Plenary Lectures

‘In 1962... it was beyond imagination that we would close this century with a higher level of national and international awareness of bioinvasions in the seas than ever before.’
At the outset, let me congratulate the conference sponsors. You are taking the initiative in a much neglected field. Marine bioinvasions have large consequences for our food supply, our economy, our fishing industry, and human health. These invasions also threaten to degrade and homogenize coastal waters in every corner of the seven seas.

Ten years ago, just after midnight on March 24, the Exxon Valdez crashed into a reef in Prince William Sound. Eleven million gallons of crude oil poured into the pristine waters, casting a shroud over hundreds of miles of shoreline. Television crews on the scene broadcast images of seabirds, otters, and sea lions, slicked black with oil. Those images fixed the world on the dangers of oil spills and led to many new laws and regulations designed to prevent another such tragedy.

Yet the biological spill taking place in Prince William Sound from oil tankers go virtually unnoticed. Just over a year ago the U.S. Fish and Wildlife Service discovered four new species of zooplankton spreading through the Sound, released from ballast water brought by tankers from Southeast Asia via San Francisco Bay. In the long run, these zooplankton, feeding on phytoplankton utilized by the Dungeness crab, may change the Sound more extensively and permanently than any oil spill. And no one has a clue—or a dime—to contribute toward a massive clean up. Were that even possible.

With just four small bioinvasive species, Prince William Sound is relatively lucky, so far. But look farther south, where a prolific and hungry European stowaway has disembarked. The green crab has begun to infest Pacific coastal waters, devouring anything from commercially valuable oysters and clams to barnacles, algae, and snails. And it’s not alone: in the northwest nearly forty percent of all aquatic species are exotic, including the Spartina alterniflora that has choked Willapa Bay, Washington, and decimated the shellfish industry. This particular invader came from our own Atlantic coastal estuaries.

It gets worse inside the Golden Gate. There, as Interior Secretary, I have worked with environmentalists, irrigation farmers, and cities to get more freshwater down California’s main rivers into the Delta and San Francisco Bay. Our goal is to help restore endangered native fish like Chinook salmon and Delta smelt. Only now I know that it is not enough to ensure healthy flows downstream; our real threats may be coming upstream.

Specifically, some 30 species of exotic fish—Asian goby, Atlantic shad, Mississippi catfish, carp, bass, perch, sunfish, goldfish—are swarming the Bay, a veritable marine zoo. An additional 200 bioinvasive species are suffocating native fisheries and helped drive the thicktail chub to extinction. Those are only the documented cases, with new arrivals every ten weeks.

Moving eastward, the Gulf of Mexico is being mugged by the brown mussel, which displaces native mollusks, threatens mangroves, and fouls water intake systems. In the Chesapeake, a hotspot with over 150 documented bioinvasive species, oyster beds now succumb not only to polluted runoff, or overharvest, but to the new arrival of a predatory whelk. I’ll let the courageous researchers detail what’s happening less than a mile away from here, in North America’s oldest coastal port and fishery. It’s too depressing for me.

It might be easier if we could simply blame the rest of the world for our troubles. But the truth is that ballast water sloshes both ways. In the early
1980s, a small, luminescent blob called Leidy’s comb jelly was pumped aboard ships along our coast, then discharged weeks later into the Black Sea. With no predators, it mushroomed into one of the most intense marine invasions ever recorded, nearly wiping out anchovies and other fisheries. Zebra mussels exchanged for jellyfish: the maritime law of reciprocity at its darkest.

No place on earth is immune from the twin threats of extinction and alien invaders. In the mid-nineteenth century, when wooden whaling ships crisscrossed the seas in bloody pursuit, Herman Melville pondered “whether Leviathan can long endure so wide a chase and so remorseless a havoc; whether he must not at last be exterminated from the waters.” He took note of how we were pushing the buffalo to extinction on the prairies, but dismissed it as impossible on the high seas, rationalizing that, surely, whales could escape to polar regions and thus become “immortal in his species.”

Mankind never used to navigate such frozen regions, even though the fouled wooden hulls like Ahab’s surely carried a few unwelcome guests. To be sure, bioinvasion from ships is as ancient as the Vikings and the Phoenicians. Even when ballast consisted of stones, dirt, and iron, some exotic bioinvasive species hitchhiked along.

What has changed in the past half-century is the rate of spread, leading to faster, wider, more complex dispersal. We reach remote ports on a weekly, daily, hourly basis—from more diverse trade routes, loaded with much larger volumes of ballast. Discharge of that ballast is nothing more than “point source pollution” and must be treated as such.

Global aquaculture—shrimp farms, public fish hatcheries, commercial oyster beds—also bears responsibility for the spread of epibionts, parasites, predators, and pathogens. So does the aquarium industry: the outbreak of giant African snails in Florida or the \textit{Candera taxijola} clone, an alga taking over the Mediterranean, originated not in ballast, but from aquarium tanks.

All these sources must be included in our response, both policy and research. But at a more immediate level, we must grasp the root of the problem. That root lies not in isolated incidents, but in scope: the dramatic rate of spread, the increasing vectors of pathogens that carried cholera to Alabama and seem to multiply toxic red tides around the world.

As a very crude rule of thumb, ten percent of invasive species will establish breeding populations; ten percent of those will launch a major invasion. At first, that one percent factor seems negligible. Then, consider how San Francisco Bay is approaching 300 exotics.

Consider also that ships in this century have grown from 3,000 tons to 300,000 tons, and the volume of ballast water slurry—pumped and sucked at 20,000 cubic meters an hour—has kept pace. Faster crossings let more species survive, reproduce, make connections, and take baggage. The fall of trade walls brings global exposure to once quiet seaside ports, and vice versa. In the ballast water of timber cargo ships traveling between Coos Bay, Oregon, and Japan, researchers found 367 species of living animals and plants.

That’s a single route. Consider how larger ports, say Norfolk and Baltimore, receive more than 12 million metric tons of foreign ballast water per year, originating in 48 different foreign ports, and 90 percent of them carried live organisms, including barnacles, clams, mussels, copepods, diatoms, and juvenile fish. Worldwide, it is estimated that tens of thousands of ships carry several thousand species daily.

Let me put this another way: In the time it takes me to deliver this speech, two million gallons of foreign plankton will have been discharged somewhere in American waters. We’d better get busy. And fast.

How? What is our response? So far it has been pitiful. Frankly, in light of the economic and ecological devastation, we have been too timid. We restrain ourselves with voluntary guidelines, a scattered approach, and limited unenforced codes. No longer.

In 1997, President Clinton, responding to concerns of scientists like yourselves, asked the Departments of Interior and Agriculture to draft an executive order for his consideration. That order, which is now before the President, will contain two broad initiatives. First, it will require federal agencies to review their existing authorities and activities to reduce the risk of bioinvaders. Second, it will create an inter-agency working group to draft a plan—possibly including regulatory and legislative change—necessary for a coordinated response to bioinvaders.

What will this look like in practice? I’ll sketch the rough outlines in pencil. For there are existing models, and while there is still much to learn, we do know this: the first and best line of defense against bioinvaders is to keep them out in the first place. Period. Not one marine bioinvasive species, after it has taken
hold, has ever been eliminated or effectively contained. There is simply no silver bullet. This is a sobering fact. It means our efforts must be focused primarily on prevention. And that, in turn, means effective regulation and enforcement.

In 1990, in response to the damage caused by the zebra mussel in the Great Lakes, the Congress enacted the Nonindigenous Aquatic Nuisance Prevention and Control Act. Among other provisions, the Act now requires ballast water exchange at sea rather than in the Great Lakes system. We should now move toward mandatory ballast exchange for not just the Great Lakes, but for all shipping in all American ports. In California, water districts whose systems are threatened by invaders working their way upstream out of San Francisco Bay have begun to call for ballast water regulation by federal and state agencies.

We need to mount a coordinated research program to better understand the threats posed by alien invaders including fish, crustaceans, mollusks, and pathogens and to guide programs of prevention and control. Perhaps we can find economical and safe means to decontaminate ballast water and sediments in situ. The Agricultural Research Service and APHIS in the Department of Agriculture, the Coast Guard, the National Oceanic and Atmospheric Administration, and the Biological Research Division of the United States Geological Service should mount a coordinated effort to understand agricultural threats, threats to natural ecosystems, and new methods of prevention and control.

Does this mean our agency budgets must catch up to, and keep pace with, the ecological devastation they target? Yes, because that devastation is economic as well. Vast as they are, the Great Lakes are easy to manage compared to the task ahead, and but offer few unqualified success stories. Yet, the results there make a strong case for why an aggressive, well-funded public response to bioinvasion is well worth the expense and effort.

We spend several million dollars a year sterilizing, catching, poisoning, and putting up barriers to suppress the sea lamprey. Well, it’s still there and it may never go away. But for every dollar we invest, the Great Lakes earn $30.25 in increased fisheries revenue. Your stock portfolio should perform as well.

Global cooperation is an imperative. Our joint efforts with Canada on the Great Lakes provides an example. Two global entities—the Convention on Biological Diversity and the World Trade Organization—should play a major role in international cooperation. The Convention on Biological Diversity is the place to begin, and indeed preliminary discussions pursuant to Section 8 of the Biological Diversity Treaty are underway. Those discussions underline the need for Senate ratification of the Biodiversity Treaty. The World Trade Organization must also take an active role in the movement to develop and harmonize regulations in this area.

Let me conclude with a cautious note of hope. You’ve all heard that the flip side of crisis is opportunity? Well, the Exxon Valdez crash gave us such an opportunity. It led Congress to require double-hulled tankers and stiffen training, navigation, and technology within the shipping industry. It prompted state, federal, and private agencies to establish habitat restoration programs and undertake comprehensive research on the North Pacific ecosystem.

We face an even greater opportunity now. The time is at hand for scientists, policy makers, industry, and the public to join together for an intensive coordinated counterattack on the threat of bioinvasions. You have initiated that process, and we in the public sector must now respond in kind.
Plenary Lecture

*Quo Vadimus Exotica Oceanica?* Marine Bioinvasion Ecology in the Twenty-First Century

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Key words: invasion ecology; historical perspective; evolutionary consequence

These are heady times in the world of marine bioinvasions, as witnessed by the gathering of over 200 persons here this morning. In January 1989, such a congregation would have been inconceivable. A new journal, *Biological Invasions*, is being launched this fall that will serve as a platform for invasion science. And as we will hear tomorrow morning, a Presidential Executive Order on exotic species will be released 10 days from now.

