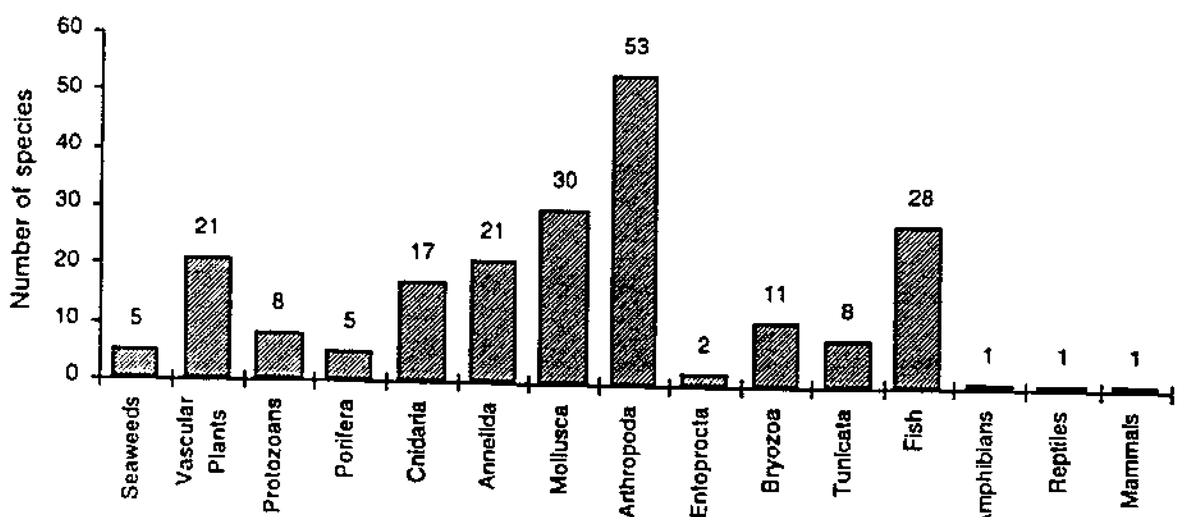
CHAPTER 5. RESULTS

(A) TAXONOMIC GROUPS OF INTRODUCED SPECIES

In all, we documented 212 species of introduced organisms in the Estuary. The numbers of species per taxonomic group are presented in Figures 2 and 3 at lower and higher levels of aggregation. Invertebrates are the most common major group of introduced species, accounting for nearly 70% of the total, followed by vertebrates and plants with respectively about 15 and 12 percent of the total. The most abundant invertebrates were the arthropods (36% of invertebrates) followed by molluscs (20%), annelids (14%) and cnidarians (12%). Nearly all the vertebrates were fish, and most of the plants were vascular plants, which were about evenly split between monocots and dicots.

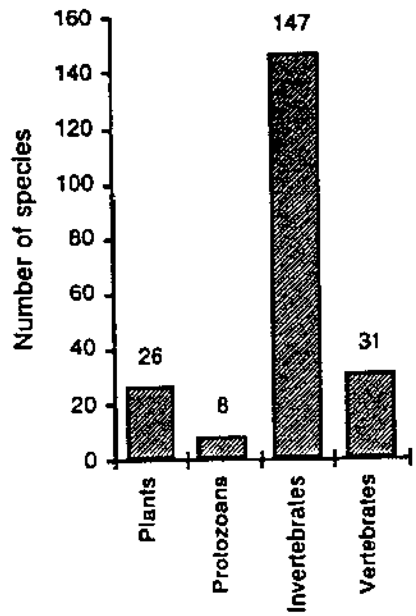
These numbers are generally in accord with our expectations prior to this study, based upon our knowledge of the Estuary's biota and consideration of other regional reviews of introduced marine and aquatic species, with the exception of the number of species of vascular plants, which we had anticipated would be higher. This result is in part due to our application of relatively more restrictive criteria for the inclusion of marsh-edge plants, as discussed in Chapter 2.

Figure 2. Invasions by Taxonomic Group: Lower-level Aggregation



For example, a study of introduced species in the Great Lakes using less restrictive criteria produced a list of 139 introduced species of which 59 species (42%)were vascular plants (Mills et al., 1993), and a similar study of the Hudson River produced a list of 154 introduced species with 97 (63%) vascular plants (Mills et al., 1995). As suggested in the "Methods" section, adding the plants in Appendix 1 (essentially terrestrial plants that have been reported in or at the edge of the tidal waters of the Estuary) to the list of organisms in Table 1 produces a list of introduced species that can more reasonably be compared to the Great Lakes and Hudson River lists. This expanded list for the Estuary contains 240 introduced species of which 49 (20%) are vascular plants. These three and one other study are compared in Appendix 5.

