(B) THE ECONOMIC IMPACTS OF BIOLOGICAL INVASIONS IN THE SAN FRANCISCO ESTUARY

The economic impacts of introduced marine, estuarine and aquatic organisms have been little studied and rarely quantified. It is clear, however, that these impacts have been substantial in the San Francisco Estuary.

These impacts are of several interrelated and intergraded types. Positive impacts have included the value of food resources and recreational (sportfishing) resources provided by some introductions of fish and shellfish; the biological control of nuisance insect populations (e. g. by mosquitofish); and fish and wildlife enhancements such as the provision of food, habitat or other resources for valued species (Table 6). Major negative impacts have included the fouling and blocking of waterways and water delivery systems; damage to or impairment of maritime structures and vessels (e. g. damage to wharves, docks, ferry slips and ships' hulls by marine wood-boring organisms; increased fuel and maintenance requirements resulting from hull fouling); disruption or impairment of vital services; damage to populations of economically important fish and wildlife species; the costs (both direct and indirect) of control efforts; and the inability, in the face of continuous new introductions, to adequately manage the Estuary's ecosystem, resulting in restrictions on activities in and near the Estuary (Table 7). We discuss certain of these impacts below.

1. EXAMPLES OF POSITIVE ECONOMIC IMPACTS FROM INTRODUCTIONS TO THE ESTUARY

(a) Food and Sport Resources

Skinner (1962) and Smith & Kato (1979) review the history of the fisheries in the Estuary. Although the introduced striped bass, American shad, white catfish, bullfrog, signal crayfish (*Pacifastacus leniusculus*) and soft-shell clam (*Mya arenaria)* all supported commercial fisheries in the Estuary in the past, only the crayfish is still commercially harvested today. These species and others, including many warm-water gamefish introduced to the Delta, continue to provide sport fisheries.

Striped bass and shad supported large commercial fisheries during the late 19th and first half of the 20th century. Striped bass were introduced in 1879 and sold in San Francisco markets by 1889. The annual catch topped 500 tons by 1899, peaked at 1,000 toms in 1903, and generally stayed over 500 tons until 1918. The commercial fishery then declined and was closed in 1935 to avoid competition with sport fishing (Skinner, 1962; Smith & Kato, 1979).

Shad were introduced in 1871, commercially harvested by 1874, and glutting the market by 1880 (Skinner, 1962). From 1900 to 1945 the Bay Area catch was often over 500 tons, and peaked at over 2,800 tons in 1917 (Skinner, 1962; Herbold & Moyle, 1989). The fish were mainly sold fresh until 1912, and thereafter salted and export to China, with the roe salted and canned; the size of the fishery was said to be limited by demand rather than by the abundance of shad. After 1945 the catch averaged around 300 tons until the fishery was eliminated in 1957 by a ban on gill-netting inside the Golden Gate (Shebley, 1917; Skinner, 1962; Smith & Kato, 1979).

Table 6. Positive Economic Impacts of Marine, Estuarine and Aquatic Organisms Introduced into the San Francisco Estuary

Details and references are provided in the species descriptions in Chapter 3.

ORGANISMS CAUGHT FOR FOOD, FUR OR SPORT

- Striped bass, American shad and catfish supported commercial fisheries in the Estuary that were sometimes substantial, until commercial fishing for these species in the Estuary was banned.
- The above species, plus black bass, crappie, sunfish and carp support recreational fisheries in the Estuary.
- Crayfish are taken from the Delta both commercially and recreationally.
- The bullfrog *Rana catesbeiana* has been both raised in ponds and harvested from public waters in California.
- The Asian littleneck clam *Venerupis philippinarum* and sometimes the Atlantic soft-shell clam *Mya arenaria* are taken recreationally. *Venerupis* is harvested commercially in the Pacific northwest and sold in Bay Area markets as "Manila clams." A few other introduced molluscs are sometimes recreationally harvested from the Bay.
- The Asian freshwater clam *Corbicula fluminea* is sometimes taken recreationally from the Delta. *Corbicula* are harvested commercially from Lake Isabella in the southern end of the Delta's watershed.
- The Asian freshwater snail *Cipangopaludina* was imported and sold in Asian markets in the late 19th century, and was reportedly planted in the Bay Area and the Central Valley "to supply the markets of San Francisco Bay."
- Watercress is an edible green which no doubt is sometimes harvested recreationally.
- Muskrat are trapped for their fur.

