recreational diving have both suffered. In 1998, I drafted a petition signed by more than 100 scientists, seeking a prohibition on the import and sale of this seaweed in the United States. It was banned in 1999, but was discovered in two California lagoons in the spring of 2000. An eradication effort based on pumping chlorine beneath rubberized tarps laid over the infested areas has cost more than \$3 million to date. Coral reefs in Florida, the Virgin Islands, Hawaii, American Samoa, and Guam, and waters north to North Carolina and California, could be vulnerable to invasion.

Also in California, a South African shell parasite, the sabellid worm *Terebrasabella heterouncinata*, widely infested abalone farms and escaped into the environment in at least one site. This parasite can deform and halt the growth of all West Coast abalone species—whose populations are already in rapid decline, with one near extinction—as well as other marine snails. It can invade habitats from intertidal rocky shores to subtidal reefs, where reducing snail populations could alter seaweed communities, thereby affecting habitat and food resources for many other species.



Figure 7. The tropical aquarium seaweed, *Caulerpa taxifolia*, overgrowing a rocky substrate in the Mediterranean Sea near Monaco. ALEX MEINESZ

Atlantic salmon are raised in and regularly escape from fish farms on both North American coasts. More than 100,000 Atlantic salmon escape from Pacific Coast farms per year, and they are now established in the wild in British Columbia (Volpe et al. 2000). Possible impacts on both coasts include competition with native salmon and the introduction of parasites or diseases to which native salmon are not adapted, and in the Atlantic, the genetic pollution of local stocks, leading to loss of fitness.

Finally, following the apparent overharvesting of fish and sea urchins in the Gulf of Maine, some rocky reefs down to 66-foot (20-m) depths have become dominated by exotic species, including green and red seaweeds and two species of colonial sea squirts (Harris and Tyrrell 2001). Recently a third exotic sea squirt has been found covering gravel, boulders, and bottom organisms on Georges Bank at depths of 135 to 157 feet (41 to 48 m) (USGS 2004) (fig. 8). In other regions they have invaded, most of these species are typically found only in bays and harbors. Thus, even organisms that are normally considered bay species may be capable of invading open waters under the right conditions.

Managing invasions

Other than local removals of salt-marsh weeds, only two successful eradications of marine invaders have occurred. In northern Australia, a mussel became established in three boat basins connected to the ocean by lock systems; the government closed the locks for three weeks and poured in biocides until everything in the basins was killed (Bax 1999). In southern California, the South African shell parasite discussed earlier was found in the intertidal zone of one cove; approximately 1.6 million intertidal snails were removed, reducing the host density to a level that was too low to sustain the parasite (Culver and Kuris 2000). The *Caulerpa* eradication effort

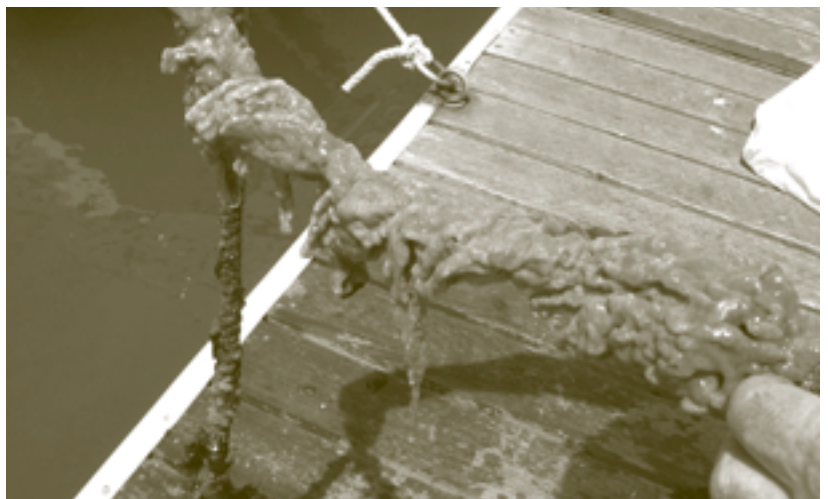


Figure 8. The European sea squirt *Didemnum* cf. *lahillei* has recently become established in New Zealand, California, and New England, including parts of George's Bank. It is shown covering a rope in Sausalito, California. GRETCHEN LAMBERT

mentioned earlier may ultimately prove to be a third successful example.

