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Nonindigenous Aquatic Species in a United State Estuary:
A Case Study of the Biological Invasions
of the San Francisco Bay and Delta

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Executive Summary

1. The San Francisco Bay and Delta region is a highly invaded ecosystem.

• The San Francisco Estuary can now be recognized as the most invaded aquatic ecosystem in North America. Now recognized in the Estuary are 212 introduced species : 69 percent of these are invertebrates, 15 percent are fish and other vertebrates, 12 percent are vascular plants and 4 percent are protists.

• In the period since 1850, the San Francisco Bay and Delta region has been invaded by an average of one new species every 36 weeks. Since 1970, the rate has been at least one new species every 24 weeks: the first collection records of over 50 non-native species in the Estuary since 1970 thus appear to reflect a significant new pulse of invasions.

• In addition to the 212 recognized introductions, 123 species are considered as cryptogenic (not clearly native or introduced), and the total number of cryptogenic taxa in the Estuary might well be twice that. Thus simply reporting the documented introductions and assuming that all other species in a region are nativeóas virtually all previous studies have doneóseverely underestimates the impact of marine and aquatic invasions on a region's biota.

• Nonindigenous aquatic animals and plants have had a profound impact on the ecology of this region. No shallow water habitat now remains uninvaded by exotic species and, in some regions, it is difficult to find any native species in abundance. In some regions of the Bay, 100% of the common species are introduced, creating "introduced communities." In locations ranging from freshwater sites in the Delta, through Suisun and San Pablo Bays and the shallower parts of the Central Bay to the South Bay, introduced species account for the majority of the species diversity.

2. A vast amount of energy now passes through and is utilized by the nonindigenous biota of the Estuary. In the 1990s, introduced species dominate many of the Estuary's food webs.

• The major bloom-creating, dominant phytoplankton species are cryptogenic. Because of the poor state of taxonomic and biogeographic knowledge, it remains possible that many of the Estuary's major primary producers that provide the phytoplankton-derived energy for zooplankton and filter feeders, are in fact introduced.

• Introduced species are abundant and dominant throughout the benthic and fouling communities of San Francisco Bay. These include 10 species of introduced bivalves, most of which are abundant to extremely abundant. Introduced filter-feeding polychaete worms and crustaceans may occur by the thousands per square meter. On sublittoral hard substrates, the Mediterranean mussel Mytilus galloprovincialis is abundant, while float fouling communities support large populations of introduced filter feeders, including bryozoans, sponges and seasquirts. The holistic role of the entire nonindigenous filter-feeding guildóincluding clams, mussels, bryozoans, barnacles, seasquirts, spionid worms, serpulid worms, sponges, hydroids, and sea anemonesóin altering and controlling the trophic dynamics of the Bay-Delta system remains unknown. The potential role of just one species, the Atlantic ribbed marsh mussel Arcuatula demissa, as a biogeochemical agent in the economy of Bay salt marshes is striking.

• Introduced clams are capable of filtering the entire volume of the South Bay and the northern estuarine regions (Suisun Bay) once a day: indeed, it now appears that the primary mechanism controlling phytoplankton biomass during summer and fall in South San Francisco Bay is "grazing" (filter feeding) by the introduced Japanese clams Venerupis and Musculista and the Atlantic clam Gemma. This remarkable process has a significant impact on the standing phytoplankton stock in the South Bay, and since this plankton is now utilized almost entirely by introduced filter feeders, passing the energy through a non-native benthic fraction of the biota may have fundamentally altered the energy available for native biota

• Drought year control of phytoplankton by introduced clamsóresulting in the failure of the summer diatom bloom to appear in the northern reach of the Estuaryóis a remarkable phenomenon. The introduced Atlantic soft-shell clams (Mya) alone were estimated to be capable at times of filtering all of the phytoplankton from the water column on the order of once per day. Phytoplankton blooms occurred only during higher flow years, when the populations of Mya and other introduced benthic filter feeders retreated downstream to saltier parts of the Estuary.