BAIT

- The golden shiner and fathead minnow are commercially raised as legally-designated freshwater bait fish in California.
- The yellowfin goby is commercially and recreationally harvested for use as bait, primarily for the introduced striped bass.
- The freshwater Asian clam *Corbicula* is harvested commercially and recreationally for bait.
- Introduced crayfish and bullfrog are caught recreationally for use as freshwater bait.
- Various other introduced fish (e. g. inland silverside) and invertebrates (e. g. the mussel *Mytilus galloprovincialis*) are sometimes used for bait.

BIOCONTROL

- The mosquitofish *Gambusia affinis* contributes to the control of mosquitoes. However, introductions of other species for biocontrol purposes (e. g. blue catfish to control the introduced clam *Corbicula*, South American *Neochetina* weevils to control water hyacinth) appear to have had no significant control effect, and have sometimes harmed desirable species (e. g. inland silverside *Menidia beryllina*).

EROSION CONTROL

- According to one study, the Atlantic cordgrass *Spartina alterniflora* may be reducing erosion at San Bruno Slough.

Table 6. Positive Economic Impacts - continued

ENHANCEMENT OF ECONOMICALLY IMPORTANT FISH AND WILDLIFE

- The South African brackish-marsh plant brass buttons provides food for waterfowl and refuge; marshes are sometimes managed to encourage its growth.
- The Atlantic cordgrass Spartina *alterniflora* might provide much-needed cover for the endangered California clapper rail.
- Threadfin shad were introduced to provide forage for sport fish, although there is doubt about how useful they are as forage; to the extent that they do provide forage they may have simply replaced native species; and some researchers believe that they may in fact compete with young sport fish and reduce the populations of sport fish.
- Many pelagic and benthic marine invertebrates form part of the trophic webs that support recreationally and commercially important fish, but may have simply replaced native invertebrates in this role.

White catfish were introduced in 1874. In 1875 the California Fish Commission predicted that they would support a commercial fishery by the following year, and in 1877 reported that they constituted an "important addition to the fish food supply of the city of Sacramento," further described in 1879 as "an immense supply of food" (Smith, 1896). By 1900 catfish were being exported to Mississippi. The Bay Area's reported annual catch of catfish ranged between 100 and 500 tons from 1905 to 1951 (Skinner, 1962), but the fishery was closed in 1953 due to declining numbers of fish(Miller, 1966a; Borgeson & McCammon, 1967).

The soft-shell clam was first collected in the Bay in 1874 and by the 1880s was the most common clam in Bay Area markets (Stearns, 1881), and public and private soft-shell clam beds were established and managed throughout the Bay (Bonnot, 1932). The annual catch in the Bay Area (including bays north to Bodega) was 500 to 900 tons in 1889-1899, 50-150 tons in 1917-1935, and then declined until the fishery closed in 1948, for reasons that are now unclear but could involve a decline in the resource or market competition from other clams (Skinner, 1962; Herbold et al., 1992). Several workers have suggested that the soft-shell clams' early abundance in San Francisco Bay was due to replacement of populations of the native bent-nose clam *Macoma nasuta*.

It is unclear when signal crayfish were introduced to California, but commercial harvest began in the Delta in 1970 to supply the Swedish market (after the native Swedish crayfish was decimated by an introduced North American crayfish disease). Initial landings of 50 tons rose to over 250 tons from 1975 to the 1980s (Osborne, 1977; Herbold & Moyle, 1989). The 1976 catch sold for a little over $300,000 (Osborne, 1978).

