INVASIVE MARINE EXOTICS AS A GROWING INTERNATIONAL PROBLEM

THE INVASION OF THE ESTUARIES

Andrew N. Cohen, San Francisco Estuary Institute, 1325 South 46th Street, Richmond, CA 94804 USA
acohen@sfei.org

Abstract

Exotic organisms may pose the greatest single threat to the biological diversity of the world's coastal regions, along with potential impacts on regional economies and public health. Estuaries, bays and harbors throughout temperate latitudes are increasingly recognized as containing a substantial component of nonindigenous organisms, with a smaller but growing number of exotics reported from open coast environments. Effects in the San Francisco Estuary indicate the potential scale of such invasions, where exotic species now dominate in several
habitats and biotic assemblages, while the rate of invasion continues to increase. Control efforts have had substantial costs and impacts, with uncertain results. Meanwhile, a variety of transport mechanisms remain virtually or entirely unregulated in terms of preventing species introductions in many parts of the world. With appropriate regulation and enforcement, invasion rates could be substantially reduced.

Introduction

There is a long-standing literary, cultural and, to some extent, scientific tradition that views the earth's marine waters as making up a single, unified, continuous, interconnected system-sometimes described as "the world ocean." However, geographers of the sea have consistently recognized that the organisms inhabiting temperate zone coastal waters are distributed in seven distinct bioregions: four in the northern hemisphere
on the eastern and western shores of the North Atlantic and North Pacific, and three in the southern hemisphere along western Africa, around New Zealand and southern Australia, and around southern South America on both
coasts (Ekman, 1953; Briggs, 1974). These regions, separated from each other by continents, by vast reaches of deep ocean inimical to the survival of coastal organisms, or by zones of tropical temperature, have developed
biotic assemblages in long-term isolation from each other, such that each region has come to host a largely distinct and non-overlapping native biota. Many organisms found in the upper portions of estuaries and restricted to brackish or freshwater environments have even more restricted distributions.

The isolation of these coastal regions, and the evolution of distinct biotas, has enriched our natural, cultural and scientific heritage in several ways. First, the number of species supported by these regions is greater than the number that would have been supported had they been more interconnected, based on what we know of species-area relationships. Second, these separate regions provide scientists with a natural series of
parallel evolutionary experiments, where in different instances we can find related species filling similar ecological roles, related species filling quite different roles, or similar roles filled by unrelated species, creating rich opportunities for comparative studies. Finally, the regions' distinct biotas support regionally distinct cultural practices, and provide diversity that is of scenic, intellectual and culinary interest to travelers.

Unfortunately the movement of coastal organisms around the globe in association with human commerce and travel, and the often indiscriminate release of these organisms into coastal environments, threatens to end the

benevolent biotic isolation of these regions. Furthermore, the incidental transport of coastal organisms appears to be on the increase, related to the globalization of the marketplace and the rapid expansion of international trade. Unless substantial efforts are made to control the transport and release of these organisms, likely consequences include a significant loss of global biodiversity; local or regional alterations in coastal ecosystem structures and functions; disruptions of some human activities and economic systems; and the loss of irreplaceable opportunities for gaining an understanding ofthe forces that govern the structure and evolution of coastal ecosystems.

An invaded estuary

The extent of change that may result from the global transport of coastal organisms is indicated by studies in the San Francisco Estuary. This ecosystem comprises the waters within the reach of the tides in and tributary to San Francisco Bay and the inland Delta of the Sacramento and San Joaquin rivers, including open waters, mudflats and tidal marshes, and regions of fresh, brackish and salt water. Recent studies have identified over 200 nonindigenous species, including plants, protists and invertebrate and vertebrate animals, that have become established in the Estuary. Exotic organisms now account for 40% to 100% of the common species in several communities, whether calculated as a percentage of total species, of individuals or of biomass. These introductions have dramatically altered species composition, habitat structure and trophic dynamics, and have caused direct economic damage measured in the billions of dollars (Cohen and Carlton, 1995).

Although most invasions of marine organisms have occurred in estuaries, bays and harbors, there are increasing reports of invasions from open coast regions. Exotic mussels have recently colonized and often dominate rocky intertidal and subtidal areas in the Carribean and South Africa (Agard et al., 1992; Hockey and Van Erkom Schurink, 1992; Hicks and Tunnell, 1995). Rocky reefs in the Gulf of Maine have been colonized by Pacific Ocean tunicates and bryozoans (Berman et al., 1992; L. Harris, pers. comm.). In California the New Zealand sea slug, introduced to San Francisco Bay by 1992, has spread out from the Bay and is now one of the most commonly collected sea slugs on soft bottoms along the southern California coast (Gosliner, 1995; D. Cadian, pers. comm.).