Despite this remarkable blossoming of interest, marine invasion science is a young science and challenges abound. The depth and breadth of the profound alteration to marine communities by invasions in the oceans remain, in large part, unknown and thus vastly underestimated. Invasions have occurred not only in estuaries and harbors but also in exposed rocky intertidal shores, coral reefs, mangrove communities, open continental shelves, and the deep sea. Indeed, it may be that, at the least, no shallow-water temperate or tropical marine community in the world now remains untouched by human-mediated bion invasions, but that hypothesis remains to be tested. This morning I will suggest ways in which we need to be more rigorous, more refined, and more aggressive in our grasp of the temporal and spatial scales of the ecology of invasions in the seas.

We need to be clearer and less hesitant about the scope of invasions that must have occurred prior to the 19th century. We need to wash away the salty cloud of antiquity that obscures the modern history of marine communities. It is impossible to overemphasize the poor picture that we have of the nature of the ocean's biota only 100 or 200 years ago. Ships with organisms on and in their hulls and in their rock and sand ballast have moved species around the world since at least the 14th century. But we too often think of invasions as beginning, more or less, in the 19th century. If in the 300-year period between 1500 and 1800, only three species a year were spread around the world (the number, of course, may be much greater), then nearly 1000 coastal species of marine organisms that are now regarded as naturally cosmopolitan are in fact "simply" early introductions.

This estimation is not a mere historical curiosity: an understanding of the number and identity of pre-19th century invaders would profoundly impact both our understanding of modern marine community ecology and our basic assumptions about and interpretation of the natural diversity, biogeography, and rate of evolution in the seas. In terms of invasion biology itself, we can ill afford to seek patterns such as the relative susceptibility or resistance of different regions to invasions, or attempt to define guilds or

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1This paper is the conference opening Plenary Lecture, with modifications, as presented on January 25, 1999. As such the lecture format is retained here and no references are cited in the text. However, an extensive and partially annotated bibliography of marine bioinvasions literature is presented at the end.

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3The first issue of *Biological Invasions* was published in October 1999.

4Secretary of the Interior Bruce Babbitt spoke on Tuesday morning, January 26, 1999. President William Clinton's Executive Order was released in Washington, D.C. on Wednesday, February 3, 1999.
clades of invaders that may be more or less likely to invade, if we persist in ignoring more than 75% of the modern invasion history in the ocean. It follows that at least some of the hundreds of pre-1800 invasions are likely to be the common, if not abundant, species where they were introduced long ago, and thus perhaps some of the most important organisms regulating community structure.

But which ones are they? How startled would we be if we could look back at some of our “best known” shallow marine communities—kelp beds, rocky shores, and coral reefs—and find that keystone species were absent in 1599 or 1699 or 1799? Why is it that we cannot tell if a species has been present for 100 years or 100,000 years, or are we not paying attention to what evolution is telling us? Should not the presence of certain clades or lineages in certain marine communities that appear to have evolutionary roots elsewhere—such as mussels of the northern genus *Mytilus* in the southern hemisphere—not surprise us? By using morphological, genetic, historical, paleontological, archeological, and other evidence we may be able to begin to look below this cryptic invasion iceberg:

• The ship-boring isopod, *Sphaeroma teredinis*, possibly native to the Indian Ocean, appeared in the Caribbean Sea or northwestern South American coast sometime in the 19th century. It bores into and destroys the seaward root tips of mangroves. It may have reset the lower intertidal limit, and thus the history of outward propagation, of the mangrove ecosystems of the tropical western Atlantic Ocean. It passes without notice in the literature of invasions.

• The Asian seasquirt, *Styela plicata*, was carried to the North American Atlantic coast perhaps two or more centuries ago and became one of the hallmark species in the concept of multiple stable state communities. The species falls outside of our general view of marine invasions.

• And, as hinted at above, the northern hemisphere mussels, *Mytilus galloprovincialis* and *Mytilus edulis*, were carried as fouling organisms by ships to the southern hemisphere for centuries, and there given a plethora of local names.

These are merely a few examples. We need iconoclastic invasion ecology. We need to question the “assumption of naturalness.” In fact, the modern historical geography of thousands of coastal species of planktonic and benthic organisms remains unknown. Thus, such species must be removed from the category of “native until shown otherwise,” and instead be placed in the rapidly growing category of cryptogenic species. Did the giant kelp, *Macrocystis pyrifera*, for example, now found in both the southern and northern hemispheres, and taken to be a classic textbook example of natural bipolarity, of necessity naturally occur in both hemispheres? Or could *Macrocystis* have been carried on the hulls of Spanish ships—since it can be a fouling organism—from the North Pacific Ocean as early as the 1500s? The early footprints of human activities across the oceans became the shipprints of the world and yet we have largely fallen virtually silent about the potential for such early invasions.

Why be concerned about earlier invasions? Why should we care about invasions of 100 or 200 or 300 years ago? There is the potential value to a greater resolution of global invasion patterns as noted earlier, but beyond that, are not such early invasions “naturalized”? Aren’t they “integrated” into the community? Isn’t the community “in equilibrium” by now? That we should invoke naturalization, integration, and equilibrating processes underscores another arena of ambiguity in our thinking in invasion ecology. The word “naturalized” was introduced in 19th-century botanical literature to mean “reproducing in the wild”—not to mean a remarkably rapid conversion over a few decades or centuries to mirror the integration that native species achieve over tens or hundreds of thousands of years. The answer is that we cannot pronounce invasions of past decades or centuries as being well integrated: there are by and large no data to support such concepts. Simply becoming abundant and widespread is not ecological integration. Simply eating or being eaten is not ecological integration. Integration implies a vast suite of interrelated functions, rather than a functional response along one or a few axes, such as predation, space utilization, or competition. We know little about the rate of these integrative processes in invasion ecology. It may be that in terms of evolutionary processes and community integration, the European periwinkle, *Littorina littorea*, which arrived on the shores of Atlantic North America in the early 19th century, arrived only “yesterday.”

Several other famous myths in invasion science are worth noting. One is that “everything that could have been introduced would have been introduced by now.” This is not simply an image in the mind of
a ship’s captain who is contemplating 100 years of
ballast water movement, nor is it the imagination of
the hopeful commercial entrepreneur. Rather, we
learn that grant proposals to investigate dispersal vec-
tors are turned down even today by a hand-wave of
such statements. That everything has not been intro-
duced by now is demonstrated every day. Were it so,
all the ship fouling organisms of Europe that could
survive and reproduce in American waters would be
here by now.

Another myth is the following: “Invasions are
part of nature. They always happen. Human-mediat-
ed invasions are only speeding up what would hap-
en eventually.” This statement is, of course, also not
ture. Most—or perhaps all—of the invasions now occur-
ing would not only not happen sooner or later, they
would never happen. Species are not “eventually”
exchanged by natural processes between San
Francisco Bay and the Black Sea, species do not
“eventually” find their way in ecological time
between Australia and England, and species do not
“eventually” move between Argentina and Puget
Sound. The fact that over geological time there is a
predictable natural ebb and flow of biota along coast-
lines and within or between ocean basins, as barriers
dissolve or are created, has little to do with the past
several centuries of human-mediated alterations to
the oceans.

Another myth is that phytoplankton have been
and are, with a few exceptions, not part of the mod-
ern invasion story. Since just the reverse may be true,
the existence of this illusion may have had profound
impacts on our ability to understand the scale of
invasions and invasion processes—and indeed may
have caused us to be several to many decades behind
in ballast management, relative to one major reason
why harmful algal (toxic phytoplankton) blooms may
have mushroomed in the past quarter century.

This sense of size-mediated invasion is a huge
bias in our science. We recognize introductions most
often among the charismatic megainvasions—clams,
crabs, seastars, large seaweeds. We recognize some
invasions among smaller organisms—copepods,
amphipods, bryozoans, hydroids, and so forth.
But when we get to very small organisms—the
diatoms, the dinoflagellates, the pfiesterias, the
brown tides (cureococues)—we simply say, with rare
exception, “no invasions here.” The transparency of
recognizing invasions only by size could not be clear-
er: not one professional phytoplankton ecologist,
biogeographer, or systematist is speaking at or attend-
ing this meeting, although we will hear again and
again about phytoplankton and ballast water from
other workers. Ironically, one of the very first inva-
sions to be recognized as being due to ballast water
was the appearance of an Asian diatom in Europe
in the early 1900s. We presume that such invasions have
continued steadily, if largely unreported, around the
world since.

We need, then, to increase the rigor of our overall
thinking about invasions. And this rigor needs to be
applied to every aspect of our science.

We need to pay more attention to the many bias-
es in making “species lists” of marine invasions if we
are to do more sophisticated comparisons. Our lists
tend to be extraordinarily sensitive to the history of
local taxonomic interest or current local available
expertise, generating lists of very different emphases.

We must be more rigorous and focused in our
thinking about whether introduced species have an
“impact” or not. In terms of ecological and evolu-
tional science every invasion has an impact. The de-
finition—the nature and extent—of impact is the ques-
tion, not whether an impact did, did not or will
occur. The extent to which invasions alter the diversi-
ity, abundance, distribution or phenology of previously
existing species can be a measure of impact. Who is
concerned—ecologists, the public, or politicians—
about the type and scale of impact is a different ques-
tion, but perhaps the question more often meant.
Why we are concerned—for example, whether the
invasion changes the ability of humans to use the
oceans as a resource—is yet another question still.
Because impact is a long sliding scale we would do
better to abandon the concepts of the “Top 10
Invaders” or “Worst 100 Invaders.” Rather, under the
assumption that all invasions alter some aspect of the
community mesh in which they find themselves
embedded, we should focus on the types and scales of
impacts that invasions have, rather than implying
that only some small percent of invasions actually
lead to impacts or cause “problems.”

Perhaps there is no more important arena where
we need to refine our thinking than in the field of
prediction. The interface between the public and sci-
cence insists on prediction, whether it is hours after an
oil spill or hours after the discovery of a new intro-
duced species. We are also interested in prediction in
our science in and of itself, whether or not there are
sociopolitical pressures, or questions from the press.
We are thus now engaged in a great search—we seek the Predictive Invasion Grail. We desire more than ever before to be able to predict who will invade, when invasions will occur, and what the impacts of the invasion will be. Thousands of invasions have occurred and yet, like the weather, it appears that we cannot predict the next invasion.

Is it all too stochastic? Can we evolve more rigorous models that better resolve the invasions—sweepstakes—the roulette nature of invasions? In predicting who will invade is it ever possible to point to some species that will forever be unsuccessful invaders? Or is the match between an invading species’ biology and the new prospective environment, in fact, a shapeshifter model of invasion ecology, where at times it appears to be a matter of trying to fit a round invasion into a square environment—but at other times the round invasion slips smoothly in?

