(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

Table 8. Recent Records of Nonindigenous Species in the San Francisco Estuary whose Establishment is Uncertain

Species	Native Range	Date Collected	Comments (references)
INVERTEBRATES			
Mollusca: Gastropoda			
Prosobranchia			
Littorina littorea	ne Atlantic	1968-70, 1976-77, 1995	14 collected at Alameda & Bay Farm islands in the northern South Bay in 1968-70, 6 collected at Selby on the east shore of San Pablo Bay in 1976-77 (Carlton, 1969, 1979a). ANC collected one specimen on the San Francisco shore in 1995.
Arthropoda: Crustacea			
Isopoda			
Ianiropsis serricaudis	Sea of Japan	1977	Oakland Estuary (Carlton, 1979a).
Munna sp. A	?	1993/94	(J. Chapman. pers. comm., 1995).
Sphaeroma sp.	?	1994	(J. Chapman. pers. comm., 1995).
Amphipoda			
Ampithoe sp.	?	1993/94	(J. Chapman. pers. comm., 1995).
Calliopiella sp.	?	1993/94	(J. Chapman. pers. comm., 1995).
Dulichia monocantha	?	1990s	(M. Kellogg, pers. comm., 1995).
Listriella goleta	?	1990s	(M. Kellogg, pers. comm., 1995). Collected in Los Angeles Harbor in the late 1980s.
Synchelidium miraculum	?	1990s	(G. Gillingham, M. Kellogg, H. Peterson, pers. comm., 1995). Collected in Los Angeles Harbor in the late 1980s.
Decapoda			
Exopalaemon carinicauda	Korea, China, Hong Kong	1993	One specimen (L. Holthuis, pers. comm., 1993).
Exopalaemon sp.	unknown	1995	One specimen, possibly *E. carinicauda* (K. Hieb, pers. comm., 1995).
unidentified Pandalid shrimp	unknown	1995	One specimen (R. Van Syoc, pers. comm., 1995).
VERTEBRATES			
Fish			
Anguilla anguilla	Atlantic, Europe	1969	European Eel, one specimen (Skinner, 1971).
Anguilla rostrata	Atlantic, e N & S America	1964, 1994	American Eel, one specimen caught in each of 1964 & 1994. A fourth and unidentified eel, dated 1987, estimated 1 m length, is preserved at the Skinner Fish Facility in the Delta (Skinner, 1971; S. Walker, pers. comm., 1994).
Lepisosteus spatula	se U S & Mississippi basin	1991	Alligator Gar, one specimen, 146 cm long (Raquel, 1992).

Francisco Bay which, however, have become important invaders in southern Tasmania in a similar climatic regime (Carlton et al., 1995). Water from bays and estuaries of the American mid-Atlantic coast could include the Atlantic comb jelly *Mnemiopsis leidyi*, which has become a devastating zooplankton and larval fish predator in the Black and Azov Sea ecosystems (Shushkina & Musayeva, 1990; Mutlu et al., 1994) and the Japanese crab *Hemigrapsus sanguineus*, which was collected in 1988 in New Jersey (McDermott, 1991) and has now spread from North Carolina to Cape Cod (G. Ruiz, pers. comm., 1995; JTC, pers. obs.). The appearance of several Atlantic coast invertebrates in the San Francisco Estuary over the past 15 years (discussed under "Transport Mechanisms" in Chapter 5) suggests that the transport of additional organisms from the Atlantic is not unlikely. Ballast water from Europe could transport the freshwater-oligohaline gammarid amphipod *Corophium curvispinum*, a major fouling organism (Carlton et al., 1996).

These are clearly only a few out of scores of examples of known invaders that have become established elsewhere and which, should they hop on the ballast water conveyor belt, would be rapidly transported to the Estuary. In addition, we expect there are many organisms which have not invaded regions outside of their native range, but which could yet become potent invaders (as was the case with the Chinese clam, *Potamocorbula amurensis*, which entered the Estuary in 1986).