Figure 3. Invasions by Taxonomic Group: Higher-Level Aggregation



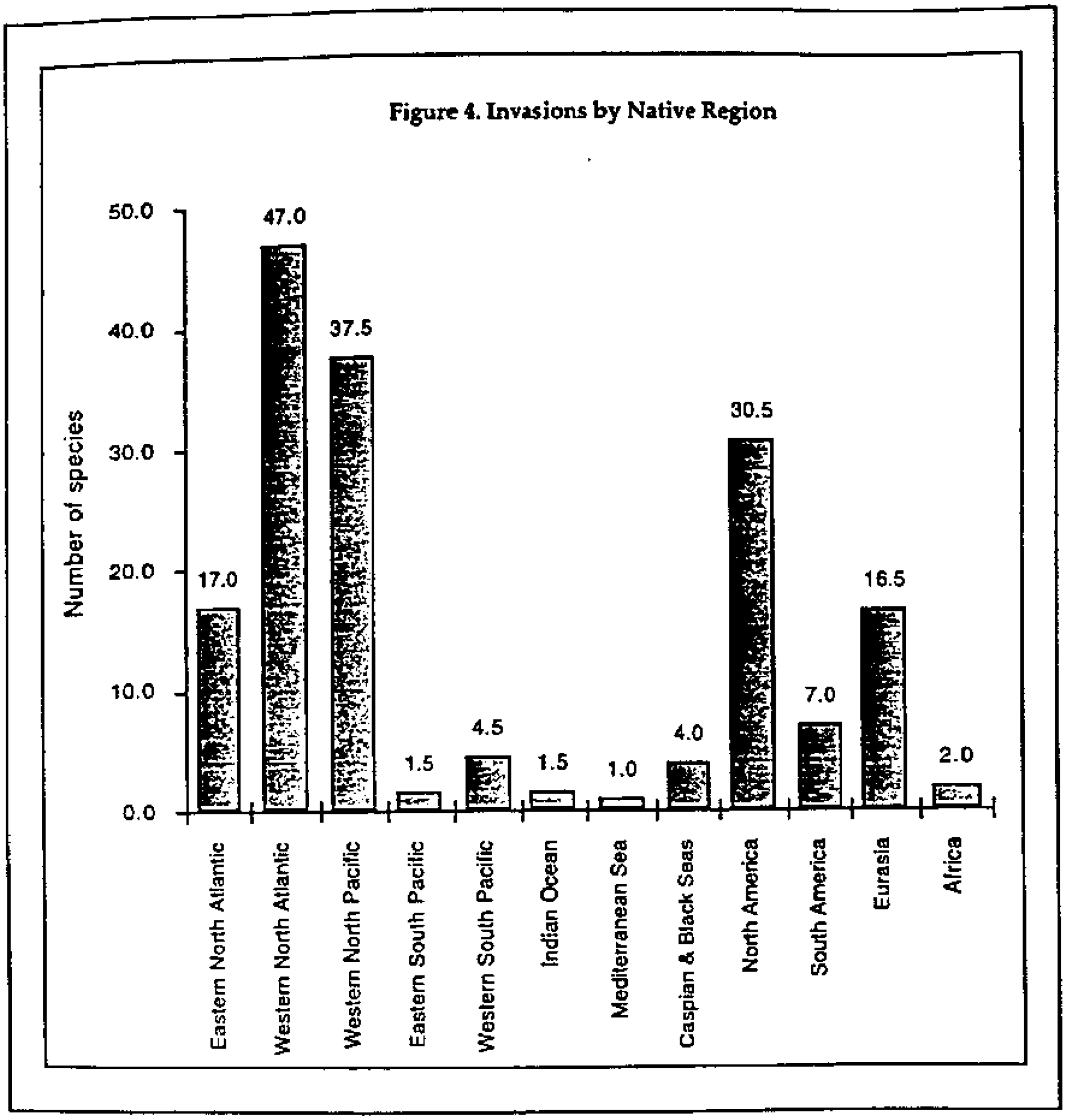
(B) NATIVE REGIONS OF INTRODUCED SPECIES

The numbers of species per native region are presented in Figure 4. Species were treated as either marine or continental species, as shown in Table 3, for assignment to appropriate regions. No introduced species were identified from the marine regions of the Eastern South Atlantic, the Western South Atlantic or the Eastern North Pacific, or from the continental region of Australia/New Zealand, so these regions do not appear in Figure 4.