Where do we look to unlock some of these questions? I suggest that we look more closely at those invasive species which, despite numerous apparent opportunities for dispersal, inoculation, and establishment, and which for centuries have failed to become introduced, suddenly become successful colonists. Rather than focusing on those species that appear to have permanently failed to invade, we should look more carefully at species that have failed to invade for centuries and then do so. These are the delayed invaders. Is it in these species that we can find answers to some of the long-term mysteries of those processes that regulate invasions?

An example is the five-centimeter-long European seasquirt, *Ascidia aspera*, a translucent, recumbent filter feeder in shallow fouling communities. This ascidian, common on hard bottoms throughout western and northern Europe was, we may speculate, on the bottoms of hundreds or thousands of vessels coming to America for 500 or more years. It first appeared in fouling communities about 1885 between Cape Cod (Massachusetts) and Long Island Sound, in southern New England, long after such communities would appeared to have been “filled” by previous ascidian invaders such as *Styela clava*, *Molgula manhattensis*, *Ciona intestinalis*, *Botryllus sp.* and *Botryllus schlosseri*, which combined formed 100 percent cover in fouling communities prior to the arrival of *Ascidia*.

Up until 1985, we might have chosen *Ascidia* as an example of a permanently unsuccessful invader, and sought compelling reasons as to why it had failed to become established in North America after half-a-millennium of presumed transport. Why then did it invade in the 1980s and not the 1880s or 1780s or 1680s? Invasion lag-time analysis (ILTA) remains virtually untouched as a field of investigation, and yet may be a singularly important key to unlocking invasion processes. This then is the *Paradox of Ascidia*, a puzzle that must be solved. If we were to pay more attention to these creatures—the ascidiellas of the world—invasion science may move forward all that much faster.

We know—or we think that we know—some of the roads that we must explore when considering ILTA: were there changes in the donor region or changes in the recipient region? Did invasion windows open or were there unusual inoculation episodes? Did the dispersal vector change in some way? These are complicated phenomena, but complicated is not the same as unknowable or unpredictable. The answers to each question have striking implications relative to the ecology, biology, and evolutionary history of invaders; each question also opens the door to many more questions. We have to pursue interactive pathways and integrative invasion ecology much more robustly. Why do we not find, in invasion biology, more examples of subtle webs such as the one that links spirochete bacteria, acorn production, white-footed mice, black-legged ticks, white-tailed deer and climatic models all in one intricate mesh to predict the potential for Lyme disease? Are we not looking? The European marine fauna continues to dribble and leak into and invade North America over a long blue line that fades vaguely into the past 500 years and yet we are surprised at every new invasion. Is this because we rarely seek out the vast arrays of physical and chemical and oceanographic and biological data now available for coastal waters in order to detect a web of environmental change—and then combine such webs with detailed vector data and our knowledge of species’ biology and ecology—that would anticipate new invasion opportunities?

For management purposes, predictive marine invasion science is now of only limited value. It may of course improve considerably. As an example, we cannot, today, look at what is inside the ballast water of a ship and imply that the contents are of little or

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5. ILTA is distinct from lag times in population "explosion" (Crooks and Stue 1999).
called our attention to the Asian shore crab (*Hemigrapsus sanguineus*) in Long Island Sound, it took an amateur naturalist to alert the scientific world to the invasion of an abundant Caribbean barnacle (*Chthamalus portuleus*) to the Pacific Islands, and another to discover the Japanese shore crab (*Pachygrapsus marmoratus*) in Hawaii, and the public knew about zebra mussels (*Dreissena polymorpha*) in the Great Lakes at least a year before scientists found them. The answer to the question of “why are there not more invasions?” is that there are without doubt many more invasions than we have been recording. The demise in the knowledge of systematic biology and natural history is a critical hole to patch if we are to gain a more accurate picture of the scale and rate of change in coastal ecosystems.

In September 1962, I was introduced to the world of exotic marine organisms by unceremoniously stepping on what I was to learn, a few days later, was a small colony of exotic tubeworms in a lagoon off San Francisco Bay. It was beyond imagination at that time that we would close this century with a higher level of national and international awareness of bioinvasions in the seas than ever before. This first conference on marine bioinvasions is very appropriately set on the edge of the 21st century. We are witnessing a vastly changing paradigm.

**Annotated References on Marine Bioinvasions: A Highly Selective Bibliography**

The following papers, and the papers they cite in turn, provide an entrée to the literature on marine introduced species. About 1,600 additional references are found in Carlton (1979). I use the hedgedithian method (Ricketts et al. 1968) of annotation here; thus, annotations are often telegraphic, not full sentences, leave out verbs and the occasional noun, and are often only understood as juxtapositions to the title of the paper itself.


See Hicks and Tunnell 1993.

6 The southern hemisphere serpulid polychaete worm
*Ficopomatus enigmaticus*, then known as *Nereocidaris enigmatic*, on the small beach on Adams Point, in Lake Merritt, in Oakland, California.


A classic paper outlining the principles of the subject.

Alpine, A.E. and J.E. Cloern. 1992. Trophic interactions and direct physical effects control phytoplankton biomass and production in an estuary. Limnology and Oceanography 37:946-955. The Asian clam, Polymesoda amurensis, plays an important role, along with other introduced bivalves, in controlling water column productivity in San Francisco Bay.


A useful discussion of the introduction into Japan of the polycheates Hyrodriodes elegans and Fitocomatus enigmaticus, the bryozoans Zoobotryon pellucidum and Bugula california, the bivalves Limnoperna fortunei, Peris vestidi, Mytilopsis sallei, and Mytilus galloprovincialis, the slipper limpet snail Crepidula onyx, the barnacles Balanus improvisus and B. eburneus, the crabs Carcinus aestuarii (as C. mcdonensis) and Pyronota tuberculata, and the ascidians (sea squirts) Molgula manhattensis and Cliona intestinalis.


Two species of the American worm, Marenzelleria, have been introduced to northern Europe; see Essink and Schröder (1997).


A rare contribution to the role of semi-submersible self-propelled exploratory platforms in the transoceanic dispersal of marine life.


The players are the native snails, Assiminea californica and Littorina subrotundata, and the introduced Atlantic snail, Osetella myosotis: "the successful establishment of this Atlantic snail in the Pacific Northwest did not arise at the expense of native species."


The insertion into marine communities in the Gulf of Maine (that body of water between Cape Cod in Massachusetts and Canada) of three recent invaders is considered: the sea squirts (ascidians), Styela clava and Botryllus diogenis, and the bryozoan, Membranipora membranacea.


An experimental demonstration of the impact of the introduced European snail, Littorina littorea, on low energy habitats of the southern New England coast: the outward growth of the Spartina marsh is compromised by Littorina eating the shoots and rhizomes of the marsh grass, while at the same time the grazing activities of the snail foreword of the marsh prevented the accumulation of soft sediments creating more exposed hard substrate onto which the marsh cannot grow.


More experiments on the ecological effects of the introduced European snail, Littorina littorea.


Professor Boalch has been one of the very few phytoplankton workers to recognize the introduction of diatoms and dinoflagellates by ballast water.


A collection of 13 papers in English and French, originating from a symposium held in Monaco in early March 1993; nine papers provide histories of introductions. The color cover appears to show the spread of the Japanese brown seaweed, Sargassum muticum, across all of the European waters into the Mediterranean in compelling yellow, green, purple, and red colors, in 1966 (first report in France), 1977 (north and south of the English channel), 1988 (much of the
rest of western and northern Europe), and 1992 (Portugal, southern Spain, and into the Mediterranean)—that is, every ten years, except for the last date, when the picture was produced for the symposium. No explanation of the cover appears in the book; in fact, it is solely a computer-based projection of the spread of Sargassum, and has no bearing upon actual records! (Inger Wallentinus, pers. comm.).


The introduced periwinkle *Littorina littorea* in New England and its utilization by the native hermit crab *Pagurus longicarpus* (see also Blackstone and Joslyn 1984.


This seaweed was intentionally planted on the Atlantic coast of France for mariculture purposes under the initial proclamation that it could not reproduce or spread. It did and it did.


The introduced species are the European periwinkle snail *Littorina littorea* and the European shore crab *Carcinus maenas*.


Of native *Ilyanassa obsoleta* by introduced *Littorina littorea*. See also the work of Whitlatch and Obrebski (1980) and Race (1982).


There is little doubt that this seastar invasion finds its roots in Japan, the common name reflects political necessities. Millions upon millions of this omnivorous seastar have become established in the Derwent estuary of southern Tasmania, Australia. It has since spread to mainland Australia.


The native mussel, *Perna perna*, in South Africa is commonly infected by digenetic trematodes while the introduced Mediterranean mussel, *Mytilus galloprovincialis*, lacks trematodes; this may lend *Mytilus* a competitive advantage.


A monographic review of ballast water prior to most of the world's studies on ballast water.


The title of this paper plays off the famous monumental mid-20th century tome, "Man's Role in Changing the Face of the Earth", although a double entendre may have been intended, as few women are responsible for the current state of the oceans.


Carlton, J.T. 1994. Biological invasions and biodiversity in the sea: the ecological and human impacts of non-


A table herein presents a series of six hypotheses as to why invasions occur when they do.


From a September 1995 symposium in Aalborg, Denmark.


The giant kelp (brown seaweed) Macrocystis pyrifera is used as an example of a possible southern hemisphere invasion of centuries ago, what might have occurred on the bottoms of 18th-century ships is further explored, and estimates are made of the potential number of invasions that could have occurred between 1500 and 1800. The entire book, less than 20 mm thick, costs US$25.50, making it largely unavailable to most workers.

Carlton, James T. 1999. Molluscan invasions in marine and estuarine communities. Malacologia 41: 439-454. Includes a summary of the names in the southern hemisphere by which the northern hemisphere fouling mussels, Mytilus edulis and Mytilus galloprovincialis, go, as well as an argument that more than a few shipworms may owe their modern distribution to the history of wooden shipping.


The results of sampling the ballast water in 159 ships arriving in Coos Bay, Oregon, from Japan: 367 species of animals, plants, and protists are reported, thus having implications for the global history, biogeography, systematics, and ecology of many phyla. In Table 1 of this paper, the number of species shown for Urochordata should be 6, not 10 (howev...
Government Accession Number AD-A294809. xxviii + 213 pp. and Appendices A-I (122 pp.).
The cover bears the date April 1995, but the report contains no new information after April 1993, when it was first submitted to the United States Coast Guard.


See the comments under Bouchain et al. 1999.


A new species of amphipod, Corophium alienense, is described from San Francisco Bay, on the basis of morphological and ecological characteristics it is regarded as native to southeast Asia, where it remains unknown.

A Japanese isopod redescribed in the late 19th century from San Francisco Bay as Simidota laevisimula.


The neoelevation of Eriocheir in England, perhaps related to drought patterns.

