MARINE AND AQUATIC NONINDIGENOUS SPECIES IN CALIFORNIA:

AN ASSESSMENT OF CURRENT STATUS AND RESEARCH NEEDS

Summary of a Program Development Workshop

Sponsored by the

California Sea Grant College System

Editors: Paul G. Olin

and

Jodi L. Cassell

Sea Grant
California

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Sponsored by the
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TABLE OF CONTENTS

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Paul Olin

Introduction

It is sometimes forgotten that the introduction of species to new locations where they are not native has taken place throughout recorded history and has in fact provided the foundation for agricultural production systems worldwide. But these introductions were largely planned and most species were well understood since they had been actively cultivated in their native range.

In recent years, international commerce has rapidly accelerated the rate at which nonindigenous (sometimes called "exotic" or "alien") species (NIS) are being introduced, particularly in coastal regions where human populations are concentrated and because marine shipping transports billions of gallons of ballast water around the world on a daily basis. However, unlike past agricultural introductions, little is known about many recently introduced species, and their effects on complex coastal ecosystems are extremely difficult to predict. Control of the introduction and subsequent dispersal of aquatic species is particularly difficult given their ease of dispersal, the difficulty of monitoring their establishment and dispersal, and the paucity of targeted control measures available for use in aquatic systems.

California is particularly exposed to NIS introductions and their consequences, given the high level of marine commerce, great diversity of coastal habitats, and productive ocean fisheries. In a comprehensive study of introductions to the San Francisco estuary, it was estimated that one new species arrives every 12 weeks (Cohen and Carlton, 1995). Whether these new species become established and what their ultimate effect on native species will be is exceedingly difficult to predict. Fortunately, most introduced species do not persist because they are low in number, are introduced at sensitive larval stages, enter adverse habitats or succumb to predation.

We do know, however, that a number of introduced species have great potential to impact coastal and freshwater aquatic ecosystems in California. These include the green crab, Chinese mitten crab, Asian clam, *Spartina alterniflora* (the alien cordgrass), water hyacinth, hydrilla, and a sabellid polychaete that parasitizes cultured abalone.

The zebra mussel, primarily a freshwater invader, is not known to be established in California, but live specimens have been intercepted at border agricultural inspections on a number of recent occasions. This is of particular concern given the thousands of miles of irrigation and water distribution canals in the state, much of which would provide excellent habitat for zebra mussels.

To address the critical topic of NIS introductions in marine and coastal ecosystems, the California Sea Grant College System convened a program development workshop in San Francisco in October 1996. Its goals were to bring researchers, resource managers, and other interested parties together from around the state to discuss species of concern, current research directions, and perhaps most importantly, needed research. The first afternoon was devoted to presentations, abstracts of which appear in the following pages.

These presentations provided a background for the facilitated discussions and brainstorming sessions which were conducted the following morning.

Participants agreed that the following would be desired outcomes from the workshop:

- Identification of marine, estuarine, and aquatic nonindigenous species and their current and potential impacts in California

- Lists of research, management, and public outreach needs for dealing with problems associated with nonindigenous species.

There was some concern that the contents of this summary might be misconstrued as an attempt to prioritize nonindigenous species issues, or be used to influence funding priorities. Given the short time frame of the workshop and the complexity of the issues addressed, participants felt strongly that this would be inappropriate. We would therefore like to emphasize that this document is a compilation of needs and concerns expressed by individuals with broad experience in research, management, and outreach; it does not represent an attempt to prioritize species or issues of concern.

Paul Olin
Jodi Cassell

WORKSHOP ABSTRACTS

BIOLOGICAL INVASIONS IN THE SAN FRANCISCO ESTUARY

Andrew Cohen, University of California, Berkeley
(editors' note: current affiliation, San Francisco Estuary Institute)

Exotic organisms may constitute the largest single threat to the biological diversity of the world's coastal waters. The waters and wetlands of the San Francisco Estuary now host over 200 nonindigenous salt water, brackish water and freshwater species, including plants, protists and invertebrate and vertebrate animals. An additional 100 to 150 species are considered cryptogenic species that, based on current knowledge, could be either native or introduced.

More significant than the sheer number of exotic species is their dominance, in number of individuals and in biomass, in many of the Estuary's habitats. In numerous studies made since the 1940s, exotic species accounted for 40% to 100% of the common or dominant species in benthic and fouling communities at sites throughout the Estuary. Most of the common fish in the Delta were introduced from the Eastern United States, and a recent study reports that in collections in the south Delta, typically more than two-thirds of the fish species and more than 95 percent of the fish have been introduced. The zooplankton fauna in the northern part of the Estuary has, since the late 1970s, been increasingly dominated by Asian copepods and mysid shrimp.

Moreover the rate of invasion has been increasing. In the period since 1850, there has been on average a new species established in the Estuary every 36 weeks. Since 1970, the rate has been a new species every 24 weeks. In the last decade we have seen about one new species arrive every 12 weeks (although we don't yet know how many will become established).

The introduction of these organisms has produced both ecological and economic effects, such as the eradication or drastic reduction of some native populations due to predation and competition. Food webs have been fundamentally altered, most dramatically by the Amur River clam, which has become so abundant that it can filter the entire water column over a significant portion of the Bay in less than a day, removing bacteria, phytoplankton, and zooplankton. Introduced cordgrasses threaten to take over much of the Estuary's mudflat areas, which are critical feeding sites for migratory shorebirds.