Control Efforts

To date, considerably more attention and funds have been applied to controlling nonindigenous coastal organisms after they have been introduced than to preventing their introduction in the first place. Several major control efforts have been implemented to block or reduce impacts from nonindigenous organisms in the San Francisco Estuary (Table 1). These efforts have generally been expensive; have entailed harmful environmental side effects and the risk of harmful side effects, including the effects of applying large quantities of biocides, and the ecological risk involved in introducing additional nonindigenous organisms in attempts at biocontrol; have possibly created occupational health risks or public health risks from the application of biocides; and have on occasion been highly controversial, involving protracted lawsuits and threats of lawsuits (Mitchell, 1985; Cohen, 1992; P. O'Brien, A. Jennings, pers. comm.). None of these efforts has yet eliminated a nonindigenous species from the ecosystem, and the extent of control has been variable.

Table 1. Major efforts to control nonindigenous species in the watershed of the San Francisco Estuary

Target Species	Motivation	Control Methods
Water hyacinth *Eichhornia crassipes*	blocks navigation, fouls marinas, fouls water diversions and pumps, blocks water flow in canals, alters fish habitat	annual applications of herbicide glyphosate; release of 3 insect biocontrols; some mechanical removal
Smooth cordgrass	blocks flood channels; prevents	application of herbicide glyphosate;

Spartina alterniflora	establishment of native plants in tidal marsh restoration	mowing; covering; burning
White bass *Morone chrysops*	potential to spread to Delta and prey on rare and endangered fish species	treatment of infested water bodies with the fish poison rotenone
Northern pike *Esox lucius*	potential to spread to Delta and prey on rare and endangered fish species	treatment of infested water bodies with the fish poison rotenone
Red fox *Vulpes vulpes*	preys on endangered California clapper rail	trapping and shooting

Proposed control efforts should be carefully assessed with these issues and limitations in mind. Various considerations suggest that control efforts are in general more likely to be effective and worthwhile if they target plants rather than animals; organisms that are emergent, floating or semi-terrestrial rather than organisms that are submersed or infaunal; and freshwater organisms rather than marine organisms. While efforts at control
will remain appropriate in selected circumstances, it should be recognized that such efforts will generally involve some environmental risk, sometimes human health or economic risk, often considerable expense, and sometimes
public controversy-and, in addition, that they will often fail. Because the costs and impacts of control efforts are multiplied when these efforts are repeatedly applied or applied routinely on a permanent basis, control
should in most cases be attempted only when there is a reasonable likelihood of eradicating the target organisms from the region.

Means of Prevention

Given the costs, impacts and difficulties of controlling nonindigenous species, a greater effort is needed to prevent their introduction. Major vectors introducing exotic species into coastal waters include ships' ballast water; aquaculture and mariculture; the aquarium and ornamental plant trades; and the importation of live seafood and bait. The regulatory actions needed to substantially reduce such introductions are in large part known, and many of them could be promptly put into effect. Such an approach might include:

* **For ballast water**: In the near-term, requiring ships coming from foreign ports to exchange their ballast water over deep ocean water (in at least 2000 meters depth and at least 200 miles from shore) whenever it is
safe to do so. Further reductions could be achieved by developing shore-based ballast water treatment in the medium-term and ship-board treatment in the long-term.

* **For aquaculture and mariculture**: Restricting aquaculture and mariculture to native organisms or organisms that are already established in the wild. Permitting the importing of additional nonindigenous organisms
only in very compelling circumstances and after full public review, and then only with careful inspection and reliable quarantine or with full isolation from the environment. Treating occurrences of new parasites or
disease syndromes in aquaulture or mariculture facilities that are not previously known from the local environment as nonindigenous species (until proven otherwise), and either promptly eradicating them or requiring that
they be kept fully isolated from the environment.

* **For the aquarium and ornamental plant trades**: Restricting commercial imports of aquatic plants and animals to organisms that have been evaluated and determined to be safe for importing. This "clean list"
approach contrasts with the current "dirty list" approach in which any organism may be imported unless it is specifically listed as prohibited (OTA, 1993) Engaging in public outreach (perhaps funded by the aquarium
industry) to persuade people to not release unwanted aquatic pets into the environment. Monitoring and managing commercial holding and rearing facilities to ensure that nonindigenous species are isolated from the
environment.

* **For the live seafood and bait trade**: Restricting the sale of live seafood and bait to native organisms, or to organisms determined to be safe for importing. Engaging in public outreach to persuade anglers not to
release live bait or transfer live bait between watersheds.

The estimated costs to the affected industries of implementing these actions ranges from insignificant costs for some measures to possibly substantial costs for others. However, the certain cost of not implementing these or similar measures is to continue a high and increasing rate of biological invasions in our coastal waters, with likely impacts on biodiversity, ecosystem functions, economic enterprises, human activities and possibly public health.

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