A monographic account of the introduced species of the fresh, brackish, and marine waters of the San Francisco Bay and Delta in central California. Available at the following websites: http://eslib.cs.berkeley.edu/ERAB:701 and http://www.fresq.gov/naa/ntvs/adc.htm (missing Figures 1 and 3, and Tables 1 and 9).

As with the European shore crab, Carcinus maenas, a plethora of dispersal mechanisms are available to Eriocheir.

An average of one new invasion occurred in San Francisco Bay, California, every 14 weeks between 1961 and 1995; a total of 234 non-native species are reported. There are more there now.

Carcinus can move around the world in the 1990s by an embarrassing variety of human mediated mechanisms, hampering the ability to decrease the probability of such invasions.


Three of the seven "most productive" species are introduced (the hyroid Cordylophora lacustris and the bryozoan Biminia franciscana) or cryptogenic (the seasquirt Molgula manhattensis).


Includes discussion of several marine species: this is not ILTA per se (see the main body of the present paper), but rather lag times of species blooms after they have become established.


Examines several hypotheses (biological, ecological, and temporal) to address the question. The amphipod *Corophium curvispinum* is a fresh- to brackish-water species to be expected in North America at any time; the dam Corbiana is a well-known bivalve invader of both Europe and North America.


This and the previous paper present quantitative studies on the Asian seaweed *Sargassum* in British Columbia. “One probable effect of the introduction of *Sargassum* has been a reduction in cover of *Rhododema*.”


An elegant analysis.


This famous book includes a chapter, “Changes in the Sea.” See Carlson (1989) for background comments by Elton.


The first monographic review of marine bioinvasions in the U.K.


A collection of ten papers on the invasion of northern Europe by two species of this North American worm, one in the North Sea and one in the Baltic (see Basterop et al., 1998).


See Krütz and Culver (1999). This is *Terebratulina heterovacuata*, a name easier to pronounce than it looks, native to South Africa but first discovered in California.


of Israel. Journal of Natural History 32:1549-1551.

Although the southern crab Charybdis longicollis came through the Suez Canal into the eastern Mediterranean in the 1950s, its parasite, the Gulf of Suez parasitic castrating sacculinid barnacle Heterosaccus dolfussi did not follow until the 1990s: "it is possible that (the crab) populations ... will suffer drastic perturbations" as a result. "In this case, a game of Jeopardy is played out between host and parasite."


Forty years after being first detected on Long Island, this Asian kelp is reported from the Gulf of St. Lawrence.


With the invasion of the Mediterranean mussel, Mytilus galloprovincialis, the native mussel, Mytilus trossulus, disappeared from southern California, but as the two are externally nearly identical, the passage of the latter went without notice.


The Asian shore crab, Hemigrapsus sanguineus, invades New England shores.


A ballast-water-mediated introduction of this intertidal mudflat snail which preys on small bivalves


Environmental Conservation 4:303-308.

An accounting of the famous attempts to remove this invading brown seaweed from English shores by hand picking. Sargassum remains a common British seaweed.


The authors propose that a San Francisco Bay population of this jellyfish is introduced from Japan by ballast water.


Including the Mediterranean mussel, Mytilus galloprovincialis, and the European shore crab, Carcinus maenas. Mytilus has displaced the native mussel, Austrovenus stelleri, in many areas.


Spatial heterogeneity yes, genetic variation, no; the introduced castrator here in Chesapeake Bay is the Gulf of Mexico sacculinid barnacle Loxothylacus panopaei.


This large (15 cm tall) brassy molluscivorous Asian whelk arrives on North American shores, possibly from the Black Sea or the Mediterranean, whose populations arose from intentional releases many years ago.


Figure 3 of this summary paper shows ten of the most common introduced species in Waitemata Harbour. All but two bivalves (the file shell Limaria orientalis and the oyster Crassostrea gigas) are also found in San Francisco Bay.


Another possible ballast water introduction into southern Australia: can such clams also survive long-distance transport in ships' sea chests?


See Agard et al. (1992).


Introduced copepods should be watched for everywhere: this Japanese species now occurs in Chilean fjords.


Carcinus maenas was discovered in British Columbia in June 1999.


See Meinesz's book.


The Asian clam, Potamocorbula amurensis (see Carlton et al. 1990 and Nichols et al. 1990) consumes the copepod, Eurytemora affinis.


The mantis shrimp (stomatopod) Gonodactylus aloha, although described as a new species from Hawaii, and although treated in this paper as cryptogenic, was introduced from the Indo-Pacific after World War II to the Hawaiian Islands. The native mantis shrimp Pseudosquilla ciliata was displaced wherever Gonodactylus was abundant.


A Chilean species introduced many years ago to North America.


Sea spiders are underreported as ship-mediated invasions in most community invasion studies.


See Freiberg and Rose, 1999. An elegant and masterful study of a South African worm making its way on the other side and other half of the world.

A wave of exotic seashells has inundated southern California at the close of the 20th century.


Intentional plantings in the 1960s of this edible crab from the Sea of Japan to the Arctic Ocean (Barents Sea) led to the successful establishment of this crab, a rare invader of the deep sea: "large males have been caught in fair numbers down to 330 meters."


"In British Columbia," says the text, this clam was "introduced from Japan in the 1930s, and then spread rapidly... In the same way, this species was introduced twenty years ago to (France) for aquaculture purposes." This is not exactly so: this clam was introduced by accident to British Columbia whereas this clam was introduced intentionally into France in the 1970s, with apparently no prior studies as to what its ecological impact might be. The authors find that the exotic clam had a more extended reproductive season and a greater number of spawning events than the native congener, R. decussatus, reminiscent of the advantages that a number of introduced species have over natives (and which eventually causes the native to become somewhat less abundant).


The first detailed published ecological information on this crab. For a copy of the whole proceedings, which is not in most libraries, write to: Connecticut Sea Grant Extension Program, University of Connecticut, 1084 Shennecossett Road, Groton, Connecticut 06340 USA.


The role of the introduced European periwinkle, Littorina littorea, in regulating the intertidal flora of New England.


A symposium (and book) published 20 years before the 1999 popularity of this subject.


First discovered in New Jersey in 1986, by the late 1990s the crab occurred from north of Cape Cod to North Carolina. It may have been introduced by ballast water, although other ship-related mechanisms (such as sea chest or external hull fouling, with small crabs in empty barnacles in the fouling matrix, for example) are possible.


The English translation (by Daniel Simberloff) of the remarkable, emotional, political story of how the aquarium seaweed Caulerpa taxifolia was released into the Mediterranean at the foot of the Monte Aquarium and the sordid events of denial and obfuscation that followed. The title, "Killer Algae", is a partial translation of that of the original French book, "Le roman noir de l'algue tueuse" (The Black Novel of the Killer Algae), and refers to the erroneous name—applied by the French press—by which the French public knows of this invasion: it means nothing outside of France, and the alga doesn't kill anything.

Although the advertising website produced by the publisher in advance of the book proclaims several times the alga doesn't kill, the publisher persisted with the title, evidently for sales purposes, doing little good to improve an
understanding of invasions by the public or political world.


*The Monniots have produced numerous papers demonstrating the role of ships in moving seasquirts as fouling organisms around the world. Many of these species have now become the aspect dominant organisms in many shallow-water communities.*


*Includes brackish water invasions, particularly those in California's Sacramento-San Joaquin estuary.*


*The committee nature of this book inevitably bubbles up occasionally.*


*The distributional ecology and physiology of the introduced barnacles, *Balanus improvisus* and *Balanus amphitrite*, in San Francisco Bay, California.*


*Of more than 20 introductions, the Atlantic clam, *Gemma gemma*, the Atlantic amphipod, *Amphelissa abdita*, and the Atlantic worm, *Streblospos benedicti*, are the most abundant.*


*Yes.*


*The Japanese oyster *Crassostrea gigas* was introduced by the Portuguese from Japan to southern Europe probably in the 16th century; it was described as a species native to Europe in the 18th century, where even now it continues to most often be referred to by the synonymous name *Crassostrea angulata*, under the guise of being a native species! Olofshol put a final nail into the junior synonymy of angulata, a matter nicely discussed by Edwards in 1976.*


*Introduced species "have significantly altered ecosystems of the southeastern Baltic coastal lagoons": one of these is *Vislula Lagoon*, whose modern-day dominance by invasions bears comparison to similar environments elsewhere around the world, such as the *Letang de Thau* (Thau Lagoon) in Sete, on the south coast of France; the *Ala Wai Canal* in Hawaii; and Lake Merritt in Oakland, California, on the east coast of San Francisco Bay.*


*Yes there are.*


*Extends the arrival of the North American clam, *Mya arenaria*, in Europe back to the 1200s, and thus within the realm of Viking transport.*

The impacts of the European periwinkle Littorina littorea in New England.


The removal of the introduced European snail Littorina littorea in lower intertidal areas in sheltered bays enhanced the growth, weight gain, and survival of the native limpet Tectura testudinaria.


Identifies 3 species of tintinnids in ballast water arriving in Coo Bay, from Japan; as Carlton and Geller (1993) had already reported 2 tintinnid species, this adds 31 to the total number of ballast species reported in Carlton and Geller.


This is the classic summary up to the mid 1970s; see Spanier and Gall (1991).


The Japanese eelgrass in Oregon: experimental manipulations demonstrate that the plant has changed the physical habitat (mean sediment grain size declined with *Z.* japonica patches as compared to unvegetated areas) and the richness and density of resident invertebrate fauna (higher in than outside of the patch).


Allozyme studies on what it takes in terms of minimum population size inoculation to make for a successful planting of non-native fish into the Hawaiian Islands. In the case, only 3 of 11 fish from French Polynesia purposefully released between 1955 and 1961 in Hawaii became established; of the three successful species, even though "only a few individuals bequeathed their characteristics to subsequent generations, no significant change in genetic diversity was observed."


The players are the introduced Atlantic mudsnail, *Ilyanassa obsoleta*, and the native California mudsnail, *Cerithidea californica*. The former eats the eggs of the latter and otherwise eliminates *Cerithidea* from the lower shore. See also the work of Whittach and Ohreski (1980) and Brenchley and Carlton (1983).


Although not mentioned by the author, virtually all of the prey of these native birds are species introduced to San Francisco Bay.