2. INTRACOASTAL TRANSPORT WITH SHIP TRAFFIC

Coastal ship traffic plays an unknown but potentially important role in transporting invasions that have established elsewhere on the Pacific coast to the Estuary. Examples include the transport of ballast water from the Columbia River (potentially transporting the Asian copepod *Pseudodiaptomus inopinus*, now well established there; Cordell et al., 1992) and from Pacific Northwest bays (which could include whole floating plants of the Japanese eelgrass *Zostera japonica*, which now occurs from Coos Bay to British Columbia). The arrival of the Atlantic oligochaete *Lumbricillus lineatus* in the Bay is also predictable, and should be specifically looked for in enriched sediments. Coates and Ellis (1980) have noted its establishment in pulp mill effluent sites in northern Vancouver Island, where it was introduced by international ship traffic.

Ballast water transport or ship fouling could play the central role in bringing to San Francisco Bay a number of species of Asian and Atlantic seasquirts that have become established in the harbors of southern California since the 1980s (G. Lambert, pers. comm., 1995). Indeed, ship fouling from these harbors is probably how the Japanese seasquirt *Ciona savignyi* arrived in San Francisco Bay, having previously become established in southern California. Coastal ship traffic from the south or the north may similarly have carried the Japanese seaweed *Sargassum muticum* as hull fouling into the Bay.

Similarly, coastal ship traffic may transport introduced organisms now established in the San Francisco Estuary, including many known in the northeastern Pacific only from the Estuary (Appendix 4), to other sites along the coast. The Estuary has likely operated in the past, and will likely continue to operate in the future, as the port of entry for many invasions of the Pacific coast.

Table 9. Introduced Species in Adjacent Areas with the Potential to Invade the San Francisco Estuary

Native Range:				
N - North	n - northern	e - eastern	ne - northeastern	se - southeastern
S - South	s - southern	midw - midwestern	nw - northwestern	sw - southwestern

Now Present in:					
BA	San Francisco Bay Area	NEC	Northeastern California	SJV	San Joaquin Valley
CC	Central California	SC	Southern California	SV	Sacramento Valley
CV	Central Valley	SCC	South Coastal California	WSN	west slope of the Sierra Nevada
NCC	North Coastal California				

Taxon	Species	Common Name	Native Range	Now Present in:
PLANTS				
Vascular Plants				
Dicotyledones	*Ludwigia peploides* var. *montevidensis*	water primrose	s S America	CV
	Nymphaea mexicana	yellow waterlilly	se U S & Mexico	SJV
	Nymphaea odorata	fragrant waterlilly	e U S	SV
	Polygonum hydropiper	marshpepper	Europe	CC
	Polygonum pennsylvanicum	pinkweed	e U S	SV
	Polygonum prolificum		e U S	BA
	Tamarix spp.	tamarisk	Europe, Asia or Africa	BA, SV, SJV
Monocotyledones	*Alisma lanceolatum*		Eurasia & n Africa	BA, SV, WSN
	Aponogeton distachyon	cape pondweed	s Africa	BA
	Cyperus difformis		Old World	BA, CV
	Echinocloa oryzoides		Eurasia	SV
	Eleocharis pachycarpa		Chile	WSN
	Fimbristylis miliacea		Old World tropics	CV
	Heteranthera limosa		midw & e U S, tropical America	SV
	Hydrilla verticillata	hydrilla	Eurasia or central Africa	SV
	Najas gracillima	thread-leaved water-nymph	ne U S	SV
	Najas graminea	rice-field water-nymph	tropical Asia	SV
	Ottelia alismoides		Africa, India, sw Pacific	SV?
	Peltandra virginica	tuckahoe	e N America	SJV
	Scirpus mucronatus		Eurasia	BA, SV
	Scirpus tuberosus		Europe	BA, CV