Striped bass has been the economically most important sport fish in the Estuary, accounting for a substantial transfer of funds, variously estimated, from those who do the fishing to those who help them fish. Skinner (1962, p. 172) reported that striped bass anglers were spending about $18 million per year on the sport. McGinnis (1984) reported that anglers took about 1 million striped bass in

1980, spending about $7 million in the process. Herbold et al. (1992) reported that the industries surrounding striped bass fishing (involving boats, marinas, and fishing equipment and supplies) were estimated to inject $45 million into local economies.

(b) Forage Fish

Several small fish have been introduced to California in part to provide forage for larger sport fish, including the threadfin shad. However, there has been considerable disagreement over the value of the threadfin as forage (ranging, according to different authors, from "major" and "important" to "minor" and "inadequate"), and its overall impact on sport fish (involving competition with young sport fish for food), as reviewed in Chapter 3.

2. EXAMPLES OF NEGATIVE ECONOMIC IMPACTS FROM INTRODUCTIONS TO THE ESTUARY

(a) Wood Boring

Mare Island, in the upper part of San Francisco Bay, was chosen as the site for a naval base partly in order to get upstream of the Bay's marine wood-boring organisms. However, the introduction of the shipworm *Teredo navalis*, which tolerated much fresher water than did the Bay's existing wood borers, led to the destruction of some fifty major wharves, ferry slips and other structures in the northern part of the Estuary between 1919 and 1921, including several at Mare Island (Figure 8).

Neily (1927) reported the damage to amount to $25 million, which, escalated to current (1992) dollars (based on the Engineering News Record: General Construction Cost Index; US Commerce Dept., 1975, 1984, 1993) is $616 million dollars. Although this figure does not include collateral damage (such as loaded freight cars that fell into the Bay when a railroad dock collapsed), disrupted service and lost business, or the subsequent costs of constructing, treating and maintaining structures to be resistant to *Teredo*, nor does it include damage from *Teredo* since 1921 or in other parts of the Bay, it does provide some quantification of the scale of potential economic impact from a single introduced organism.

Other introduced wood-borers in the Bay are the shipworm *Lyrodus pedicellatus*,, and the isopods *Limnoria tripunctata* and *L. quadripunctata*, and *Chelura terebrans*. Although modern, chemically-treated pilings, marine timbers and marine wood products are considerably more resistant to borer infestations than untreated wood, borer damage continues to occur to the Bay's wooden pilings, docks and boat hulls. However, no current estimates of this damage are available.

(b) Ship Fouling

Hull fouling and other ship fouling have a large but generally little-recognized economic impact. For example, Gordon & Mawatari (1992) report estimates that a coating of slime 1 mm thick on an otherwise clean hull can increase skin friction up to 80 percent and reduce speed up to 15 percent, an estimate

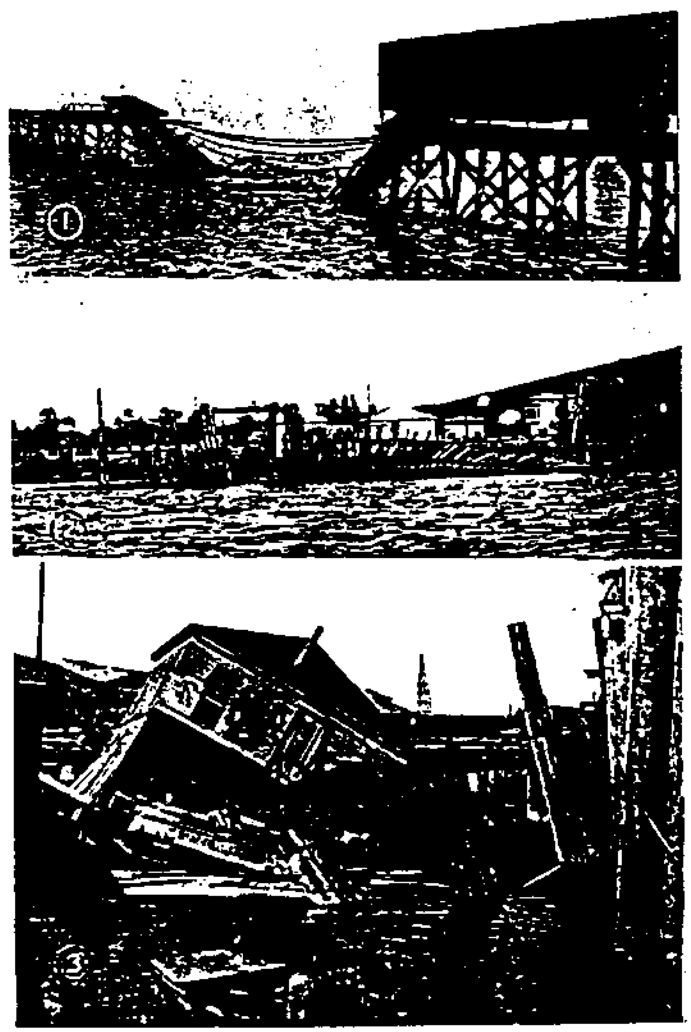
Figure 8. Some Examples of Damage Caused by the Wood-boring Shipworm *Teredo navalis* in the San Francisco Estuary