A symposium of 16 papers:

- Introduced marine species of the North Sea coasts
- Exotic flagellates of coastal North Sea waters
- Red algal exotics on North Sea coasts
- Introduced brown algae in the North East Atlantic, with particular respect to Undaria pinnatifida (Harvey) Stranggar
- From introduced species to invader: what determines variation in success of Codium fragile ssp. tomentosoides (Chlorophyta) in the North Atlantic Ocean?
- On the population development of the introduced razor clam Ensis americanus near the island of Sylt (North Sea)
- Introductions and developments of oysters in the North Sea area: a review
- *Mya arenaria* - an ancient invader of the North Sea coast (see Strasser, 1998)
- Rapid colonization of new habitats in the Wadden Sea by the osmoregurant Littorina saxatilis (Olens)
- The neozoon Eliminius modestus Darwin (Crustacea, Cirripedia): Possible explanations for its successful invasion in European water
- The recent arrival of the oceanic isopod Idotea metallica Bosc off Helgoland (German Eights, North Sea): an indication of a warming trend in the North Sea?
- The Asian decapod Hemigrapsus penicillatus (de Haan, 1835) (Grapsidae, Decapoda) introduced in European waters: status quo and future perspective
- Dispersal and development of Marenzelleria spp. (Polychaeta, Spionidae) populations in NW Europe and the Netherlands
- Ecophysiological capability of Marenzelleria populations inhabiting North Sea estuaries: an overview
- Styela clava Herdman (Urochordata, Ascidiae), a successful immigrant to North West Europe: ecology, propagation and chronology of spread
- Exotic invaders of the meso-algal zone of...
estuaries in the Netherlands: why are there so many?

The introduced Japanese mussel, Musculista, when experimentally added to Zostera beds, causes eelgrass rhizomes to grow 40% less than controls.

The first thorough global review of introduced marine algae.

Species from the Black and Caspian Seas are often euryhaline and have formed a conspicuous global element in the invasions picture.


Uses Chesapeake Bay as a model system, with 196 introduced and cryptogenic taxa used for analysis: while 39 (20%) of these species were believed to have had "some significant impact", the authors could find quantitative data on impacts for only 12 of the 39, representing only 6% of the 196 species surveyed!


An early paper on the invasion of this comb jellyfish (cnemophore) from the Americas to the Black Sea.


A mid-century look at a fauna dominated by introduced species.


The Caribbean barnacle, Chthamalus proteus Dando and Southward, 1980, invades the Hawaiian archipelago, but exactly when it did so in the previous 20 years is surprisingly unclear.

…through the Suez Canal; see Por 1978.

"In experimental communities of sessile marine invertebrates, increased species richness significantly decreased invasion success, apparently because species-rich communities more completely and efficiently used available space, the limiting resource in this system." Species contributing to this richness and said to be native in this Long Island Sound, Connecticut, fouling community were the blue mussel Mytilus edulis, the ascidian sea squirts Molgula manhattensis, Ciona intestinalis and Botryllus schlosseri, and the bryozoan Cryptopora pullulans: with the exception of the mussel, all of these species, however, are either cryptogenic or introduced from Europe.


A claim that was once widespread through the cold waters of the Northern Hemisphere until the Pleistocene glaciers wiped it out from the Eastern Pacific and the Eastern Atlantic, only to be introduced (not reintroduced!) to the Eastern Pacific and the Eastern Atlantic by humans so that its modern distribution parallels its ancient distribution. Readers will note that the author's reference to the “Pacific west coast” means Asia.


A major controlling species focused upon in this foundation paper is the stalked seaweet (ascidian), Styela plicata, which forms one of the stable points in the fouling community at Beaufort, North Carolina, and directly and indirectly impacts many other species in the community. Unbeknownst to the author, this is an Asian species introduced in the 18th or 19th centuries to Atlantic North America.


See Sutherland 1974. Introduced or cryptogenic species (not so noted by the author) included among the fouling community’s “foundation species” include the ascidians (ascidians) Styela plicata, Molgula manhattensis, and Botryllus schlosseri, the barnacle Balanus amphitrite and Balanus reticulatus (identified as Balanus tinimbabulum), and the bryozoan Anguinaella palmaria.


An interesting case wherein the “endemic” brackish water Zintenzer seeding (once listed in the endangered species Red Book) is found to be the introduced North American species *Doridella obscura*.


A thorough demonstration of the control that the European periwinkle, *Littorina littorea*, exerts on upper and mid-intertidal algal patches.


An experimental study in this winter-recruiting species in Argentina. The authors argue that a combination of reproductive phenology, the absence of predators, the neutral or positive interaction with algae, and “spatial and temporal partitioning of the substrate all on this barnacle to successfully outcompete intertidal mussels and other barnacles species of both sheltered and exposed” sites. Remarkable too is the very presence of this barnacle in eastern South America: *Balanus glandula* finds its original home in the Eastern Pacific (from Alaska to Mexico), and is one of the very few native western North American species to ever leave home.


A few French ecologists are steadily documenting the many Asian species that came in with massive inoculations of Japanese oysters commencing in the 1970s.


A large red seaweed established in Narragansett Bay, Rhode Island, south of Cape Cod; first record July 1996.


Includes a detailed review of the fouling kampfazoa. *Barentsia benedenti*, widely spread by ships and perhaps oysters.


In San Francisco Bay; see Carlton et al. 1990 and Nichols et al. 1990.

The interactions between the native California mudsnail *Cerithidea californica* and the introduced Japanese mudsnail *Batillaria attenuamentia*; small *Batillaria* are absent in the presence of *Cerithidea*, a species more specialized for feeding on small particulate material. See also the work of Race (1982) and Breinley and Carlton (1983).


One of the first studies on the biology of ballast water.


*A multicyrate record of the appearance of this North American horseshoe crab in European ports.*


A sine qua non for those interested in the role of ships in dispersing marine life around the world.


*On Cape Cod in New England, USA; exactly how the introduced snail inhibits the growth of the native snail is not clear.*


A remarkable and unusual story: this coral remains known only from the fossil record in South America, with living populations known only from the Mediterranean Sea, where it is introduced. Professor Zibrowius reports (pers. comm.) that he should not have used the term hermatypic: the coral in question has zooxanthellae but is not a reef-builder; see Zibrowius and Ramos (1983).


The most thorough summary to date of Mediterranean invasions. Not 1991 as often cited.


The Japanese snail, *Rapana venosa* (here called *Rapana thomaisiana*), the North American clam, *Mya arenaria*, and the Indo-Pacific clam, *Scapharca inaequilabiata*, were detected in the Black Sea in 1947, 1966, and 1968 respectively: "The resulting changes in the structure of the bottom biocenoses after these introductions are in many cases comparable with or exceed the consequences of other episodic environmental events and other kinds of anthropogenic activity."
Key Threats from Marine Bioinvasions: A Review of Current and Future Issues

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Abstract: Australia has been actively researching and developing management strategies for invasive marine species since the mid-1980s, following the discovery that several species of toxic dinoflagellates were likely of foreign origin. While the problem of introduced marine pests is far from solved, an evaluation of the results of efforts to date suggest four key points. First, exotic species have been, and continue to be, introduced by a range of vectors; priorities for management action need to be based on a critical evaluation of the real risks posed by each vector, and encompass an understanding that even major effort directed at a few vectors will not prevent new incursions of major pest species. Second, eradication of new incursions is achievable, but is uncommon and limited to those situations where the pest was either detected quickly or otherwise still had a limited distribution. For most species, practical options for rapid eradication still need to be developed. Third, long-term options for pest management have to take into account social and cultural issues that make some options unfeasible. And fourth, groups likely to pose major threats in the future include pathogens, marine macroalgae, and genetically enhanced production lines developed for use in mariculture. The development of options to deal with these issues will rely heavily on an integration of techniques for management strategy evaluation, fundamental marine ecology, and the emerging science of marine bioinvasions.

Key words: Australia, ballast water, eradication, hull fouling, introduced marine pest, pathogen, pest management

Introduction

For the last decade, Australia has had a national program explicitly to deal with ballast water introductions and their management. Australian government agencies (and particularly the Australian Quarantine and Inspection Service—AQIS) have long recognized the threat posed by exotic marine organisms introduced by shipping, and have led the agenda at the International Maritime Organization to do something about the problem (Paterson 1994). Domestically, Australia has had a continuous program of research and management into ballast water and other potential vectors since 1989 and undertook world-first studies on ballast water exchange and heat treatment as partial solutions to the ballast water problem (Manning et al. 1996). The recently (1999) released Australian government Oceans Policy emphasizes the country’s continued commitment to managing ballast water as a vector, including support for a nationally integrated management regime, the development of practical management tools, and implementation of a national process for identifying and responding rapidly to new pest incursions and outbreaks. This process is an extension of Australia’s existing programs to deal with exotic terrestrial pests such as rabbits, cats, and a plethora of weeds.

Some aspects of the Australian situation are unusual to it, such as the strong social commitment to protecting its unique biota, but the vectors for marine invaders (Carlton 1996) and many of the species themselves are shared problems worldwide (e.g., Cohen and Carlton 1997; Clark et al. 1998; Trowbridge 1998). In this paper, I review some of the conclusions that we have gleaned from dealing with these vectors and pests over the last decade, presented as an assessment of the critical threats we currently and are likely to face in the near future. The issues covered and ideas presented are idiosyncratic, but also reflect to an extent emerging priorities in Australia.
Table 1. Introduced marine species in Australian waters, divided by state and likely mode of introduction, as compiled through January 1998. The table includes some species of uncertain taxonomic status and some cryptogenic species; species are listed independently if they occur in more than one state; and most species are allocated more than one transport mechanism as they could have been transported in each. Key: WA – Western Australia, SA – South Australia, Vic – Victoria, Tas – Tasmania, NSW – New South Wales, Qld – Queensland, NT – Northern Territory.

<table>
<thead>
<tr>
<th>State</th>
<th>Number of Species</th>
<th>Hull Fouling and boring</th>
<th>Mariculture</th>
<th>Dry Ballast</th>
<th>Ballast Water</th>
<th>Intentional</th>
</tr>
</thead>
<tbody>
<tr>
<td>WA</td>
<td>53</td>
<td>36</td>
<td>23</td>
<td>12</td>
<td>18</td>
<td>3</td>
</tr>
<tr>
<td>SA</td>
<td>48</td>
<td>30</td>
<td>24</td>
<td>7</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>Vic</td>
<td>104</td>
<td>61</td>
<td>52</td>
<td>13</td>
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<td>NSW</td>
<td>56</td>
<td>36</td>
<td>23</td>
<td>8</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
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<td>0</td>
<td>2</td>
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</tr>
</tbody>
</table>

**Invasion mechanisms**

Cohen and Carlton (1997) listed ten broad categories of mechanisms theoretically available for transoceanic transport, many of which have numerous subcategories (e.g., Cohen and Carlton 1995; Eno et al. 1997). The significance of each is debatable, doubtless varies among sites, and has changed over time. For many species, transport could have occurred by any one of several vectors. International shipping simultaneously offers transport opportunities via hull fouling, sea chests, and ballast, and species prone to transport as hull foulers are often also amenable to transport in mariculture shipments. Determining with certainty the vector for a particular unintentional introduction is impossible, and in all cases has to be decided on the basis of probability (although in some instances, the probability approaches 1, e.g., the introduction of *Mnemiopsis leidyi* into the Black Sea in ballast water). Data on the number of larvae in ballast tanks or the number of species attached to hulls or in a mariculture shipment only tell us that a particular transport mechanism is operating, but say little about consequent rates of successful invasion and impacts.