Although some introduced fish economically supported commercial fisheries for a time, virtually all have since declined or closed (perhaps due either to stresses on the ecosystem or to a pattern of boom and bust common to many invading species). Recreational fisheries remain, some of which are maintained by stocking programs. Three accidentally introduced clams (two marine, one freshwater) have supported commercial fisheries, but most economic effects of introductions have been negative. In the period from 1919 to 1921, an introduced wood-boring shipworm caused between $2 billion and $20 billion (in 1992 dollars) of damage to shoreline structures. Hull fouling, the partial result of introduced organisms in the Estuary, reduces vessel speed and increases fuel consumption. California spends about $400,000 per year controlling exotic plants in the Delta, and has spent over $2 million (and poured more than 20 semi-trailer loads of fish poison into California waters) to keep two exotic fish from reaching the Delta. Activities to control exotic fouling organisms, plants and fish release poisons into the environment, which create additional environmental, occupational, and possibly public health costs.

Exotic species may also be contributing to the increasing number of endangered species in the Estuary. Their continuous arrival makes the ecosystem fundamentally unmanageable by continually changing the cast of characters. These factors may have the greatest implications for the whole of California's economy by hindering economic activities in and on the shore of the Estuary, and especially by complicating or interfering with management of the California water delivery system.

BALLAST WATER MANAGEMENT AND POLICY

James T. Carlton, Marine Sciences, Williams College, Mystic, Connecticut

Ballast water is today considered to be the number one vector responsible for the accidental translocation and introduction of nonindigenous (exotic) marine organisms across and between the world's oceans. As a result, a primary management and policy goal both nationally and internationally has been to address both short-term and long-term mechanisms to reduce ballast-mediated invasions.

At the national level in the United States, two public laws, the National Aquatic Nuisance Species Prevention and Control Act of 1990 and the National Invasive Species Act (NISA) of 1996, address ballast water management in addition to numerous other issues associated with aquatic species invasions. NISA calls for the United States Coast Guard to issue guidelines and to initiate educational programs aimed at requesting vessels to exchange their ballast water in the open ocean.

At the international level, the United Nations International Maritime Organization in London has a Ballast Water Working Group that is drafting an annex to the International Convention on the Prevention of Pollution from Ships (MARPOL) for international ballast water management. This will focus initially on open ocean ballast exchange (OOBE). There are several fundamental limitations of OOBE, including the inability of many vessels in storm conditions to undertake deballasting and reballasting, and the often incomplete nature of the exchange process for those ships that do attempt the process. Ballast management treatment technologies have been the subject of numerous desk studies in Japan, Australia, Canada, the United States, Scotland, England, Germany, Poland, and elsewhere.

Two field demonstrations have been conducted: high-volume microfiltration on a modified vessel in the Great Lakes (funded by the Great Lakes Protection Fund), and thermal treatment on vessels voyaging between Japan and Australia (funded largely by the Australian shipping industry). Biological and ecological studies on the biota in ballast water arriving in Chesapeake Bay have been conducted with Maryland Sea Grant funding at the Smithsonian Environmental Research Center (SERC) in Edgewater, Maryland, in the laboratory of Dr. G. Ruiz. A study on ballast water by the Marine Board of the National Academy of Sciences' National Research, "Stemming the Tide: Controlling Introductions of Nonindigenous Species by Ships' Ballast Water," is an in-depth examination of potential ballast water treatment technologies.

NONINDIGENOUS FRESHWATER AQUATIC PLANTS IN CALIFORNIA

Lars W. J. Anderson, U.S. Department of Agriculture
Agricultural Research Service, Aquatic Weed Control, University of California, Davis

The spread of non-native flowering aquatic plants has increased dramatically over the past 25 years in California and has created many economic and ecological impacts. Demands on the state's water resources have exacerbated these impacts, which include irrigation water delivery, recreational and domestic (drinking) uses, and fisheries and waterfowl habitats.

The species causing most of the problems are: *Hydrilla verticillata* (hydrilla), *Eichhornia crassipes* (water hyacinth), *Egeria densa* (Egeria), *Myriophyllum spicatum* (Eurasian watermilfoil), and *Myriophyllum aquaticum* (Parrot feather). Recent introductions and the spread of *Lythrum salicaria* (Purple loosestrife) also threaten the state's riparian systems. The hallmark of the invaders is their ability to utilize low light levels (in the case of submersed plants) and their rapid, prolific, and varied reproductive abilities.

Of these plants, only hydrilla has a pest rating of "A" by the state, which requires it to be eradicated. Costs for hydrilla eradication have averaged about $1 million annually over the past 20 years. This program has no doubt prevented the introduction of hydrilla into the Sacramento/San Joaquin Delta. However, both water hyacinth and egeria now infest several thousand acres in the Delta. Water hyacinth has been under management for 15 years, and a bill authorizing the management of egeria passed the state legislature in 1996. The combined costs of these efforts will probably equal or exceed the hydrilla eradication expenditures. Management of water hyacinth and egeria via biological control agents should be the long-term goal, yet effective herbicides and selective mechanical control need to be used in the interim to prevent further spread of these weeds. Likewise, the spread of *M. spicatum* in Lake Tahoe demands immediate action in spite of varied regulatory and political inertia.

ZEBRA MUSSELS AND POTENTIAL IMPACTS IN CALIFORNIA

Jeff Janik, California Department of Water Resources, Sacramento

The zebra mussel, *Dreissena polymorpha*, is a freshwater species that has spread rapidly throughout the lakes and rivers of the Eastern United States and Canada since its introduction in 1988. In response to the potential threat to water distribution systems and aquatic ecosystems in the state, California initiated a program of zebra mussel exclusion in 1993. The principal method for exclusion is enforcement of the state Fish and Game code at California border inspection stations. Inspections are designed to find and confiscate plants and animals that are illegal and could cause serious damage to California agriculture.