The Estuary's marine introductions are dominated by species from the Western North Atlantic (accounting for 41% of all marine introductions), the Western North Pacific (33%) and the Eastern North Atlantic (15%). The Western North Atlantic provided mainly mollusks, arthropods and annelids, the Western North Pacific predominantly arthropods, followed by annelids, and the Eastern North Atlantic provided a few species from each of several groups. The Estuary's continental introductions are dominated by species from North America (54% of continental introductions; mainly fish) and Eurasia (29%, mainly plants).

Table 3. Treatment of Introduced Species as Marine or Continental, for Analysis by Native Region

PLANTS	
Seaweeds	marine
Vascular Plants	
Spartina spp.	marine
all other vascular plants	continental
PROTOZOANS	marine
INVERTEBRATES	
Annelida	
Oligochaeta	
Branchiura sowerbyi	continental
Limnodrilus monothecus	marine
Paranais frici	marine
Potamothrix bavaricus	continental
Tubificoides spp.	marine
Varichaetadrilus angustipenis	continental
Polychaeta	
Manayunkia speciosa	continental
all other polychaetes	marine
Mollusca	
Cipangopaludina chinensis malleata	continental
Melanoides tuberculata	continental
Corbicula fluminea	continental
all other molluscs	marine
Arthropoda: Crustacea	
crayfish	continental
all other crustaceans	marine
Arthropoda: Insecta	
Anisolabis maritima	marine
Neochetina spp.	continental
Trigonotylus uhleri	marine
Entoprocta	
Barentsia benedeni	marine
Urnatella gracilis	continental
all other invertebrates	marine
VERTEBRATES	
Fish	
gobies	marine
Alosa sapidissima	marine
Morone saxatilis	marine
all other fish	continental
all other vertebrates	continental



(C) TIMING OF INTRODUCTIONS

Analyses of the timing of introductions, done with the intent to distinguish pulses or patterns of invasions, are fraught with difficulties. In the San Francisco Estuary, as everywhere, larger and more conspicuous species (such as certain crabs, fish, and mollusks) tend to be noticed relatively soon after their arrival, while smaller and more cryptic organisms may be present but remain unnoticed for scores of years until the arrival of an appropriately specialized biologist. For example, the

Bay's mud-dwelling worms received little attention until Olga Hartman began sampling in the Bay in the 1930s, and thus some of the polychaetes derived from the Atlantic might well have been introduced (with Atlantic oysters) as early as the 1870s. The biases introduced by taxonomist-dependent records of arrival are not limited to the earlier part of this century. With enough effort from appropriate taxonomic experts, many species of tiny introduced organisms—such as protozoans, nematodes, flatworms and so forth—could certainly be collected today and identified from San Francisco Bay for the first time, although they may have been in the Estuary for 100 or more years.

Given these challenges, we have, as noted in Chapter 2, excluded from our tabulations of the temporal patterns of introductions both those species whose only available dates of first record are the first written accounts, and those species for which the date of first record seems a clear artifact of the arrival or participation of an interested taxonomist (e. g. Olga Hartman in the 1930s (polychaetes), Eugene Kozloff in the 1940s (symbiotic protozoans), Willard Hartman in the 1950s (sponges), and Ralph Brinkhurst in the 1960s (oligochaetes)), or an artifact of an especially focused sampling effort (e. g. the *Albatross* survey of 1912-23, and our survey of Bay fouling communities in 1993-95), or simply the fortuitous discovery of a species in a restricted habitat or locality (such as *Transorchestia enigmatica*, known only from the shore of Lake Merritt, and *Littorina saxatilis*, known only from ten meters of cobbly beach in the Emeryville Marina), and whose inclusion would provide a misleading view of the invasion history of the Estuary. These species are marked with an asterisk (*) in Table 1.

The dates of first record were tabulated in five time periods (four 30-year periods and one 26-year period) beginning in 1850. Tabulations of the dates of first record in the Estuary are shown in Figure 5, and of the dates of first record in the northwestern Pacific region in Figure 6. The results show a clear trend toward more first records in more recent periods. Over 40% of the first records of introductions in the Estuary date from 1970 or later, and over 63% from 1940 or later. Since the first records for the northeastern Pacific are inclusive of the records for the Estuary, they necessarily average somewhat earlier; nevertheless, 51% still date from 1940 or later.

Some of these results should be interpreted with caution. The dates of arrival must of course precede the dates of first record, by an unknown but possibly significant average period. And although we have excluded records that would cause a specific and obvious temporal bias, there might exist a general bias toward increasing numbers of first records, which could be caused by such changes as an increase in sampling effort, by the development of improved techniques for sampling and sorting, by a general increase in taxonomic knowledge, by an increased availability and improvement of keys and other identification tools, or by other changes.