Table 9. Introduced Species in Adjacent Areas - continued

Taxon	Species	Common Name	Native Range	Now Present in:
INVERTEBRATES				
Mollusca: Gastropoda	*Planorbella duryi*	Seminole ram's horn	Florida	NCC, SC
	Pseudosuccinea columella	mimic lymnaea	e U S	CC, SC
	Radix auricularia	big ear radix	Europe	BA, CV, SC
VERTEBRATES				
Fish	*Esox lucius*	northern pike	north-central U S & Canada	WSN
	Hypomesus nipponensis	wakasagi	Japan	CV, NCC
	Lepomis gibbosus	pumpkinseed	e U S	BA, SC, NEC
	Micropterus coosae	redeye bass	se U S	WSN, SCC
	Micropterus puntulatus	spotted bass	s & midw U S	WSN
	Morone chrysops	white bass	midw U S	WSN, SCC
	Notropsis lutrensis	red shiner	south-central U S	SJV,SC
	Salmo trutta	brown trout	Europe	WSN
	Salvenius fontinalis	brook trout	e U S	WSN
	Tinca tinca	tench	Europe	BA
Reptiles	*Trionyx spiniferus*	spiny soft-shell turtle	se U S & Mississippi basin	BA

3. TO 7. ONGOING INOCULATIONS BY OTHER MECHANISMS: FISHERIES PRODUCTS, FISHERIES ACTIVITIES, AQUARIA RELEASES

In Table 10 we list additional evidence for five additional vectors for ongoing inoculations into the Estuary. These are (3) the live bait and lobster industries (releasing not only the subject organisms but the living seaweed used as packing material and numerous associated invertebrates); (4) the herring-roe-on-kelp fishery (transporting live *Macrocystis* kelp and associated invertebrates into the Bay); (5) live bait releases of bait fish; (6) private party releases of fish and shellfish; and (7) releases from home or school aquaria. Each of these mechanisms is known to have resulted in the at least temporary establishment of one or more non-native species in the Estuary. There are few regulatory mechanisms in place to manage the extent or minimize the impact of these vectors.

Table 10. Examples of Ongoing Inoculations of Nonindigenous Species into the San Francisco Estuary

MECHANISM: Species Inoculated

BALLAST WATER:
Includes a wide variety of planktonic estuarine organisms from many parts of the globe. Common types of organisms include the adult or larvae of calanoid, cyclopoid and harpacticoid copepods, spionid, polynoid and other polychaete worms, diatoms, barnacles, bivalves, snails, flatworms, decapods, chaetognaths, tintinnids, mysid shrimp, isopods, bryozoans, phoronid worms, amphipods, dinoflagellates, hydroids and other taxa (Carlton & Geller, 1993).

BAIT WORM SHIPMENTS:
Includes a variety of organisms from the Maine coast, including the baitworms *Nereis virens* and *Glycera dibranchiata*; the seaweeds used for packing them, especially *Ascophyllum nodosum*; and epiphytic seaweeds and small intertidal and epiphytic invertebrates found on the *Ascophyllum*. Recent examinations of such shipments arriving at bait shops in the Bay Area found large numbers of live snails, bivalves, amphipods, isopods, harpacticoid copepods, marine mites, insect larvae, polychaetes, oligochaetes, nematodes and forams (Lau, 1995; ANC & JTC, pers. obs.). This mechanism is likely responsible for the recent establishment of one Atlantic periwinkle in the Bay and the occasional presence of another. New bait worms now beginning to be marketed in California, such as the Asian worm *Namalycastis abiuma*, may become established in the Estuary or carry with them additional, yet unknown, organisms.

HERRING-ROE-ON-KELP FISHERY:
Includes the kelp *Macrocystis pyrifera* collected from the Channel Islands in southern California and placed in San Francisco Bay as a substrate for herring spawning (Moore & Reilly, 1989; Oda, 1989), and organisms found on *Macrocystis*. Although it had been thought that *M. pyrifera* would not reproduce and become established in the Bay, it has been found attached, and therefore reproducing, in the Bay (L. Solarzano, pers. comm., 1994; ANC & JTC, pers. obs.).