From Neily, 1927.

(1) Failure of dock at Oleum, Contra Costa County, Oct. 8, 1919, dumping several loaded freight cars into San Francisco Bay.

(2) Collapse of the South Vallejo Ferry Slip, Solano County, Nov. 4, 1920.

(3) Collapse of the Benicia Municipal Wharf and House, Oct. 7, 1920.



generally borne out by towing tests (WHOI, 1952). Ross & Emerson (1974) calculated that "a luxuriant growth of barnacles on a one-square-foot area of a ship may weigh as much as six pounds. On a large ship, the barnacles and other fouling organisms can add as much as three hundred tons to a ship's weight...a heavily fouled ship may need as much as 50 percent more fuel to move the same distance." In 1928 it was reported that U. S. shipping interests spent $100 million annually dealing with fouling (WHOI, 1952, citing Visscher, 1928). In the 1940s, the British Admiralty estimated that hull fouling on naval vessels increased fuel consumption by 35% to 50% after six months in temperate waters or after three months in tropical waters (WHOI, 1952). More recently, Haderlie (1984) reported that "all classes of [U. S.] naval ships show a ten percent average yearly increase in fuel consumption between dry dockings, and...most or all of this is due to increased drag caused by hull and propeller fouling." He further reported that in 1975 the U. S. Navy spent $15 million a year applying antifouling coatings to its vessels, but that despite this "the increased drag from hull fouling was adding over $150 million to the navy's annual fuel bill."

Hull fouling can thus result in a significant loss of maximum speed and maneuverability, increased fuel consumption and decreased range, as well as necessitating increased maintenance and more frequent drydockings—issues of concern to all vessels but especially to military vessels (Haderlie, 1984). WHOI (1952) and Haderlie (1984) reported other impacts of ship fouling, including blocked fire mains; restricted or blocked flow to the main condensers serving the ship's engines, preventing the development of full power; other fouled seawater pipe systems, sometimes requiring the complete dismantling of these systems; fouled propellers causing increased vibration on board ship and loss of power; increased hull corrosion; fouled sonar domes causing degradation of performance due to reduced sound transmission and reception, increased self-noise due to turbulence, and interference with mechanical operation; and increased self-noise of the ship hull, a problem for military ships seeking to evade detection by enemy sonar.

Such considerations have lead to the development and widespread use of anti-fouling compounds containing tributyltin (TBT), copper, mercury, arsenic and other materials which are toxic both to fouling and to nontarget marine organisms, and to those working with these compounds. The cleaning and maintenance of TBT-coated hulls has contributed to the creation of toxic "hot spots" in the Estuary.