In the three years since the inspection program began, zebra mussels have been found nine times on trailered boats entering the state. Three of the boats were transporting live zebra mussels at the time of inspection. The zebra mussels were removed and these boats reinspected before being launched. It appears that overland transport of zebra mussels on or in boats is a threat to California waters. In addition to transport by recreational boats, other potential pathways of introduction include ballast water from commercial shipping, and shipments of aquatic plants and live baitfish.

It is difficult to predict which water bodies in the state will be at risk to zebra mussel colonization. Published data on the tolerance ranges of zebra mussels to temperature, calcium, and pH can be used for comparison to existing water quality conditions. Studies by the State Water Project indicate that water-quality conditions are suitable for zebra mussel survival throughout most of the Project's pipes and canals that distribute freshwater throughout the state. Temperature may be a limiting factor to zebra mussels during late summer in the southern part of the state.

SPARTINA IN THE SAN FRANCISCO BAY REGION

Donald Strong, Bodega Marine Laboratory, University of California, Davis

Cordgrasses introduced from the Atlantic states have spread very rapidly in Pacific estuaries in Northern California, Oregon, Washington, and British Columbia. The earliest introduction of *Spartina alterniflora* has led to dense coverage of about 30% of the intertidal area in Willapa Bay, Washington. The most recent introduction, to San Francisco Bay, has resulted in rapid colonization of the south end of the Bay. Atlantic cordgrasses are a substantial threat to wildlife, fisheries, and traditional uses of Pacific estuaries. Replacing the naturally open mud of Pacific estuaries with monospecific grass prairie, the dense canopy and tightly locked rootmats of these weeds exclude shorebirds, native vegetation, fish, and many invertebrates.

In California, *S. alterniflora* competes vigorously with the native *S. foliosa*, overgrowing and crowding out this shorter native. We have found that *S. alterniflora* hybridizes with *S. foliosa*. We have made hybrids in the greenhouse and identified these by means of molecular systematics, with RAPD (randomly amplified polymorphic DNA) digests amplified with PCR (polymerase chain reaction). We have found hybrids in San Francisco Bay in areas where the alien and native species grow closely together, identifying these with the molecular systematic techniques.

Biological control is not a promising solution to control of *S. alterniflora* in San Francisco Bay, because the native species would probably be vulnerable to any agents that would harm the alien. However, in Willapa Bay, where the plant was introduced many decades ago and grows in the absence of congeners, biological control shows promise. *S. alterniflora* from Willapa Bay are severely harmed and even killed by the plant hopper *Prokelisia marginata*. In San Francisco Bay, chemical control is promising because preliminary work shows that, if carefully applied in the spring of the year, glyphosate will kill the alien. Mechanical control (i.e., cutting the stalks) also may offer promise.

Single Trophic Level Impacts of an Introduced Predator (European Green Crab) in a Diverse Marine Food Web

Edwin Grosholz, Department of Zoology, University of New Hampshire, Durham
(editors' note: current affiliation, Department of Environmental Science and Policy, University of California, Davis)

Coastal marine ecosystems are particularly susceptible to invasions by nonindigenous species, as indicated by the 200 exotic species in San Francisco Bay. Surprisingly, there is little quantitative information documenting the impact of marine invasions on native species. Therefore, our ability to quantify the risks that future introductions pose for biodiversity, ecosystem function, and fishery stocks in nearshore coastal habitats is extremely limited.

Our work has tried to remedy this by measuring many direct and indirect impacts of an introduced marine predator, the European green crab (*Carcinus maenas*), on a range of organisms from benthic invertebrates to shorebirds in Bodega Harbor, California. The green crab was first discovered on the reserve of the Bodega Marine Laboratory of the University of California, Davis in 1993, where extensive data had been collected for ten years prior to the invasion. The preinvasion data quantify the population dynamics of more than 24 benthic invertebrate taxa and 13 species of shorebirds. These long-term data, together with manipulative experiments in the laboratory and the field, permitted a test of the present impact of the green crab on the Bodega Harbor food web.

This work has demonstrated that green crabs have dramatically reduced the abundance of several key invertebrate species, including the native shore crab (*Hemigrapsus oregonensis*) and native clams (*Transennella confusa* and *T. tantilla*). However, wintering shorebird populations have not shown a response to these reduced abundances of invertebrate food resources. Preliminary field experiments testing the susceptibility of commercial species to green crab predation indicate that adult and juvenile green crabs readily prey on juvenile (YOY) Dungeness crabs (*Cancer magister*) of equal size or smaller, and that adult green crabs can prey on Pacific oysters (*Crassostrea gigas*) greater than 80 mm in length.

The Present Status of the Chinese Mitten Crab in South San Francisco Bay

Kathleen Halat, ESPM, University of California, Berkeley

The Chinese mitten crab (*Eriocheir sinensis*) is native to the rivers and estuaries of China and Korea along the Yellow Sea. These crabs are catadromous, meaning that juveniles grow and develop in freshwater, and adult crabs migrate to the sea to reproduce and die. Mitten crabs were first captured in shrimping and research trawls in the south portion of San Francisco Bay during the winter of 1993. Juvenile mitten crabs are presently well-distributed throughout most of the sloughs and tidal creeks in South San Francisco Bay.

High densities of mitten crab burrows can cause accelerated bank erosion and slumping. Densities of burrows were as high as 24/m2 (measured along the vertical bank face) in one South Bay slough during the summer of 1996. Although mitten crabs in the South Bay commonly overlap in habitat and dietary preference with the red swamp crayfish (*Procambarus clarkii*), no negative correlation was found between the presence of crabs and crayfish during the summer of 1996.