One measure of the relative importance of the different transport vectors is the proportion of invasive species attributed to each by different studies. Cohen and Carlton (1995) estimated that four major vectors were historically of roughly equal importance in San Francisco Bay: ship fouling (26% of introduced species), ballast water (24%), accidental introductions due to mariculture (22%), and deliberate introductions (20%). Their study included a large number of freshwater species, however, which inflated the last category. Eno et al. (1997) suggested the largest single identifiable transport mechanism for introduced marine species in Britain (31% of the species) was accidental introduction associated with mariculture. Fouling accounted for about 26% and ballast water for another 18%, with an additional 12% of species equally likely to have been introduced by either of these shipping-related vectors. Deliberate introductions accounted for a further 8% of the introduced species. Cranfield et al. (1998) stated that "most (69%) of the adventive species...arrived in New Zealand as part of hull fouling communities," attributing only 3% to ballast water and 21% to either fouling or ballast water. It is not clear from the report whether vectors other than hull fouling, such as mariculture shipments, were considered in detail. Our evaluation of the introduced species in Australian waters (Table 1) suggests that the dominant modes of introduction to Australia historically are hull fouling and accidental releases associated with mariculture, followed by ballast water, dry ballast, and intentional releases. Ballast water accounts for 15-20% of the invasive marine species we have thus far found in Australia.

From a management perspective, a more useful analysis is the relative importance of transport vectors for pest species, here defined as those species likely to cause significant social, health, economic, or environmental damage. The Australian Joint Ministerial Taskforce on Managing Marine Pest Incursions recently (1999) reviewed the known invasive species in Australian waters and overseas against a set of criteria (Table 2), to produce a list of 12 species against which incursion response plans would be developed. This list excluded freshwater species, and also excluded pest species already widely distributed in Australian waters. The latter include the New Zealand screw shell (*Maoricardinus rostrus*), the European shore crab (*Carcinus maenas*), the Mediterranean fan worm (*Sabellaria spallanzani*), the Pacific oyster (*Crassostrea gigas*) and three species of toxic dinoflagellates (genera *Gymnodinium* and *Alexandrium*).

Of the established pest taxa, only the toxic dinoflagellates almost certainly arrived in ballast tanks (Hallegraeff and Bolch 1991). Of the remaining species, the Pacific oyster was deliberately intro-
Table 2a. Interim selection criteria developed by the National Taskforce on Managing Marine Pest Incursions

Criteria

Necessary and sufficient information to justify including a species on the trigger list (all four need to be satisfied)

1. Demonstrable invasive history.
2. One or more relevant transport vectors are still operating.
3. Demonstrable impact in native or invaded ranges on:
   - economy
   - environment
   - human health
   - amenity
4. Inferred as likely to have major impacts in Australia based on the overseas data and characteristics of Australian environments and marine communities.

Necessary and sufficient information to justify removing species from the trigger list (any one needs to be satisfied)

1. Scientific, empirical data show that impacts overseas are less than previously thought.
2. Scientific, empirical data show that impacts in Australia are likely to be less than previously thought.
3. Already is or becomes widely distributed in Australia.

Interim List

<table>
<thead>
<tr>
<th>Species</th>
<th>Common Name</th>
<th>Native Distribution</th>
<th>Introduced Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caulerpa taxifolia</td>
<td>Marine Algae</td>
<td>Native strains</td>
<td>Invasive &quot;hybrid&quot; in Mediterranean Sea</td>
</tr>
<tr>
<td>Aquarium strain</td>
<td></td>
<td>circumtropical</td>
<td></td>
</tr>
<tr>
<td>Eriochirus sinensis</td>
<td>Chinese Mitten Crab</td>
<td>North West</td>
<td>Europe; West Coast North America</td>
</tr>
<tr>
<td>Miniomus leioides</td>
<td>Comb Jelly</td>
<td>Western Atlantic</td>
<td>Black Sea; Mediterranean</td>
</tr>
<tr>
<td>Myphius sika</td>
<td>Black Striped Mussel</td>
<td>Caribbean</td>
<td>Hong Kong; India; Singapore; [Darwin, NT]</td>
</tr>
<tr>
<td>Pfiesteria piscidia</td>
<td>Dinoflagellate</td>
<td>North West Atlantic</td>
<td>?? (proposed as introduced to N America)</td>
</tr>
<tr>
<td>Potamocorpus amurenensis</td>
<td>Asian clam</td>
<td>North West Pacific</td>
<td>North East Pacific (SF Bay)</td>
</tr>
<tr>
<td>Rapana thomasi</td>
<td>Gastropod</td>
<td>North West Pacific</td>
<td>Black Sea, East Coast North America</td>
</tr>
<tr>
<td>Sargassum muticum</td>
<td>Asian Seaweed</td>
<td>North West Pacific</td>
<td>North West Pacific; England</td>
</tr>
</tbody>
</table>

In Australia, but not widespread

Asterias amurenensis | Northern Pacific Seastar | North West Pacific | Tasmania, Victoria |
Cedreneria fragmenta | Broccoli weed, Dead man's fingers | North East Pacific | Tasmania, Victoria |
Musculista senhousia | Asian Date or Bag mussel | North West Pacific, South Asian Seas | Tasmania, Victoria, Western Australia |
Undaria pinnatifida  | Undaria Seaweed, wrack | North West Pacific | Tasmania, Victoria |

Produced, the European crab likely arrived in dry ballast, the screw shell was accidentally introduced in oyster shipments from New Zealand, and the rest were most likely fouling organisms in the broad sense of the term (including, for example, transport in sea chests). Of the "dangerous, but not yet here" species, two (M. leioides and Pfiesteria piscidia) are clearly ballast water species, two (Rapana thomasi and Potamocorpus amurenensis) are most likely to be introduced in ballast water, one (Sargassum muticum) is a fouling species, Eriochirus sinensis would likely be introduced intentionally or in ballast water (Cohen and Carlton 1997), and the hybrid form of Caulerpa taxifolia will most likely be introduced in the aquarium trade, though it is also easily transported fouled in fishing gear, anchors, and the like (Meinesz et al. 1998).

This analysis suggests two points. First, no single vector or small subset of vectors accounts for all pest species; targeting any single vector will, therefore, not stop the introduction of species with significant pest potential. But second, by far the single most active transport mechanism historically for pest species is fouling, which accounts for five of the nine established pests. Among threatening species, ballast water is more significant, accounting clearly for two species, the most likely vector for two more, and a potential vector for another.

The distinction between fouling, in a broad sense, as the dominant historical vector and ballast water as a major recent threat is consistent with our analysis of invasion patterns in Port Phillip Bay (Victoria, Australia) (Hewitt et al. 1999). Even so, fouling appears to currently be a threat equal or greater to ballast water, in Port Phillip Bay and elsewhere in Australian waters. Two additional observations appear to support this point.

First, Australian scientists have now surveyed 15 ports for exotic species. All ports surveyed had exotic
maritime species. However, ports receiving very high levels of ballast water are not generally any more invaded than those receiving little ballast water (Hewitt, in prep.). The exotic species found typically have been in Australian waters since prior to the use of ballast water, and appear to have been introduced into the high ballast water ports by domestic transport, rather than international shipping.

Second, the major invasion events in Australia over the last decade can be attributed to fouling, mariculture operations, and natural dispersal. None appear to be unambiguously a consequence of ballast water transport. These events include the introductions to Australia of Asterias amurensis, Undaria pinnatifida, Codium fragile ssp. tomentosoides, and Mytilopsis sallei; the domestic translocation of A. amurensis and U. pinnatifida from Tasmania to Victoria; the spread of Sabella spallanzani and Maoricuphus roesenus; and the invasion of C. maenas from the mainland to Tasmania.

Of these, the only invasions definitively mediated by ballast water are those involving A. amurensis. Evidence for this is the presence of A. amurensis larvae in ballast water of ships (Martin and Sutton, in prep.). However, we have also collected adults in sea chests of these same vessels, have had several apparently reliable reports of deliberate attempts to spread the species, and small juveniles are cryptofauna in fouling communities and hence routinely found in aquaculture equipment and on mussel ropes, which are moved by the aquaculture industry among sites. With regard to the initial introduction into Australia, the probable point of introduction (the Derwent estuary in Tasmania) receives little ballast water from the original source location in Japan (e.g., in 1991, the only year for which hard data are available, there was only one visit to Hobart from Japan that resulted in a ballast water discharge, and that vessel was from well outside the area that genetic analysis indicates as the probable source location; qualitative information for other years indicate a similar picture). Large volumes of Japanese sourced ballast water are discharged at sites near the Derwent, but improbable scenarios are required to explain why the animals are common in the Derwent, but not at these sites (Ward and Andrew 1995). In contrast, each year the Derwent harbors a sizable fleet of Japanese fishing vessels from areas that genetic analysis (Ward and Andrew 1995) suggests as the probable source location for the invaders. These vessels, which historically were often heavily fouled (Hobart Port Authority, pers. comm.), dock in the Derwent for several weeks at a time. We conclude that although most of the media and many scientific reports have reported A. amurensis as a ballast water introduction in Australia, the evidence suggests otherwise.

There are several likely reasons why the assumption was made that ballast water was the relevant vector for A. amurensis, and why Australia has emphasized managing this vector, despite evidence of the historical and current role of hull fouling, sea chests, and associated vectors as sources of invaders, and pest species in particular.

First, ballast water unambiguously results in the introduction of exotic species, some of which achieve pest status. Several of the more prominent invasions can be linked to ballast water: in Australia, Gustaff Hallegraeff’s work on the transport of toxic dinoflagellates in ballast water (see Hallegraeff and Bolch 1991) was a key discovery that stimulated much of the Australian effort. The zebra mussel ( Dreissena polymorpha) and its likely introduction in freshwater ballast had a similar effect in North America, as did M. leidyi in Europe. The predomiance of ballast water as a likely vector for the threatening species not yet in Australia at least in part justifies the current emphasis.

Second, ballast water is conspicuous and the scale of the vector sounds threatening. The perceived threat and the conspicuous nature of ballast water as a vector have made it the transport mechanism to which new invasions are often quickly linked in public and political arenas. With regard to the latter, media emphasis and recent high-profile technical publications have alerted both managers and environmentalists to the problem, and prompted an emphatic reaction.