Though ships may be fouled by both native and non-native organisms, virtually all of the common fouling organisms in San Francisco Bay are introduced (e. g. Graham & Gay, 1945; Banta, 1963; ANC & JTC, pers. obs.). Thus fouling impacts for vessels spending much of their time in San Francisco Bay are largely due to introduced species.

(c) Waterway Fouling

The fouling of Delta waterways by water hyacinth became serious enough by the early 1980s to block ferry boats from reaching Bacon Island and prevent the island's produce reaching the market. In 1982 the California Legislature passed a bill ordering the control of water hyacinth in the Delta. Control efforts included setting up barriers to keep masses of hyacinth out of navigation channels, spraying

Table 7. Negative Economic Impacts of Introduced Marine, Estuarine and Aquatic Organisms

A. Examples in the San Francisco Estuary

Details and references are provided in the species descriptions in Chapter 3.

WATERWAY FOULING	
• Water hyacinth *Eichhornia crassipes* • European milfoil *Myriophyllum spicatum* • Elodea *Egeria densa*	• Navigational and recreational impacts include blocking passage through navigable waterways and access to marinas and berths, and fouling propellers and the water intakes of boat engines; impacts have been serious enough to shut down marinas and bar ferry boats from their routes. • Interference with salmon migration. • Costs of herbicide applications (including environmental and occupational health impacts). • Costs of biocontrol efforts. • Costs of mechanical removal and disposal.
FOULING OF VESSELS AND MARITIME STRUCTURES	
• Many kinds of plants and animals, including seaweeds, sponges, hydroids, tubeworms, mussels, barnacles, bryozoans and sea squirts	• Increased frictional resistance of ship and boat hulls, resulting in slower speeds, increased transit times, increased fuel costs, reduced maneuverability, and reduced effectiveness of military vessels. • Cost of anti-fouling coatings. • Costs of pollution from the use of anti-fouling compounds formulated with tributyltin, copper, mercury, creosote or other toxic materials. • Occupational health costs of manufacturing, applying and maintaining coatings of anti-fouling compounds formulated from toxic materials. • Other increased maintenance costs, including the cost of time spent in drydock rather than in service.
WOOD BORING	
• Shipworms *Teredo navalis* and *Lyrodus pedicellatus* • Isopods *Limnoria* spp. and *Chelura terebrans*	• Damage to wooden maritime structures and vessels. • Disruption of service. • Increased maintenance costs. • Increased construction costs. • Impacts from the use of toxic anti-fouling compounds, as noted above.
BURROWING	
• Muskrat • Crayfish *Orconectes* and *Procambarus* • Isopod *Sphaeroma* • Chinese mitten crab	• Damage to levees, the walls of ditches, stream banks and shorelines.
• Isopod *Sphaeroma*	• Damage to styrofoam flotation of marina docks.

Table 7. Negative Economic Impacts - continued

FOULING OF WATER SYSTEMS	
• *Corbicula* , and to a minor degree, *Urnatella* and *Cordylophora*	• Increased sedimentation in canals reducing flow rates. • Increased maintenance costs.
• *Water hyacinth*	• Fouled irrigation pumps and fish screens.
PREDATION ON AND COMPETITION WITH ECONOMICALLY IMPORTANT SPECIES	
• Many species of fish • Crayfish *Orconectes virilis* and *Pacifastacus leniusculus* • Bullfrog *Rana catesbeiana*	• Reduction of populations of commercial and sport fish. • Elimination of the Sacramento perch *Archoplites interruptus*, a sport fish, from its native waters. • Reduction in populations of certain native fish, crayfish and frogs contributing to their listing or potential listing as threatened or endangered species, resulting in: - interference with water diversions, including restrictions on the location, timing and volume of diversions and on the construction of new diversion facilities; - interference with other construction and development projects, both inside and outside the Estuary, • Costs of control efforts, such as rotenone applications. • Kills of nontarget sport fish from rotenone applications. • Occupational and environmental health costs of rotenone use.
• Atlantic oyster drill *Urosalpinx cinerea* and odostomiid snail *Boonea bisuturalis*	• Predators or parasites on oysters, clams and mussels.
PROMOTION OF UNDESIRABLE SPECIES	
• Parrot's feather *Myriophyllum aquaticum*	• Said to provide excellent mosquito habitat.
CROP DAMAGE	
• Crayfish *Orconectes virilis* and *Procambarus clarkii*	• Eat rice shoots, as apparently does the recently introduced Chinese mitten crab *Eriocheir sinensis* in China.
INTERFERENCE WITH WATER QUALITY MONITORING	
• Mussel *Mytilus galloprovincialis*	• Fifteen years of estuarine water quality monitoring, based on comparing contaminant levels in the same species of mussel in different bays, may have been rendered questionable by the introduction of this second and virtually indistinguishable species of mussel which may take up and metabolize contaminants at a different rate.