Prior to 1996, mitten crabs were abundant only in South San Francisco Bay. Mitten crabs are now commonly collected in North San Francisco Bay and in the Delta. Over time, activities of mitten crabs could pose a serious threat to both the biological communities and the structural integrity of levees in the North Bay and Delta.

Sabellid Polychaete Pest of Cultured Abalone: Current Exotic Pest, Future Introduced Species?

Carrie Culver, Marine Science Institute, University of California, Santa Barbara

California entrepreneurs have played a key role in the development and commercial success of abalone aquaculture. Viewed as an economically viable and important enterprise, this industry has expanded over the past 10 years. However, significant financial losses are currently being experienced as the result of the introduction of an undescribed polychaete pest into culture facilities.

Identified as a member of the family Sabellidae, and native to South Africa, it is likely that this pest was introduced by importation of infested South African abalone for commercial research. Spread throughout the industry was rapid because both seed and larger abalone were transferred among growers. Although the polychaete infestations do not impact abalone meat quality, shell growth rates decrease or virtually cease in heavily infested stock. Time to market, which is already relatively slow, is further delayed. Worst cases result in an unmarketable product due to growth cessation or shell deformities.

Attempts to eradicate the worm are ongoing, but to date have not been successful. Failed methods include air exposure, freshwater treatment, severe temperature exposure, chlorine treatment, and several insecticides. In addition, several control techniques (e.g., application of wax to dorsal side of shell, isolation of stocks) are currently being used. These methods are labor intensive and costly and at best only minimize the rate and extent of spread to other abalone stocks.

Since this is a nonindigenous species, establishment in the environment is also of concern. Introduction into natural habitats is highly probable and may have already occurred, given the worm's broad host specificity and the various avenues of introduction available (e.g., onshore facility discharge, offshore cage culture, outplanting). Fortunately, its benthic larval state will impede its rate of spread. Thus, while establishment of the sabellid is still geographically restricted, immediate attention to reduce its opportunity to spread could prove effective and keep this exotic pest from becoming a widespread introduced species in nature.

Ascidian Introductions into Southern California Harbors and Marinas

Charles and Gretchen Lambert, Department of Biological Sciences,
California State University, Fullerton

When Ritter and Forsyth (1917) assayed the ascidians of San Diego and other Southern California harbors, the West Coast native species *Ascidia ceratodes* and *Pyura haustor* were the dominant ascidians, along with numerous *Ciona intestinalis* (which Ritter and Forsyth considered to be introduced).

Since that time, many species of ascidians have arrived; some have spread and persisted in these harbors. The arrival and persistence of *Styela clava* and *S. plicata* have been well-documented (see Abbott and Johnson 1972 for review); along with *Ciona intestinalis,* they have replaced the native species. Sometime between 1945 and the 1960s, *Botryllus schlosseri* arrived. A number of additional non-indigenous species have been observed: *Styela canopus* (formerly *S. partita*) was first encountered in 1972 in south San Diego Bay. *Microcosmus squamiger*, first collected in Alamitos Bay in 1986, is now abundant from San Diego to Ventura. The Japanese species *Ciona savignyi*, first recorded in Long Beach harbor in 1985, is now common in all harbors. *Ascidia "interrupta,"* a long-siphoned species clearly distinct from the native *Ascidia ceratodes*, was first collected from Harbor Island in San Diego Bay in 1983. In 1994, a third species of Ascidia, which remains unidentified, was collected; it is very similar in external morphology to *A. ceratodes*. *Symplegma oceania*, first encountered in 1991, is now present in various locations on both sides of San Diego Bay. The East Coast ascidian *Molgula manhattensis*, first collected in San Francisco Bay in the late 1950s (Trason 1959), was found in Long Beach and Newport harbors in 1984 and is now also in Marina del Rey and Ventura. A more recent introduction is *Polyandrocarpa zorritensis*, first collected in Oceanside Harbor in 1994 and found to be abundant also in San Diego and Mission bays.

The arrival of these ascidians and their relative abundance in all harbors in Southern California from San Diego to Santa Barbara raises concerns about their persistence and further spreading.

IMPACTS OF NONINDIGENOUS SPECIES IN CALIFORNIA'S ESTUARIES (UPSTREAM OF CARQUINEZ STRAIT)

Bruce Herbold, University of California, Davis

The estuarine community of San Francisco has been invaded almost as much as the habitat has been altered. Major habitat alterations have preceded most of the successful introductions of nonindigenous species. These habitat changes fall into two major categories: hydraulic mining and water project development.

Hydraulic mining accompanied the introduction of a number of species with either semibuoyant eggs or which guarded their eggs in nests, whereas many native fish have adhesive or buried eggs. Water development has produced stable salinity regimes year-round, allowing stenohaline fish, like channel catfish, to successfully invade. Higher salinities during drought conditions appear to have favored the establishment of brackish water species in recent years.

Successful introductions have typically been followed by tremendous population growth and then a period when the new species appears to be integrated with the other species present. Effects among lower trophic levels are easily demonstrated, but so far impacts on higher trophic levels have generally been less evident. Substantial changes in prey community density and composition have not prevented relatively high populations of native fish species in years of suitable hydrology, suggesting that habitat conditions control estuarine fish production more than do food chain impacts of introduced species. Interactions between particular pairs of similar species give the clearest causes for concern.