LIVE BAIT FISH:
Includes probable ongoing "bait bucket" releases of the red shiner *Notropis lutrensis* into the fresh waters of the Estuary and its tributaries (McGinnis, 1984; Jennings & Saiki, 1990).

Table 10. Examples of Ongoing Inoculations - continued

PRIVATE PARTY RELEASES OF FISH OR SHELLFISH TO ESTABLISH FOOD OR SPORT RESOURCES:
In recent years these types of releases probably account for the white bass established in the San Joaquin River drainage and northern pike established in the Feather River drainage, both likely to spread downstream to the Delta; Chinese mitten crab established in San Francisco Bay and tributary streams and likely to spread into the Delta and Central Valley rivers; blue crab collected from the Delta, the Bay, and nearby coastal waters, but not established; and possibly the alligator gar and Atlantic eels collected but not established in the Delta. Nonindigenous organisms currently imported alive to Bay Area markets, and thus readily available for release into the Estuary along with any parasites and epizoics they carry, include green-lipped mussels from New Zealand, blue crabs from Chesapeake Bay and American lobsters from Maine. The packing materials for these shellfish, sometimes discarded into the Bay from dockside restaurants and distribution and repacking centers, may contain yet additional organisms. For example, the seaweed (*Ascophyllum nodosum*) used to pack Atlantic lobsters was found, on arrival in the Bay Area, to contain at least 29 other species of invertebrates and 7 other species of seaweed from the Atlantic (Miller, 1969).

RELEASES FROM AQUARIA:
Can introduce and establish a variety of organisms, which in the past have likely included plants (and the oligochaetes and entoprocts living on them), snails, fish and turtles.

8. INTRACONTINENTAL RECREATIONAL VESSEL TRAFFIC

Recreational vessels entering the San Francisco Bay and Delta from northern or eastern states have the potential to transport with them, on their hulls or in incidental water aboard the vessel, a broad variety of aquatic pest species, including aquatic weeds (such as *Hydrilla*), snails (such as the New Zealand snail *Potamopyrgus antipodarum*, introduced to the Middle Snake River system of southern Idaho, and sometimes occurring in densities of 100s of 1,000s of snails per square meter; Carlton et al., 1996), and, especially, Eurasian zebra mussels (*Dreissena polymorpha* and *Dreissena bugensis*), which between 1993 and 1995 have been intercepted at the California border on recreational boats coming from the Midwest and the Great Lakes.

Our certainty that there will be additional invasions of the Estuary stands in contrast to our limited ability to predict exactly which species (or even which trophic guilds) will invade and when they will invade. Carlton (1996b) discusses six scenarios, none mutually exclusive, that seek to explain why invasions may occur when they do; these include changes in the donor region, new donor regions, environmental changes in the recipient region, changes in the dispersal vector, the phenomenon of invasion windows, and stochastic inoculation events. All of these pertain to potential invasions of the San Francisco Estuary. A recent example of a combination of several of these processes apparently led to the successful invasion and subsequent persistence of the Asian clam *Potamocorbula amurensis* in the Bay (as discussed in Chapter 3).

Predicting specific guilds of invaders is often an elusive endeavor. However, we note as an example the absence of certain truly euryhaline-oligohaline taxa from the Estuary where native marine and freshwater counterparts exist. Oglesby's (1965) proposal that the Atlantic worm *Nereis succinea* was successful in the Bay because it inserted itself in this intermediate microhabitat—that is, that it was an "insertion invader"—suggests that similar opportunities may be available for other taxa. We note two such examples (Table 4) among Bay isopods and amphipods. Also to be expected are further warmer-water species as new colonists in the Bay. The Bay has had a continuous history of such southern species establishing on warm bay margins, including the barnacle *Balanus amphitrite*, the tubeworm *Ficopomatus* and the bryozoan *Zoobotryon*.

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[1]Remarkably, Cloern (1982) does not mention that any of these species are introduced, and while Officer et al. (1982) note that Musculus and Tapes are introduced, they focus on the phenomenon of benthic filter feeding in San Francisco Bay as a "natural eutrophication control" process.