Third, the prospect of a technical/operational solution to the problem for an industry used to dealing with such issues (and that acknowledges a problem that needs to be solved) contrasts with the more complex solutions that are likely to be required to address fouling, intentional introductions, and accidental and casual releases from mariculture operations. National and international processes are being developed and implemented to deal with these other vectors, but they often lack the focus or prominence attached to ballast water.

Uncertainty about the relative importance of different vectors as a source of invasive species is not a
viable excuse to do nothing. Societal and political pressure to respond to these invasions forces managers to make decisions in the face of uncertainty about underlying biology or effectiveness of policy settings. In this environment, I suggest we need to deliver three messages.

1. Provide realistic expectations to management agencies attempting to solve the problem. The diversity of vectors means that even a perfect system of sterilizing ballast tanks will not prevent new, damaging, and high-profile invasions. In the Australian context, even if such a system was available, it is debatable whether it would have had any effect on the invasions and recent range expansions by *U. pinnatifida*, *S. spallanzani*, or possibly even *A. amurensis*.

2. Manage the manageable. If the technology and political, social, and industrial will exists to deal with ballast water, but not yet other vectors, then deal with ballast water. But at the same time, we should continue to emphasize the multifaceted nature of the threat, and seek to ensure that a focus on ballast water does not preclude the availability of resources to deal with other vectors.

3. Develop and help implement management structures and strategies that are compatible with, if not also actually effective against, multiple invasion pathways. In so doing, we can help ensure that effort invested now will be equally useful in the future, should the evidence cause a shift in the emphasis of response actions.

Reflecting these messages, the Australian Ballast Water Management Advisory Council is likely to shortly be re-configured as the Australian Introduced Marine Pests Advisory Council. The AQIS has developed action plans for the next several years that address a range of vectors, rather than continuing to focus solely on ballast water.

**MANAGING PEST POPULATIONS**

Responding to established pest populations has three logically distinct components: (1) early detection of and, if possible, eradication of new incursions, (2) containing infections by minimizing the rate of spread of established pest species, and (3) long-term pest management.

Logically, the most effective time to eradicate a new pest is before it is well established and has spread from the point of initial infection. Three recent examples demonstrate the viability of the approach. In 1998, early detection and rapid response by South Australian Fisheries led to the elimination of a patch of about 20 New Zealand greenlip mussels, *Perna canaliculus*, detected by chance during a research survey. This action appears to have eradicated the invader from South Australian waters (J. Gilliland, pers. comm.). Joint action by scientists and industry appears to have recently eradicated an undescribed South African sabellid that infested *Tegula funebralis* and *Halothais refrigiens* in California (Culver and Kuris, in prep.). In 1999, a large-scale, coordinated program led by the Northern Territory government and involving most Australian states, several Commonwealth agencies, and a number of industry and community groups eradicated an incursion of a dreissenid, *Mytilopsis sallei*, from three Darwin marinas (Bax 1999). The incursion response involved closing the infested marinas, a prolonged program of poisoning using chlorine and copper sulphate, and the tracking and checking of every vessel that had left the marinas since the estimated date at which the dreissenid invaded. The eradication program cost A$2.8 million, and has led to a whole-of-government review of incursion response mechanisms.

Such attempts often fail, however. A recent effort to trap out *A. amurensis* from Port Philip Bay, Victoria, proved to be too little, too late, as did earlier attempts to physically eradicate infections of *S. muticum* in England, *C. taxifolia* in Spain, and *U. pinnatifida* in Tasmania. The practicality of an eradication attempt critically depends on the nature of the invader, the scale of the infestation (and hence the rapidity with which it was detected), and the willingness of relevant authorities and the community to invest the often considerable effort required. Our experience has been that expectations regarding the effort involved are typically unrealistic, so that insufficient resources are made available for the eradication attempt to have any real hope of success. In response, we are currently preparing a management-oriented guide to rapid response options (Bax, in prep.), that will review what has and has not been successful in the past, recommend response actions for different groups of organisms, specify the likely costs (human and financial), and outline the theoretical and conceptual underpinnings for the response action.

Detection of new pest incursions also frequently leads to demands for it to be contained until effective countermeasures can be developed. In Australia,
public education programs and some management actions have been instituted in an attempt to reduce the rates of spread of *U. pinnatifida, C. fragile* spp. *tomentosoides* and *A. amurensis*. A similar program against *U. pinnatifida* is underway in New Zealand. The critical issues clearly relate to potential transport vectors, the extent to which they can be managed, and, again, the willingness of government to act. Our experience has been that marine quarantine zones are difficult politically to establish, are often not maintained once the original flurry of activity has passed, and rarely incorporate a community awareness program sufficiently well designed and coordinated as to generate the level of voluntary compliance typically required. The notable exception was the quarantine erected to contain *M. sallei* in Darwin. The very rapid and strong response by government agencies, which included declaring a state of emergency, impounding vessels, at-sea hull inspections, and a well-coordinated public relations campaign, was effective, but also expensive. Legal action for compensation arising from the quarantine is still pending.

Once a pest species is established, the options for its long-term management are still few. In Australia, two crucial sets of issues emerge almost immediately when control options are discussed. The first is an attitude of defeatism. Most managers have stated implicitly or explicitly that once a pest is established, we have to learn to live with it. The reasoning behind this attitude flows from the second issue: the social milieu in which control needs to be undertaken differs fundamentally from those for land or freshwater-based control programs (Lafferty and Kuris 1996). There are three critical differences. First, the ocean is perceived by much of the public as pristine; this perception is illogical and easily refuted in principle, but difficult to overturn in practice. Because of it, suggestions of releasing a local biocide or an exotic biological control organism sometimes evoke strong, negative reactions, based on a perception that it would degrade the pristine ocean. The second difference is the perceived fenceless ocean, which has two important consequences: because marine organisms are perceived to have unlimited dispersal potential, (1) managers assume that local actions are not likely to have local impacts on the target organism, and (2) a segment of the community assumes that any management action, but particularly biological control, will impact adjacent areas, and more to the point, their adjacent areas (a manifestation of the “not in my backyard” syndrome). The third critical difference is that the ocean is utilized by hunter-gatherers (fishermen) who (1) are suspicious of any perceived threat to their independence or fishing success and (2) harvest dispersed resources, which makes it difficult to assign a dollar value to pest impacts or recover cost of control actions. There are obvious exceptions to the last point, such as mariculture operations and pests that affect industrial operations, but these are a minority. Lafferty and Kuris (1996) also raise the point that the level of control required for a marine pest may often be less than required for terrestrial agricultural pests. This is probably true in principal, but may not be true in practice; conservation groups typically push a strong agenda for complete eradication, even if this is currently impractical with available technology for widely distributed pests.

Table 3. Evolution of potential control options for *Asterias amurensis*, using the criteria proposed by Norton (1988). Based on Goggin (1998). The criterion of economic desirability is assumed to have been answered in the positive before any of these options are applied.

<table>
<thead>
<tr>
<th>Method</th>
<th>Effective</th>
<th>Environmentally Acceptable</th>
<th>Practically Advantageous</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physical Control</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trapping</td>
<td>Small scale only</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Hand collection</td>
<td>Small scale only</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Dredging</td>
<td>Small/Medium scale</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Mopping</td>
<td>Small/Medium scale</td>
<td>?</td>
<td>Yes</td>
</tr>
<tr>
<td>Fencing</td>
<td>Small scale only</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Chemical Control</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Broadcast</td>
<td>Medium scale only</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Injection</td>
<td>Small scale only</td>
<td>Yes</td>
<td>?</td>
</tr>
<tr>
<td>Barriers</td>
<td>Farm scale only</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td><strong>Environmental Remediation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rehabilitation</td>
<td>?</td>
<td>Yes</td>
<td>?</td>
</tr>
<tr>
<td>Redulate nutrients</td>
<td>?</td>
<td>Yes</td>
<td>?</td>
</tr>
<tr>
<td><strong>Biocontrol</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Native predator</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Native parasite</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Exotic predator</td>
<td>?</td>
<td>No</td>
<td>?</td>
</tr>
<tr>
<td>Exotic parasite</td>
<td>?</td>
<td>Yes</td>
<td>?</td>
</tr>
<tr>
<td><strong>Genetic Control</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Programmed fatality</td>
<td>Yes</td>
<td>Yes</td>
<td>?</td>
</tr>
<tr>
<td>Inducible fatality</td>
<td>Yes</td>
<td>Yes</td>
<td>?</td>
</tr>
<tr>
<td>Vectored sterilization</td>
<td>Yes</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>
Norton (1988) provides a useful process to evaluate the conflicting objectives of pest eradication and the pristine ocean syndrome. He suggested that for any pest management program to be successful it must fulfill all of five criteria: it must be (1) technically possible, (2) practically feasible, (3) environmentally acceptable, (4) economically desirable, and (5) politically advantageous. The last is perhaps the most important and the most often overlooked. The crucial standard is not that a management approach be politically acceptable, but rather that the politicians and/or bureaucrats who ultimately will approve application of a control mechanism must benefit from this decision. A good recent Australian example is the proposed use of ichthyocides to kill carp in rivers. Although it appears to be technically feasible to develop a carp-specific biocide, approving the release of such a "poison" into waters in which children swim and farm stock and human communities draw drinking water would be a "brave" decision by a minister, and hence one that may never be taken.

We have applied Norton's (1988) approach to evaluate possible control options for A. amurensis in the Australian cultural context (Table 3) (Goggin 1998). From this and similar exercises we have undertaken for other species, pest management options can be ranked on the basis of political and social likelihood of being supported. In descending order of acceptability, these are:

1. Do nothing; the problem might go away.
2. Rehabilitate the environment, in the belief that pests are only problems in degraded areas.
3. Physically remove pests from important sites (fish farms, marine reserves) and ignore the rest.
4. Utilize the pests commercially.
5. Deploy species-specific biocides, reproductive inhibitors, etc.
6. Encourage native predators.
7. Deploy general biocides, selectively applied.
8. Encourage native diseases and parasites.
9. Apply novel genetic approaches that affect only the pest.
10. Apply classical biocontrol, using exotic parasites.
11. Apply classical biocontrol, using exotic nonviral diseases.
12. Apply novel genetic approaches that involve modification of native species (i.e., to use them as vectors).

On the basis of our discussions, two additional approaches are unlikely to be supported in Australia under any circumstances: biocontrol using an exotic predator and biocontrol using a viral disease (or even worse, a genetically modified virus). I suspect these options would not be supported anywhere.