IMPACTS OF THE ASIAN CLAM ON SAN FRANCISCO BAY REGION

Janet K. Thompson, U.S. Geological Survey, Menlo Park, California

The introduction of the Asian clam, *Potamocorbula amurensis*, into San Francisco Bay in 1986 has resulted in several ecosystem changes. The most apparent has been the disappearance of the summer phytoplankton bloom in the northern Bay. Studies of the annual cycles of past and present phytoplankton populations and *P. amurensis* populations have shown that the phytoplankton reduction is most likely due to over grazing by *P. amurensis*. This over grazing is a result of the fact that shallow water *P. amurensis* populations filter the water column at least once a day, while the phytoplankton double less than once per day. Although it has not yet been established whether this reduction in phytoplankton has reduced the size of fish populations, the populations of several important food sources for larval and adult fish have declined coincident with the decrease in phytoplankton; for example, the opossum shrimp (*Neomysis*) has shown population reductions which are believed to be due to food limitation, and populations of the copepod *Eurytemora affinis* have decreased in number as a result, in part, of consumption of their larvae by *P. amurensis*.

Less frequently discussed than the demise of the phytoplankton is the possible reduction in other sources of particulate organic carbon (e.g., detritus, bacteria, and bacteria on particles) due to grazing by *P. amurensis*. Estimates of the amount of carbon consumed by the *P. amurensis* populations in the northern Bay are two to nine times higher than the amount of carbon produced by the phytoplankton. Previous work has shown that *P. amurensis* can effectively filter and assimilate free-living bacteria, and thus it is likely that this filter feeder is consuming water-borne bacteria and detritus. Primary production in the northern Bay has never been high, and thus detritus and bacteria have probably always been an important food source for small secondary producers. It is unknown what percentage of this food source is now consumed by *P. amurensis* and how this reduction might affect other levels of the food web.

It is probable that these changes to the lower levels of the food web have resulted in changes to the higher trophic levels. Although pelagic predators (e.g., midwater fish, dabbling ducks) may have lost a primary food source, bottom-feeding predators (e.g., sturgeon, diving ducks) now have an enhanced food source. The reduction in food for pelagic fish and invertebrates may shift the system from one dominated by pelagic consumers to one dominated by bottom-feeding fish and birds. However, because *P. amurensis* has been shown to be a bioaccumulator of trace elements such as cadmium and selenium, this shift in the food web may prove to be detrimental to the bottom-feeding predators.

EFFECTS OF NONINDIGENOUS SPECIES ON NATIVE SPECIES (THE EELGRASS *ZOSTERA MARINA*) IN SOUTHERN CALIFORNIA LAGOONS

Thorsten B. H. Reusch and Susan L. Williams, Biology Department,
San Diego State University, California

The introduced Asian mussel *Musculista senhousia* is now the most abundant macroinvertebrate species at several sites and co-occurs with eelgrass, *Zostera* sp. in both its native and new habitat.

Controlled field experiments revealed that dense beds of *M. senhousia* (600 g dry mass/m2) negatively affected the vegetative propagation of the clonal angiosperm. Potential mechanisms of resistance by the invaded community to proliferation of the mussel have been studied. When occurring as extended meadows, eelgrass caused a 60% decline in bivalve growth rates in comparison to unvegetated habitat. Also, when mussel populations above the carrying capacity were transplanted below the canopy, parts of the mussel population died through starvation. In contrast to those extended meadows (5 m), fragmented eelgrass beds are probably much more prone to local *Musculista* invasion. In addition, mortality rates of *M. senhousia* through native predators, in particular muricid snails, were significantly higher inside the eelgrass bed than in adjacent sand flats.

Impacts of Nonindigenous Species

Workshop participants broke down the impacts of nonindigenous species into a number of categories. These groupings at times overlap considerably since a particular species often exerts influence in more than one category.

Positive Economic Impacts

The multi-billion dollar agriculture industry in California is comprised almost entirely of nonindigenous species as is the aquaculture industry, which is dominated by introduced bivalves and finfish. A number of other nonindigenous aquatic species have provided positive economic impacts, usually because a commercial or recreational fishery has been developed to exploit them. The following is a partial list:

- *Morone saxatilis*: The striped bass supports a sport fishery in California.
- *Venerupis philippinarum* (formerly *Tapes japonica*): The manila clam provides recreational clamming opportunities.
- *Mya arenaria*: The Atlantic soft-shelled clam is fished recreationally in California.
- *Homarus americanus*: The Maine lobster is imported live for human consumption.
- Ascidians: A number of species are being evaluated for production of chemicals with potential pharmaceutical applications.

There are also a number of species which may have potential for culture as human food or aquatic vegetation management. These include the following:

- *Pyura hauster* and the Japanese species, *Halocynthia roretzia*: These ascidians are cultured in Japan and Korea.
- *Corbicula fluminea*: This freshwater Asian clam is used for human food, bait, and in the aquarium trade.
- *Eriocheir sinensis*: The Chinese mitten crab is harvested for human consumption in many Asian countries and has fishery potential in the United States.
- *Tilapia* sp.: Tilapia have been imported in various locations for vegetation control, and they provide recreational fishing opportunities south of the Tehachapi Mountains.
- *Pacifastacus leniusculus*: The signal crayfish was introduced from the Pacific Northwest and supports a commercial fishery.
- *Crassostrea gigas*: The Pacific oyster is the primary species cultured in California.
- *Crassostrea virginica*: The Eastern Chesapeake oyster is also cultured in California.
- *Rana catesbiana*: Bullfrogs are captured and consumed by California residents.
- *Ctenopharyhgodon idellus*: The grass carp is used for food and in the control of some aquatic plants.

Potential Human Health Concerns
Some nonindigenous species are pathogens, vectors, or intermediate hosts of human pathogens. In addition, all freshwater plant introductions can increase mosquito habitat; crabs, clams, and other predators can bioaccumulate toxins produced by the red tide dinoflagellates; and filter-feeding organisms can become contaminated through accumulation of natural and introduced toxins.