However, the interconnectedness of ocean waters, the huge number of easily dispersed young produced by many marine organisms, and the difficulty of locating and treating organisms in subtidal waters make eradication or even significant control of most marine invaders a daunting task. The techniques typically employed on land—applying herbicides and insecticides; trapping, shooting, and poison-baiting animals; and applying the chemical rotenone to ponds or lakes to kill off unwanted fish—are inapplicable or ineffective for most marine organisms. Furthermore, with new invaders arriving at a rapid rate, resource managers could not implement the number of control efforts needed to contain them all *even if* effective methods were available.

Fortunately, there are some things we can do to substantially reduce the transport and release of exotic marine organisms and prevent many of them from arriving in the first place. First, intentional importations and releases should be subjected to rigorous, public review before being allowed and, if allowed, should include precautionary procedures to prevent the accidental introduction of parasites or other associates. These standards have probably been met for the few government releases of exotic marine organisms considered in recent years. However, such standards are not applied to the importation and handling of exotic organisms intended for use in aquaculture, in the aquarium, for live bait, as seafood, or in research or education. An essential step is changing the federal management of imports from the current “dirty list” approach, which allows the importation of any organism unless it is proven to be dangerous, to a “clean list” approach in which exotic organisms proposed for importation under a set of procedures must be shown to be safe (as recommended by the U.S. Fish and Wildlife Service 30 years ago).

Second, we must reduce as far as possible the number of exotic organisms unintentionally transported with ships in ballast water and hull fouling. As of this writing, 30 years after the United Nations first recognized the ballast water problem, federal agencies still do not bar ships from dumping exotic organisms into U.S. marine waters. This is not because the problem is especially complex: killing or removing organisms that are contained in tanks of water is simple compared to most environmental challenges. And though several existing federal and state laws could limit the discharge of exotic organisms in ballast water, agencies have not made use of them (Cohen and Foster 2000). Controlling the transport of organisms attached to the hulls of ships is more complicated, but maintenance requirements targeting the most heavily fouled vessels might be feasible and reasonably effective.

The big picture

The organisms that inhabit coastal waters are distributed in distinct bioregions separated by continents, by areas with different water temperatures, and by reaches of deep ocean inimical to coastal life. Each of these coastal bioregions, developing in relative isolation from the others, has evolved its own unique assemblage of native organisms. These native assemblages are increasingly threatened by the transport of species across the barriers that separate bioregions. In most cases, it will be difficult or impossible to control the populations or stop the spread of exotic organisms after they have crossed these barriers and become established in a new bioregion. Instead, the preservation of distinctive ecologies in waters of the National Park System and other marine protected areas will require a vigorous defense of natural bioregional boundaries by regulating the activities that transport organisms across them.

Literature cited

- Bax, N. J. 1999. Eradicating a dreissenid from Australia. *Dreissena!* 10(3):1–5.
- Cohen, A. N., and J. T. Carlton. 1998. Accelerating invasion rate in a highly invaded estuary. *Science* 279:555–558.
- 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(4):787–883.
- Culver, C. S., and A. M. Kuris. 2000. The apparent eradication of a locally established marine pest. *Biological Invasions* 2:245–253.
- Harris, L. G., and M. C. Tyrrell. 2001. Changing community states in the Gulf of Maine: Synergism between invaders, overfishing, and climate change. *Biological Invasions* 3(1):9–21.
- Lott, A. S. 1954. A long line of ships: Mare Island's century of naval activity in California. U.S. Naval Institute, Annapolis, Maryland.
- U.S. Geological Survey (USGS). 2004. USGS Woods Hole Science Center Web site on “Marine invasive species: *Didemnum lahillei*, a colonial tunicate” available from <http://woodshole.er.usgs.gov/project-pages/stellwagen/didemnum/index.htm> (last modified and accessed 15 April 2004).
- 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(3):899–903.
- Whitfield, P. E., T. Gardner, S. P. Vives, M. R. Gilligan, W. R. Courtenay, G. Carleton-Ray, and J. A. Hare. 2002. Biological invasion of the Indo-Pacific lionfish *Pterois volitans* along the Atlantic Coast of North America. *Marine Ecology Progress Series* 235:289–297.

About the author

Andrew N. Cohen is an environmental scientist and the director of the Biological Invasions Program at the San Francisco Estuary Institute, 7770 Pardee Lane, Oakland, CA 94621. He can be reached at 510-746-7367 and acohen@sfei.org.