On the other hand, several factors in the analysis create a bias toward a lower number of first records in the most recent period relative to earlier periods.

- The length of the most recent period is a little under 26 years long, compared to 30 years for the earlier periods. Extrapolating to 30 years at the same rate of production of first records as has prevailed in the period so far would add another 9 species to the recent period's tally for the Estuary, and 7 species to the tally for the northeastern Pacific.

- While a substantial number of first records were excluded (for the reasons discussed above) from the third, fourth and fifth periods, virtually none were excluded from the first two periods.
- Some organisms collected in the most recent period but excluded from the list of introductions because of inadequate evidence to determine whether they are established (see Table 8) will probably, with the passage of time, be recognized as established.

Figure 5. Invasions into the San Francisco Estuary by Period

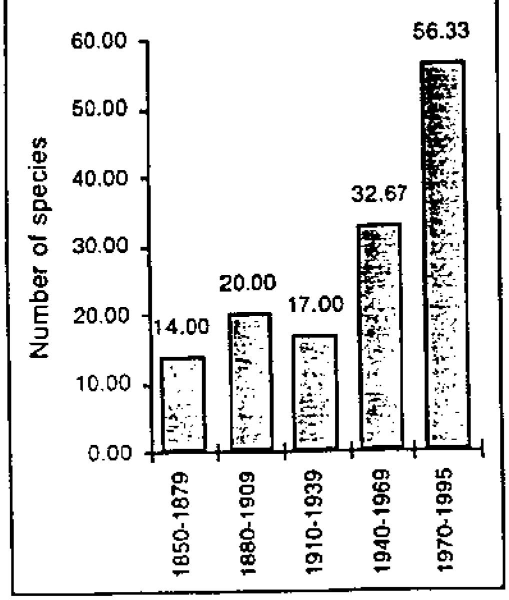
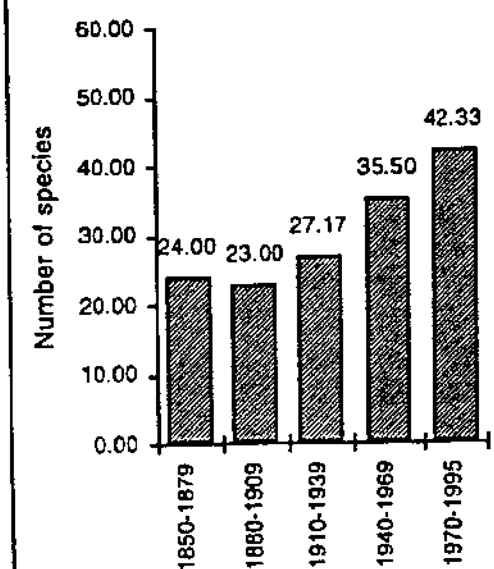


Figure 6. Invasions into the Northeastern Pacific by Period



- With the passage of time, the taxonomic problems that bar the listing of some species will be resolved. There appear to be a substantial number of species that were only recently recorded from the Estuary that fall into this category.

Taking these factors into account, it appears that the data signal a substantial pulse of invasions detected in the Estuary since 1970. The overall rate of introductions to the Estuary (212 species between 1850 and 1995) averages one new species established every 36 weeks. In the period since 1970, the dates of first record indicate a rate of one new species every 24 weeks (even after excluding one-third of the 212 documented introductions from the analysis, for reasons discussed above).

(D) MECHANISMS OF INTRODUCTION

Carlton (1994) presented a tabular overview of global dispersal mechanisms by human agencies in five broad categories: (1) Vessels; (2) Aquaculture, Fisheries, and Aquarium Industries; (3) Other Commercial, Government, and Private Activities; (4) Scientific Research; and (5) Canals. These have been reviewed in detail by Carlton (1979a, 1979b, 1985, 1987, 1992a) and by Carlton et al. (1995). Our data indicate that all of these mechanisms except for canals have served to transport non-native species to the San Francisco Bay area. Within these categories, twelve mechanisms (Table 1) and their approximate time of initiation relative to human-mediated invasions of the San Francisco Estuary are summarize here (a thirteenth mechanism, "gradual spread," accounts for the arrival of a number of species, including muskrats, purple loosestrife, and watercress, all in the 20th century, that spread either naturally, by human activities, or both, from eastern to western North America).