Following is a partial listing of nonindigenous species with the potential to adversely affect human health:

- *Eriocheir sinensis*: The mitten crab is an intermediate host of the oriental lung fluke, *Paragonimus westermanii.*
- Ascidians: Ascidians in Japan have been associated with respiratory problems in oyster shuckers working with heavily fouled shellstock and gear.
- *Ilyanassa obsoleta*: The Eastern mud snail is an intermediate host for the shistosome flatworm responsible for swimmer's itch.
- *Vibrio cholerae*: This bacteria can be transported in ballast water and has the potential to cause cholera.

Interference With Recreational Activities
The following introduced species have the potential to impact recreational and commercial fishing, birding, swimming, and boating.

All of the introduced freshwater aquatic plants have significantly disrupted water recreation in California and caused substantial costs for cleanup and eradication efforts. These include hydrilla (*Hydrilla verticillata*); elodea (*Egeria densa*); parrot feather (*Myriophyllum aquaticum*); water hyacinth (*Eichornia crassipes*); Eurasian watermilfoil (*Myriophyllum spicatum*); and purple loosestrife (*Lythrum salicaria*).

Other introduced estuarine plants such as the Eastern cordgrass (*Spartina alterniflora*) can cause major alterations in mud flat and estuarine habitats by converting them to cordgrass marshes. This will likely affect bird abundance and behavior and has the potential to interfere with recreational birding.

The zebra mussel (*Dreissena polymorpha*) is a classic example of a species that has had major ecological and economic impacts in areas where it has been introduced. If introduced to California, zebra mussels would substantially alter water distribution systems and aquatic ecosystems with the potential to impact recreational fishing and boating.

The newly identified rickettsia-like protozoan thought to be responsible for withering foot syndrome in abalone could drastically affect both the commercial and recreational abalone fishery. While it is uncertain if this organism is introduced, it first became evident through clinical symptoms in 1986. The introduced sabellid worm could also impact abalone stocks if this species becomes established in the wild.

The toxin producing red tide dinoflagellates restricts shellfish harvesting and, as mentioned previously, also raiseshuman health concerns regarding seasonal bioaccumulation of toxin. The burrowing isopod, *Sphaeroma quoyanum*, burrows into any soft substrate and can destroy softened wood docks and other floating structures. Two Russian jellyfish, *maeotias inexspectata* and *Blackfordia virginica*, have been introduced elsewhere and could find their way to California. All of these introduced species have the potential to interfere with recreational and commercial fishing, birding, swimming, and boating.

Many nonindigenous species have the ability to colonize boat hulls and floating structures. The increased drag and weight can result in significantly higher fuel costs and even threaten the stability of floating structures and docks. Species of primary concern in this regard include the zebra mussel (*Dreissena polymorpha*), the Mediterranean mussel (*Mytilus galloprovincialis*), quagga mussels (*Dreissena bugensis*), and the colonial ascidians (*Ciona intestinalis, C. savignyi, Styela clava, S. plicata, Symplegma reptans* and *Microcosmus squamiger*).

Control Costs

Species identified as having significant control costs include all of the previously mentioned introduced freshwater plants. In addition, *Spartina alterniflora* is becoming well established; and experience from Washington and Oregon suggests that control efforts will be costly and ongoing.

Controlling the zebra and quagga mussels, *Dreissena polymorpha* and *D. bugensis*, is estimated to have cost more than $100 million in the Great Lakes region since 1988. Similar or greater expenditures should be anticipated if these species become established in California.

Other species with significant control costs for removal are fouling ascidians, such as *Ciona intestinalis, C. savignyi, Styela clava, S. plicata, Symplegma reptans*, and *Microcosmus squamiger.* The sabellid worm presently affecting abalone culture facilities has caused some businesses to fail and resulted in serious losses to others. The mussel *Musculista senhousia*, which damages eelgrass beds, and the northern pike and white bass, which could affect fisheries and aquatic communities, would be costly to control.

Ecological Impacts Of Control Measures

In addition to the financial burden, serious concern was expressed about the environmental impacts of control and eradication measures. The following species were identified in these discussions, but this concern would be relevant to any species whose control involves mechanically disrupting habitat or the use of pesticides:

Hydrilla verticillata, *Egeria densa*, *Myriophyllum aquaticum*, *Eichornia crassipes*, *Myriophyllum spicatum*, *Spartina alterniflora* and *Lythrum salicaria* are all controlled using wetland and aquatic herbicide applications. The freshwater northern pike was recently eradicated from a California lake using a rotenone solution. The use of molluscasides is one management tool for the control of zebra mussels.

Impacts On Habitat, Water Flow, And Agriculture

The following species were identified as having adverse economic impacts because they cause habitat alteration, erosion, or restriction of water flow due to fouling and burrowing activities:

All of the introduced freshwater plants, including hydrilla (*Hydrilla verticillata*), elodea (*Egeria densa*), parrot feather (*Myriophyllum aquaticum*), water hyacinth (*Eichornia crassipes*), and Eurasian watermilfoil (*Myriophyllum spicatum*), are capable of seriously impairing irrigation distribution systems by forming dense mats.

Zebra mussels (*Dreissena polymorpha*) have fouled and completely clogged water intake pipes of up to 12 inches in diameter at power plants and municipal water facilities in the Great Lakes Region. Zebra mussel control has cost the region an estimated $100 million since 1988. This species could seriously impede water flow in canals and pipes of the California Water Project.