• Phytoplankton populations in the northern reaches of the Estuary may now be continuously and permanently controlled by introduced clams. Arriving by ballast water and first collected in the Estuary in 1986, by 1988 the Asian clam Potamocorbula reached and has since sustained average densities exceeding 2,000/m2. Since the appearance of Potamocorbula, the summer diatom bloom has disappeared, presumably because of increased filter feeding by this new invasion. The Potamocorbula population in the northern reaches of the Estuary can filter the entire water column over the channels more than once per day and over the shallows almost 13 times per day, a rate of filtration which exceeds the phytoplankton's specific growth rate and approaches or exceeds the bacterioplankton's specific growth rate.

• Further, the Asian clam Potamocorbula feeds at multiple levels in the food chain, consuming bacterioplankton, phytoplankton, and zooplankton (copepods), and so may substantially reduce copepod populations both by depletion of the copepods' phytoplankton food source and by direct predation. In turn, under such conditions, the copepod-eating native opossum shrimp Neomysis may suffer a near-complete collapse in the northern reach. It was during one such pattern that mysid-eating juvenile striped bass suffered their lowest recorded abundance. This example and the linkages between introduced and native species may provide a direct and remarkable example of the potential impact of an introduced species on the Estuary's food webs.

• As with the guild of filter feeders, the overall picture of the impact of introduced surface-dwelling and shallow-burrowing grazers and deposit feeders in the Estuary is incompletely known. The Atlantic mudsnail Ilyanassa is likely playing a significantóif not the most importantórole in altering the diversity, abundance, size distribution, and recruitment of many species on the intertidal mudflats of San Francisco Bay.

• The arrival and establishment in 1989-90 of the Atlantic green crab Carcinus maenas in San Francisco Bay signals a new level of trophic change and alteration. The green crab is a food and habitat generalist, capable of eating an extraordinarily wide variety of animals and plants, and capable of inhabiting marshes, rocky substrates, and fouling communities. European, South African, and recent Californian studies indicate a broad and striking potential for this crab to significantly alter the distribution, density, and abundance of prey species, and thus to profoundly alter community structure in the Bay.

• Nearly 30 species of introduced marine, brackish and freshwater fish are now important carnivores throughout the Bay and Delta. Eastern and central American fish -- carp, mosquitofish, catfish, green sunfish, bluegills, inland silverside, largemouth and smallmouth bass, and striped bass -- are among the most significant predators, competitors, and habitat disturbers throughout the brackish and freshwater reaches of the Delta, with often concomitant impacts on native fish communities. The introduced crayfish Procambarus and Pacifastacus may play an important role, when dense, in regulating their prey plant and animal populations.

• Native waterfowl in the Estuary consume some introduced aquatic plants (such as brass buttons) and native shorebirds feed extensively on introduced benthic invertebrates.

3. Introduced species may be causing profound structural changes to some of the Estuary's habitats.

• The Atlantic salt-marsh cordgrass Spartina alterniflora, which has converted 100s of acres of mudflats in Willapa Bay, Washington, into grass islands, has become locally abundant in San Francisco Bay, and is competing with the native cordgrass. Spartina alterniflora has broad potential for ecosystem alteration. Its larger and more rigid stems, greater stem density, and higher root densities may decrease habitat for native wetland animals and infauna. Dense stands of S. alterniflora may cause changes in sediment dynamics, decreases in benthic algal production because of lower light levels below the cordgrass canopy, and loss of shorebird feeding habitat through colonization of mudflats.

• The Australian-New Zealand boring isopod Sphaeroma quoyanum creates characteristic "Sphaeroma topography" on many Bay shores, with many linear meters of fringing mud banks riddled with its half-centimeter diameter holes. This isopod may arguably play a major, if not the chief, role in erosion of intertidal soft rock terraces along the shore of San Pablo Bay, due to their boring activity that weakens the rock and facilitates its removal by wave action. Sphaeroma has been burrowing into Bay shores for over a century, and it thus may be that in certain regions the land/water margin has retreated by a distance of at least several meters due to this isopod's boring activities.