Table 7. Negative Economic Impacts - continued

ECOSYSTEM INSTABILITY/MANAGEMENT UNCERTAINTY	
• Continuous high rate of introductions	• New species continually being introduced into the Estuary's biota resulting in unmanageable fluctuations in populations of important species, in turn resulting in added restrictions on many activities (including water diversions, wastewater discharges, dredging, levee maintenance, construction) in and near the Estuary.
B. Some Examples from Elsewhere	
FOULING	
• Zebra mussel *Dreissena polymorpha*	• The European zebra mussel was introduced to the Great Lakes in ballast water in 1986 and rapidly spread to 14 states and 3 Canadian provinces. - It has seriously fouled and in some cases caused the complete blockage of the water intakes for municipal water systems, industrial process water systems, and cooling water systems for power plants. It has incurred costs through the disruption of services; increased monitoring and maintenance requirements; changes in operations; the retrofitting of existing facilities and added costs in the construction of new facilities to make them less vulnerable to mussel fouling; the construction of redundant facilities to prevent service disruptions; the increased use of chlorine (with attendant occupational, public and environmental health costs). - It has interfered with commerce and recreation by fouling navigational buoys, maritime structures and vessels, with attendant costs. - It has fouled recreational beaches. In the past year, live zebra mussels have been found attached to boats and trailers entering California from the eastern states.
PREDATION ON ECONOMICALLY IMPORTANT SPECIES	
• Green crab *Carcinus maenas*	• This European crab was introduced to the eastern United States in ship fouling and destroyed commercially valuable soft-shell clam (*Mya arenaria*) beds in New England and Maine in the 1950s. Control efforts included fencing, trapping and poisoning. The green crab became established in San Francisco Bay in the late 1980s.

Table 7. Negative Economic Impacts - continued

• Chinese mitten crab *Eriocheir sinensis*	• Introduced in ballast water, this catadromous, burrowing crab became phenomenally abundant in the rivers and upper estuaries of Germany in the 1930s, causing damage to trap and net fisheries and to river banks, leading to a government-sponsored control program that, at its peak, trapped and destroyed tens of millions of crabs per year. The mitten crab became established in San Francisco Bay in the 1990s.
• *Mnemiopsis leidyi*	• Discovered to the Black and Azov seas in the early 1980s, this northwestern Atlantic ctenophore or 'comb jelly' became phenomenally abundant by 1988, decimating the zooplankton and virtually destroying the region's anchovy and sprat fisheries.
DISEASE	
• 'red tide'-forming dinoflagellates and other bloom-forming plankton	• Blooms of dinoflagellates that produce sometimes-lethal paralytic shellfish poisons (PSP) have resulted from introductions of these plankton to Australia and probably other parts of the world.
• Oriental lung fluke	• In China, the mitten crab *Eriocheir sinensis* is the second intermediate host of this debilitating human parasite; human hosts are infected by eating raw or inadequately cooked, infected crabs. With the mitten crab now established in the Bay Area, and snails available that are capable of serving as first intermediate hosts, the lung fluke could become established in California.
• cholera pathogen *Vibrio cholerae*	• In 1991 during the South American cholera epidemic, ships' ballast water from that continent arriving in U. S. ports in the Gulf of Mexico frequently carried the cholera pathogen, which was also found in fish and oysters in those ports.

herbicides, and releasing biocontrol agents, at a cost that reached $400,000/year (L. Thomas, pers. comm., 1994), though it only partly alleviated the problems.