Eastern cordgrass (*Spartina alterniflora*) can cause major alterations in mud flat and estuarine habitats, which can affect bird abundance and behavior and potentially impact other aspects of estuarine communities and food webs. The conversion of intertidal mudflat habitat to cordgrass marsh would remove much of the feeding areas for migratory waterfowl using the Pacific flyway and also eliminate habitat utilized by juvenile fish and invertebrates, such as halibut and Dungeness crab.

The Asian clam (*Corbicula fluminea*) has dramatically altered the phytoplankton abundance at the base of the food web. This dramatic habitat alteration will reverberate through higher trophic levels with unpredictable results.

The introduced protozoan *Myxosoma cerebralis* has caused enormous losses in both wild and hatchery populations of salmonid fishes. Originally introduced to the Eastern United States from Europe, this pathogen is now present in most states.

Aquaculture

The introduced sabellid worm and the withering foot rickettsia seriously impair abalone growth and survival. The zebra mussel would be an unwanted resident in freshwater aquaculture systems where it would occlude pipes and foul tank walls. Shellfish growers are concerned about the rapid spread of the green crab, which preys on cultured clams and oysters. If green crab predation can be controlled, then shellfish farmers must fear the conversion of their intertidal growing areas to cordgrass marsh if the alien cordgrass *Spartina alterniflora* is allowed to flourish.

Commercial Fisheries

Competition for phytoplankton between native zooplankton and introduced clams could dramatically reduce the recruitment of some commercially important fishes such as halibut, salmon, sturgeon and striped bass. Many other introduced species can affect commercial fisheries through predation, habitat alteration and competition. Some examples follow.

The green crab preys on young Dungeness crab and in the future might cause a decline in this important commercial fishery in California and the Pacific Northwest. The Chinese mitten crab and its larvae compete for food with and prey on juvenile fish and invertebrates while modifying habitat through burrowing activities. Sabellid worms could impair abalone fisheries if they became established in the wild, while the striped bass competes with and preys on native fish including salmonids. The burrowing isopod *Sphaeroma* could impact fish populations through habitat alteration resulting from its burrowing activities.

Effects On Ecosystem Processes And Community Structure

The means by which nonindigenous species can alter ecosystem processes and community structure include competition for food and habitat, predation, and habitat alteration. Some of these are direct effects, such as physical competition for space. Others are indirect, as in the case of alterations in energy availability and flow via nutrient cycling through different trophic levels. The following species were identified as having significant potential to alter community structure, species diversity, and abundance:

Mytilus galloprovincialis, Philine auriformis, Morone chrysops, Hydrilla verticillata, Egeria densa, Myriophyllum aquaticum, Eichornia crassipes, Myriophyllum spicatum, Spartina alterniflora, Lythrum salicaria, Aurelia "aurita," Maeotias inexpectata, Blackfordia virginica, Sphaeroma quoyanum, Eriocheir sinensis Potamocorbula amurensis, Dreissena polymorpha, Carcinus maenus, Dreissena bugensis, Musculista senhousia, Ilyanassa obsoleta, Rana catesbiana, Morone saxitalis, Trochammina hadai, Littorina saxatilis, Mnemiopsis leidyi, and the colonial ascidians *Ciona intestinalis, C. savignyi, Styela clava, S. plicata, Symplegma reptans,* and *Microcosmus squamiger.*

Outreach Education Needs

There were numerous suggestions for general outreach efforts to increase the level of awareness about nonindigenous species in society as a whole. Other suggestions were more specific. The ideas resulting from brainstorming sessions have been sorted into the general headings below, though many are applicable to more than one category. The order of categories and topics is not meant to reflect priorities.

General Recommendations

- Establish an exotic species website.
- Establish priorities and coordinate between education and research priorities.
- Increase research support to evaluate the effectiveness of outreach approaches.
- Develop a hot list of high-profile exotics and obtain and distribute pictures of major invaders, such as the ascidian *Microcosmus squamiger*.
- Develop television spots on alien aquatic species.
- Encourage people to write to the U.S. Fish and Wildlife Service on behalf of continuedfunding for the Aquatic Nuisance Species Digest.

Targeted Recommendations

General Public

- Work toward establishment of an Exotic Species Week to increase public awareness.
- Educate the public about the problems created by introduced species, including their modes of introduction and the consequences (e.g., the impacts of moving live mitten and green crabs from one watershed to another).
- Educate the Asian community regarding release of live exotics.
- Educate anglers about the effects of translocating sportfish and baitfish and about appropriate methods for disposing of exotic bait worms and bait packing materials such as seaweed.

Decision-Makers

- Educate elected officials and management agencies about specific impacts, such as the potential for sabellid release in the wild.
- Educate elected officials and management agencies about potential public health concerns, such as those relating to the Chinese mitten crab.

Students/Teachers

- Educate lower grades on the types and importance of exotic species.
- Develop teacher education packets for K-6.
- Publish a book about exotic marine species for elementary school children.

Industry/Stakeholders

- Include enclosures on exotic species with boater registration mailings.

- Provide education and outreach to ports and shipping companies.
- Educate ship operators about ballast water issues.

Outreach on Zebra Mussels

- Educate Western states on the potential impact of zebra mussels.
- Educate boaters, decision makers, and the general public about potential avenues for zebra mussel importation, transport, and dispersal.
- Create zebra mussel education and outreach efforts at state and regional levels (including distribution of pictures of Zebra mussels to boaters).
- Notify commercial boat transport companies about zebra mussel concerns.

Management Needs

Workshop participants identified numerous management needs during a brainstorming session. Suggestions were grouped into basic categories as outlined below. The order of categories and topics is not meant to reflect priorities.