A key element in this ranking is reversibility. Up to option 8, if things go wrong, no permanent change to the system has been made due to the response action itself. From option 9 onwards, participants in our workshops were very loathe to commit, which is reasonable given uncertainties on the specifics of each application. However, there was very strong resistance to the permanent introduction of another exotic species—a disease or parasite—to address a problem caused by the original introduction. This contrasts remarkably with Australia's relatively frequent importation and release of insect biological control agents against terrestrial weeds, and reflects the social considerations discussed above.

This ranking does not reflect the likelihood of success. Options 1 and 2 are largely wishful thinking, though option 2 has benefits in its own right and constitutes a "no-regrets" attempt at pest remediation. Physical removal is only likely to be successful against species early in an invasion, and will be limited to those species that can be easily identified and removed. Application of physical removal on a large scale, e.g., commercial harvesting, can generate strong advocates, but was not supported by fisheries and marine environmental agencies on the basis of institutionalizing a pest and encouraging its translocation to areas not already infested. Biocidal approaches were close to the nervousness threshold, but were generally considered acceptable if suitable safety tests were done, collateral damage was slight, and an effective delivery mechanism could be found; the last requirement was considered a major technological difficulty. Among biocontrol options, the only broadly supported approach was enhancing native species to combat the invader, though it was also agreed this would probably not be effective in the long term. Genetic approaches that only modified the target species was also considered likely to be widely supported. Classical biocontrol were broadly seen as an option of last resort, which would require extensive public consultation before it was approved.

Next Pests: What are the Key Threats

The social, economic, and political factors that define a marine pest species are rarely based on a quantitative assessment of real impacts. More often,
pest status is conferred on the basis of perceived impacts in other areas and aspect dominance. The central issue, unexamined for most species, is whether a pest does something substantially different from the endemic species it displaces or co-exists with, and, ultimately, whether it distorts nutrient and energy flows and shifts community composition to the point where the effects are conspicuous and/or local species face extinction. Although any exotic species must have an impact, this statement alone is clearly inadequate to justify the cost of reducing its impacts. Invasive species offer huge opportunities to investigate in a quantitative and robust way the dynamics of marine communities, but the extent to which the impacts of a particular species justify remediation can be difficult to determine.

In that light, what are the real threats? I suggest three groups of organisms that not only have a high likelihood of invading, but also are likely to cause substantial ecological and economic impacts.

1. Marine pathogens, parasites, and fungi—Hallegraeff (1993) noted the apparent recent increase in the frequency of toxic algal blooms, which he attributed to the introduction of exotic species in ship’s ballast. Since then, outbreaks of marine pathogens, often unexplainable, have occurred with increasing frequency. Examples range from the pilchard kills off southern Australia and New Zealand (Jones et al. 1997), which might be the result of an as-yet-unidentified viral agent, well-publicized Pfiesteria outbreaks on the U.S. east coast, toxigenic Vibrio cholera in the U.S. Gulf states (McCarthy and Khambaty 1994), lobster kills attributable to Vibrio fluvialis off Maine, and seal kills in the Mediterranean, suggested to be the result of blooms of introduced toxic dinoflagellates (Hernandez et al. 1998).

Marine pathogens are particularly dangerous in two respects. First, the vectors that can transport them are diverse, defenses against them are difficult to develop, and legislative barriers to minimize risks may be difficult to enforce. Australian efforts to prevent importation of fresh Canadian salmon products, for example, as a means of protecting the current disease-free status of the stocks has been rejected by the World Trade Organization as an unjustified trade barrier. This decision is being appealed. Second, pathogens have the potential to fundamentally alter the dynamics of marine systems, perhaps more so than any other group. The decimation of the Caribbean urchin, Diadema antillarum, in the 1980s, due apparently to a marine pathogen of unknown origin (Lessios et al. 1984), had a profound effect on algal-coral dynamics throughout the region and fundamentally altered the composition of Caribbean reef communities (Hughes 1994). There are similar reports in other regions. Duncan et al. (1982) reported on a mass die-off of a large keystone predator seastar in the Sea of Cortez, attributed to unusually warm temperatures and the action of an as-yet-unidentified pathogen, and suggested major changes in benthic communities as a result. A similar die-off of the seastar, Astreas rubens, off the coast of the northeastern United States occurred in the 1990s, again for unknown reasons (“ray rot disease”), but attributed at least in part to stress due to water temperatures. Anthropogenically enhanced dispersal of marine pathogens to naïve populations may prove to be one of the major challenges globally to marine industries and ecosystems, and is one that we are particularly poorly prepared to handle.

2. Invasive marine macroalgae—Introduced macroalgae are already common and causing substantial concern: U. pinnatifida in Australia, New Zealand, and Europe; C. fragile ssp. tomentosoides in America, Australia and New Zealand; S. muticum in Europe; and a number of species of Catenella at sites worldwide. As well, there are increasingly more frequent reports of pest macroalgal blooms at both temperate and tropical sites (Raffaelli et al. 1998), often involving broadly distributed genera and attributed, possibly incorrectly, to outbreaks by native species (as per arguments in Carlton 1996). Introduced macroalgae have a number of features that facilitate their invasion, most notably an ability to easily transport by a variety of vectors and, in many instances, limited dispersal abilities of motile reproductive stages (facilitating population establishment), as well as vegetative and clonal reproduction. Invasive plants may often do little more than increase local diversity or replace native congeners (Trowbridge 1998), but in at least some cases they clearly occupy habitats and reach such high densities that they become space dominants and fundamentally change community dynamics. Again, preventative options against such invasions are poorly developed, nor do we have any effective means to combat such species once they have invaded. Physical removal has proven unsuccessful in a number of instances, and herbicidal and biological options are still far from being developed.
3. Genetically enhanced production species—The invasion of the Mediterranean by an artificial hybrid of *C. taxifolia*, selectively bred for increased growth and environmental tolerances (Jousson et al. 1998), is likely to be only the first of what may in the long term prove to be one of the major problems facing marine systems. Work is underway worldwide to produce species for marine mariculture that grow faster and are more environmentally tolerant than existing species. At least some of these species, such as Pacific oysters (*C. gigas*), are already considered pests in Australia when feral, a situation likely to only worsen when “super-oysters” are introduced. Unlike terrestrial systems, where production lines are often competitively inferior because they are selected for rigidly controlled farm conditions, mariculture often relies on what are essentially natural and unregulated environments, and, hence, in the short term at least, will seek organisms capable of increased production under natural conditions. When these enhanced plants and animals are introduced, it may well be impossible to stop their spread and consequent impacts on native communities. Although the problem has been recognized and some work to contain such production organisms is underway (e.g., the Australian “sterile ferals” project), it is very unclear that caution, regulations, and technological solutions will be adequate to counter advocates driven by increased profit margins and increasing demand worldwide for seafood products. The vectors associated with the introduction of these super-competitors at first are likely to be quite different from those with which we are currently concerned, but as shown in the Mediterranean, once such a taxon is established, the familiar vectors, such as fouling on anchor chains, rapidly come into play in spreading the pest (Meiners et al. 1998).

The prospects for managing these threats are mixed. Marine pathogens are likely to be manageable by reducing the likelihood of transport and by modifications of mariculture and human health operations post-invasion to minimize impacts. As ballast water appears to be a very suitable vector for pathogens, it is crucial that treatment processes for it are effective against them. Treatments that deal only with metazoans and their larvae not only may be targeting the lesser threat, but may even exacerbate the threat due to pathogens (Desmarchaler 1997). Dealing with marine invasive plants, although technically challenging, is likely to be able to borrow from the Integrated Pest Management (IPM) approaches developed for terrestrial weeds, including topical application of specialized herbicides, physical control, and classical biological control. The information we require to implement IPM for any marine plant is lacking, but the conceptual approaches appear to be in place. This is not likely to be true for genetically enhanced invaders. For these, as is the current situation with *C. taxifolia* in the Mediterranean, problem species will need to be approached on a case-by-case basis.

**Conclusions**

Australia’s decade of concerted and coordinated attempts to manage the problem of introduced marine pests has resulted in some successes, some failures, and a far better understanding of the scope of the problem and the scope for management action. A principle outcome of such knowledge is a much greater public and political appreciation of the problem. But this appreciation has led to demands that scientists and managers solve the problem, which has proven difficult at best.

Australia has structured its approach to introduced marine species around a zonal defense system. The first zone—take and transport—is targeted by the Australian Ballast Water Management Advisory Council and the Australian Quarantine and Inspection Service, as well as several states. The Northern Territory, for example, evaluates the risk posed by arriving recreational yachts and fishing vessels, and, when in doubt, requires a hull survey and sterilization of any plumbing open to seawater prior to allowing international vessels into berths.

Zone 1 is permeable. Even assuming we could sterilize ballast tanks and clean hulls, sea chests, and internal plumbing, pests would still arrive. To the extent that we have done none of that, or demonstrated that what management actions we have initiated, such as exchanging ballast at sea, are even effective at reducing the rate of invasions, we have barely slowed the invasion rate, if at all. But the preconception that once a species arrives, you have lost the game is not only unacceptable, but wrong. Several successful eradication attempts have been launched in the last few years, though all combined an element of good luck, good planning, and a suitable, still contained incursion. Australia is formalizing a process to maximize its luck, by establishing a nationally coordinated system to manage its second defense zone—the receiver ports. Action is seen to be primarily a state
responsibility and, since the successful eradication of the black-striped mussel in particular, focuses on rapid detection of new pest species, development of tactical control options, and the establishment of an effective system of communication among state and commonwealth agencies that would need to be involved. Public awareness campaigns have been put in place in all Australian states, and several are developing programs for routine surveillance of high-risk environments. As well, work has begun at developing more effective and better targeted biocides than the broad spectrum chemicals employed in Darwin.

The third zone of defense is long-term pest control. We have begun testing commercial harvesting as a means of reducing pest numbers, are assessing the potential of environmental remediation to reduce the numbers of A. amurensis and U. pinnatifida, and have projects underway looking into both biological control and the development of novel biomolecular techniques for pest control. Which, if any, of these approaches will prove useful is still to be determined.

At times, the biological, bureaucratic, and political complexity of the problem is daunting. But, slowly, management structures are being put in place that encourage (and in some instances) require protocols to lower risks of new introductions; programs have begun to be better integrated nationally, particularly through the actions of the recently established Australian National Taskforce on Managing Marine Pest Incursions; and managers are beginning to appreciate the scale of the resources required to solve the problem. The cost of eradicating the dreissenid, *Mytilopsis sallei*, in Darwin, at just under A $3 million, drove home not only the cost of poor barrier controls, but also the threat that even one particularly bad pest species posed to Australia’s biodiversity and marine industries.

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**Literature Cited**


**SOURCES OF UNPUBLISHED MATERIAL**


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