(d) Water System Fouling

The Asian freshwater clam *Corbicula fluminea* plugged condenser tubes at the federal water project's pumping plant in the South Delta, colonized the bed of the project's Delta-Mendota Canal (trapping sediment and forming bars that reduced delivery capacity, requiring the dewatering of the canal and the dredging of over 50,000 cubic yards of clam-bearing material), and in southern California plugged underground pipes, turnout valves, and irrigation sprinklers (Ingram, 1959; Hanna, 1966; Eng, 1979).

(e) Bank Burrowing

As discussed earlier in this chapter under "Bio-eroders," several introduced species burrow in and damage both natural banks and man-made embankments, including muskrat, two species of crayfish and the Chinese mitten crab in fresh and brackish areas, and the isopod *Sphaeroma quoyanum* in the more saline waters of the Bay. In addition, we have found the styrofoam blocks that provide flotation for marina docks frequently riddled with *Sphaeroma* burrows, and though no quantitative data are available, it seems that this must substantially shorten their lifetime.

(f) Predation and Competition Harming Economically Important Species

Several intentional introductions may have had the "side effect" of reducing populations of other economically important species. Economically important species in this context include both species that are hunted or fished, and species that, because of their declining populations, become listed or become candidates for listing under the state or federal endangered species act (or otherwise become species of special concern), triggering limitations on economic activities. Examples of such "side effects" suggested by various researchers include the following.

- In the 19th century, the destruction of water celery, a common duck food, by introduced carp might have reduced populations of canvasback and other ducks (Smith, 1896, citing Jordan & Gilbert, 1894).
- Shebley (1917) reported carp to be the principal cause of destruction of the Sacramento perch, by eating its eggs and digging up its nests. Moyle (pers. comm.) has suggested that predation by striped bass and black bass may have been the major cause of the elimination of Sacramento perch from the Delta. McGinnis (1984) suggests that competition with introduced sunfish was the cause.
- Several workers have suggested that threadfin shad compete with the fry of gamefish, including black bass (McConnell & Gerdes, 1961; Von Geldern & Mitchil, 1975), crappie (McConnell & Gerdes (1961) and striped bass (McGinnis, 1984).
- Inland silverside may compete with striped bass (McGinnis, 1984) and prey on the eggs and fry of the endangered Delta smelt (BDOC, 1994; Moyle, pers. comm.).
- The Shasta crayfish *Pacifastacus fortis* was proposed for listing, in large part due to competition from the introduced crayfish *Orconectes virilis* and *Pacifastacus leniusculus* (Anon., 1987).

(g) Prevention and Control Costs

Substantial costs have been incurred through efforts to eradicate populations of two predaceous, nonindigenous fish present in the Delta watershed—white bass and northern pike—before they reach the Delta where it is feared they would reduce populations of endangered species and sport fish. For both fish, eradication efforts have centered around massive applications of the fish poison rotenone. The northern pike effort, for example, was preceded by three years of environmental review and litigation and a ban on fishing in the area (resulting in economic losses to the local economy), followed by the application of 12 semi-trailer loads of rotenone by 60 workers who were on site for over two weeks, with the cost of the on-site work alone totaling over a million dollars. The costs due to nontarget fish kills (which were substantial), other environmental health costs and occupational health costs are unknown.

The effort failed to eradicate northern pike from the watershed.

(h) Instability and Management Uncertainty

The greatest impact from introductions to the Estuary may be restrictions on the operation of the California water system. In recent years a combination of litigation, new legislation, and regulatory realignment has placed increasing environmental demands on the water agencies that store and divert water from the Estuary's watershed (DWR, 1993). Specifically, the agencies' ability to withdraw water increasingly depends on whether they can restore and sustain healthy populations of anadromous and native fish. This in turn will depend on the water agencies' and regulators' level of understanding of the ecosystem and their ability to figure out the necessary habitat conditions, including the amount and timing of instream flows needed, to maintain the fish.