Prevention

- Make it a first priority to "stop 'em before they get here."
- Manage aquaculture to prevent introductions to culture facilities and the environment.
- Deal with discharge from aquaculture, live markets, and importers (in particular, as a means to prevent escapement of the sabellid worm into the wild).
- Continue inspection programs for boats and trailers at key sites.
- Develop zebra mussel regulations prohibiting importation.
- Provide management of bait imports to prevent invasions of exotic species.

Coordination and Management

- Coordinate state and regional NIS management.
- Refine and improve prioritization process for addressing issues involving nonindigenous species, including agencies, non-governmental organizations, and universities.

Control and Eradication

- Initiate a concerted effort to eradicate *Spartina* from San Francisco Bay.
- Eradicate *Littorina saxatilis*.
- Eradicate or control nonindigenous plants early, before they spread.
- Monitor abalone culture and initiate sabellid control and eradication.
- Work to develop a gel herbicide for introduced cordgrass.
- Test biological control agents for Egeria densa, Eurasian watermilfoil, and water hyacinth.
- Explore possibilities for developing fisheries for pests such as the mitten crab.

Ballast Water Management

- ♦ Implement ballast water regulations and establish monitoring protocols.
- ♦ Develop cooperative agreements with international monetary organizations for control and monitoring of ballast water discharges.
- ♦ Extend the 1996 NIS Act to cover intracoastal shipping.
- ♦ Subsidize industry to implement ballast management practices.
- ♦ Have new ballast tanks pre-piped to be ready for whatever treatment is found to work.

Research Needs

The research needs identified by workshop participants are grouped in broad categories below. The order of categories and topics is not meant to reflect priorities.

Taxonomy

* Initiate research on nonindigenous species by a team that includes broad taxonomic expertise.
* Fund research on taxonomic relationships.
* Develop a network of taxonomers to identify invaders.
* Develop techniques for molecular and chemical taxonomy.

Community Level Research Needs

* Include the shorebirds and changing benthic communities in research.
* Study community resistance to impacts of nonindigenous species and possibilities for enhancing ecological resistance to invasions (e.g., the responses of aquatic plants to changes in sediments).
* Evaluate the potential for introduction of human diseases and parasites.
* Determine the impacts of introduced parasites.
* Establish long-term monitoring of key indicator species.
* Determine the impact of green crabs on Dungeness crab stocks.
* Compare the different roles of nonindigenous species in native and invaded habitats.
* Review the interactions between aquatic plants and fish.
* Continue to research bioaccumulation and the impacts of NIS.
* Examine contaminant accumulation potential of future introduced species.
* Evaluate herbicides and potential impacts on the benthic community.
* Conduct field and laboratory studies on the range and physical interactions of introduced and native species, such as green crab predation on shellfish .
* Study the potential for hybridization between native and introduced species.

Introduction and Dispersal

* Collect information on vectors such as bait transport, live food markets, aquaculture.
* Document the history of trade and shipping routes and their role as dispersal vectors.
* Document what species are threats in foreign ports.
* Determine if the Sabellid worm has become established in offshore areas.
* Document Sabellid escapement potential.
* Determine worldwide distribution and spread of introduced species.
* Compile information on failed introductions.

Ballast Water Research

* Evaluate treatment of ballast water using heat, ultraviolet radiation, or filtration.
* Develop methods to verify that ballast exchange has actually occurred (e.g., study indicator species to help in policing ballast exchange).
* Identify what is in ballast water.
* Study alternatives to ballast water exchange.
* Develop effective control measures and enforceable and verifiable compliance monitoring for ballast water.
* Identify where ballast water is coming from and how much is being transferred.

Control and Eradication

* Develop Sabellid worm control and eradication methods.
* Develop control measures for green crabs and zebra mussels.
* Develop methods to control or replace seaweed shipped with bait worms.
* Conduct research on eradication methods for *Littorina saxatilis.*

Nonindigenous Species Monitoring

* Monitor urban lagoons and other potential incubators of nonindigenous species.
* Conduct baseline studies and develop faunal lists.
* Monitor Chinese mitten and green crabs.

Species Specific Research

* Establish physiological tolerances of nonindigenous species to parameters such as temperature and salinity.
* Investigate the biology, ecology, and impacts of the most threatening pest species.
* Do quantitative experiments on *Sphaeroma* burrowing.
* Determine the impact of mitten crab burrowing in the San Francisco Bay Delta.

Closing Comments

The issues surrounding nonindigenous species are exceedingly complex. Workshop participants stressed that conducting long-term research to answer questions posed by managers and ecologists is important but especially difficult, given the rapidly changing nature of many invaded ecosystems and the number of environmental variables involved. However, despite these difficulties, they felt it essential that nonindigenous species be investigated in the larger context of the ecosystems in which they reside.

There was agreement on the eventual need to prioritize species, issues, and needs, but participants felt that the workshop had been too short to allow them sufficient time to attempt this in any meaningful way. Thus, the issues along with outreach, management and research needs identified during discussion and brainstorming sessions should not be viewed as definitive nor should they be used to influence funding priorities.

Those in attendance suggested that a subcommittee be formed to develop a strategy for continued action and that a second meeting be organized, with larger numbers of participants, but with fewer formal presentations and more time for discussion.

Workshop participants expressed great concern over the lack of knowledge about nonindigenous species at all levels of society, from the general public to regulators and legislators. They agreed that there was a pressing need for more educational outreach as well as for greater coordination at the local, state, regional, national, and international levels. Fortunately, the passage by Congress in late 1996 of the National Invasive Species Act provides a framework for regional and national coordination. This legislation should provide a catalyst to increase the level of awareness of nonindigenous species and their potential impacts among a broader audience.

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