4. While no introduction in the Estuary has unambiguously caused the extinction of a native species, introductions have led to the complete habitat or regional extirpation of species, have contributed to the global extinction of a California freshwater fish, and are now strongly contributing to the further demise of endangered marsh birds and mammals.

• Introduced freshwater and anadromous fish have been directly implicated in the regional reduction and extinction, and the global extinction, of four native California fish. The bluegill, green sunfish, largemouth bass, striped bass, and black bass, through predation and through competition for food and breeding sites, have all been associated with the regional elimination of the native Sacramento perch from the Delta. The introduced inland silversides may be a significant predator on the larvae and eggs of the native Delta smelt. Expansion of the introduced smallmouth bass has been associated with the decline in the native hardhead. Predation by largemouth bass, smallmouth black bass and striped bass may have been a major factor in the global extinction of the thicktail chub in California.

• The situation of the California clapper rail may serve as a model to assess how an endangered species may be affected by biological invasions. The rail suffers predation by introduced Norway rats and red fox; it may both feed on and be killed by introduced mussels; and it may find refuge in introduced cordgrass, although this same cordgrass may compete with native cordgrass, perhaps preferred by the rail. Other potential model study systems include introduced crayfish and their displacement of native crayfish; introduced gobies and their relationship to the tidewater goby; and the combined role that introduced green sunfish, bluegill, largemouth bass, and American bullfrog may have played in the dramatic decline of native red-legged and yellow-legged frogs.

5. Though the economic impacts of introduced organisms in the San Francisco Estuary are substantial, they are poorly quantified.

• Although some of the fish intentionally introduced into the Estuary by government agencies supported substantial commercial food fisheries, these fisheries all declined after a time and are now closed. The signal crayfish, Pacifastacus, from Oregon, whose exact means of introduction is unclear, supports the Estuary's only remaining commercial food fishery based on an introduced species.

• The striped bass sport fishery has resulted in a substantial transfer of funds from anglers to those who supply anglers' needs, variously estimated, between 1962 and 1992, between $7 million and $45 million per year. However, striped bass populations and the striped bass sport fishery have declined dramatically in recent years.

• Government introductions of organisms for sport fishing, as forage fish and for biocontrol have frequently not produced the intended benefits, and have sometimes had harmful "side effects," such as reducing the populations of economically important species.

• Few nonindigenous organisms that were introduced to the Estuary by other than government intent have produced economic benefits. The clams Mya and Venerupis, both accidentally introduced with oysters, have supported commercial harvesting in the Bay or elsewhere on the Pacific coast, and a small amount of recreational harvesting in the Bay (though these clams may have, to some extent, replaced edible native clams); the Asian clam Corbicula is commercially harvested for food and bait in California on a small scale; the Asian yellowfin goby is commercially harvested for bait; muskrat are trapped for furs; and the South African marsh plant brass buttons provides food for waterfowl. There do not appear to be any other significant economic benefits that derive from nongovernmental or accidental introductions to the Estuary.

• A single introduced organism, the shipworm Teredo navalis, caused $615 million (in 1992 dollars) of structural damage to maritime facilities in 3 years in the early part of the 20th century.

• The economic impacts of hull fouling and other ship fouling are clearly very large, but are not documented or quantified for the Estuary. Most of the fouling incurred in the Estuary is due to nonindigenous species. Indirect impacts due to the use of toxic anti-fouling coatings may also be substantial.

• Waterway fouling by introduced water hyacinth has become a problem in the Delta over the last fifteen years, with other introduced plants beginning to add to the problem in recent years. Hyacinth fouling has had significant economic impacts, including interference with navigation.

• Perhaps the greatest economic impacts may derive from the destabilizing of the Estuary's biota due to the introduction and establishment of an average of one new species every 24 weeks. This phenomenal rate of species additions has contributed to the failure of water users and regulatory agencies to manage the Estuary so as to sustain healthy populations of anadromous and native fish, resulting in increasing limitations and threats of limitations on water diversions, wastewater discharges, channel dredging, levee maintenance, construction and other economic activities in and near the Estuary, with implications for the whole of California's economy.

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