However, the achievement of an adequate level of understanding to reliably manage the Estuary is severely hampered by a rate of introduction averaging (at least) one new species established in the Estuary every 24 weeks. For example, the arrival, growth and spread of the Asian clam *Potamocorbula amurensis* in 1986-87 appears to have fundamentally altered trophic relations in the northern reach of the Estuary, and perhaps made models and calculations based on pre-1987 data obsolete and irrelevant (Nichols, 1985; Cohen, 1990; Alpine & Cloern, 1992; Cohen & Carlton, 1995). A constantly changing species composition may make the ecosystem even less stable, and major functional shifts more common. Under such conditions, the reliable management of the Estuary required of (and promised by) the water agencies may be impossible. Since water from the Estuary's watershed supports much of California's population, industry and agriculture, the costs of failure could be substantial.

3. Some Examples of Potential Impacts

(a) Food Resources

Some organisms introduced to the Estuary might possibly be harvested and marketed. The European green crab *Carcinus maenas*, the Chinese mitten crab *Eriocheir sinensis*, and the yellowfin goby are commercially harvested for food in parts of their native range (Cohen et al., 1995). The Asian sea squirt *Styela clava* is harvested and eaten in Korea (Abbott & Newberry, 1980). Water hyacinth leaves are sold as a vegetable in markets in the Philippines (Ladines & Lontoc, 1983).

(b) Disease

Hallegraeff and his coworkers have demonstrated that toxic dinoflagellates that produce paralytic shellfish poisons (PSP) were introduced to Australia from Japan in ballast water sediments (Hallegraeff et al., 1989; Hallegraeff & Bolch, 1991). The introduction of toxic dinoflagellates to the northeastern Pacific could have costly impacts. In the Philippines, three outbreaks in five years of a PSP-producing dinoflagellate previously unreported from the region cost the local mussel industry about $15 million, poisoned over a thousand people and killed at least thirty-four (Corrales & Gomez, 1989). In San Francisco Bay clams and mussels are commonly collected for food in a poorly monitored and largely unregulated sport fishery (Sutton, 1981). Although there is no commercial shellfishery in the Bay, dinoflagellates that arrive there in ballast water could be readily carried by coastal currents or by coastal transport of ballast water to commercial shellfish beds to the north.

In July, 1991 during the South American cholera epidemic, the U. S. Food and Drug Administration discovered the causative organism of cholera, *Vibrio cholerae*, in oysters and fish from Mobile Bay, Alabama. Subsequently sampling of ballast water from nine ships arriving in Alabama and Mississippi from South America revealed *Vibrio cholerae* in one third of them (US Federal Register, 1991). It has been suggested that cholera could have initially reached South America via ballast water (Ditchfield, 1993).

(C) FUTURE INVASIONS

Many transport vectors releasing exotic species into the San Francisco Estuary remain active, and new invasions are certain to occur. These fall into eight categories discussed below, for each of which we give examples of potential invaders. In addition, at least 36 species of introduced aquatic plants, snails, fish, and one turtle are established in regions adjacent to the greater Bay-Delta system (Table 9), some of which will undoubtedly spread into the Estuary.

1. Ongoing Inoculations by Ballast Water from outside the Northeastern Pacific

Ships release in ballast water scores if not hundreds of new species on a monthly basis into the San Francisco Estuary (Table 10). That this highly successful vector remains active in the Estuary is indicated both by the number of new invasions now occurring (Table 1) and by the continual appearance but uncertain establishment of both small and large crustaceans in the Bay (Table 8).

Around the world there have been a number of important invasions, linked to ballast water release, whose temperate climate biology suggest that these species could become established in the San Francisco Estuary. Ballast water from Japan could include the larvae of the carnivorous North Pacific Sea Star *Asterias amurensis* and several species of Japanese dinoflagellates not yet established in San