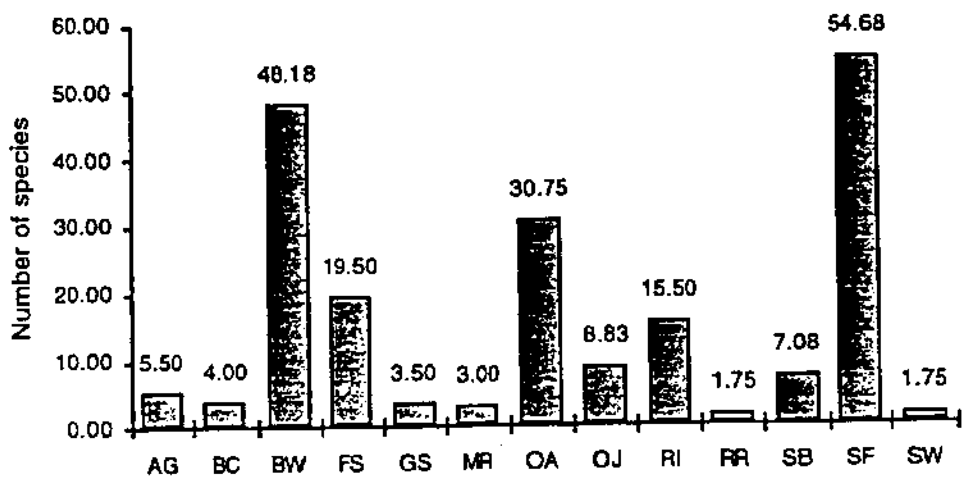
We focus here primarily on those mechanisms that serve to transport new species to the northeastern Pacific, rather than on intraregional vectors. The latter may include, for example, the intentional movement of fish between watersheds by members of the public with the intent of establishing new populations for sport fisheries or pest control (such as the mosquitofish *Gambusia*); the accidental movement of invertebrates in river gravels dredged for use as aggregate for concrete (such as the Asian clam *Corbicula*), and the spreading of organisms by dredging activity (such as the cordgrass *Spartina alterniflora*). No studies are available on the scale or role of these within-system vectors. We note later that such work would be of great value in terms of both understanding dispersal potential and dispersal histories and in establishing management policies.

1. VESSELS

(a) In ship fouling or boring into wooden hulls (SF)

The transport of marine organisms to San Francisco Bay by ships has been theoretically possible since the 16th century, when ships either traveling along the coast and passing by the entrance to the Bay, or making landfall on the shores of the gulf outside the Bay, could have released organisms that made their way into the Bay. Thus, for example, Carlton & Hodder (1995) have shown that vessels passing the California coast in the 1570s could have released larvae-laden hydroid polyps that could have drifted into the Bay. The first ship known to actually enter the Bay was the *San Carlos*, on August 5, 1775 (Galvin, 1971). By the turn of the 18th century a number of ships from the Atlantic and Pacific oceans had entered the Bay (Kemble, 1957). After 1849, international shipping to the Bay picked up dramatically due to a combination of the California Gold Rush, the increased export of lumber, grain, minerals, furs, hides, and other products from the rapidly developing industries of central California, and increased colonization and industrialization in general. Kemble (1957) reviews the general maritime history of the Bay area.

Figure 7. Invasions by Type of Transport Mechanism



Little is known of the modern role of ship fouling in transporting marine animals and plants into San Francisco Bay, although there is evidence that this mechanism could assume an increasingly higher profile due to the decreasing use (for environmental reasons) globally of effective antifouling paints (such as those including tributyltins (TBTs)) (A. Taylor, BHP Inc., Australia, pers. comm., 1995). The earliest clear records of ship fouling-mediated introductions (though not recognized as such at the time) are the collections of several North Atlantic fouling organisms in San Francisco Bay between 1853 and 1860: the barnacle *Balanus improvisus* (1853), the hydroid *Tubularia crocea* (1859) and the hydroid *Sarsia tubulosa* (1860) (Table 1). Approximately 26 percent of Bay invasions (55 species) have arrived by ship fouling and boring (Figure 7).

(b) In solid ballast (rocks, sand, etc.) carried in a ship's hold (SB)

No history of the release of ships' solid ballast into the Bay Area is available. It presumably parallels the general history of shipping into the Bay, but source regions for rock and sand ballast, amounts released, and so forth remain to be investigated.

That rock and sand ballast may have played an early role is suggested by the appearance of the South African shore plant brass buttons (*Cotula coronopifolia*) and the Atlantic marsh snail *Ovatella myosotis* in the Bay in the 1870s (Table 1). Another example of such activity was the release of ballast derived from Chilean port regions (such as Iquique and Valparaiso) into the Oakland Estuary up until about the 1920s, a transport vector that may have led to the introduction of the southern hemisphere beach hopper *Transorchestia* into nearby Lake Merritt. About 3 percent of Bay invasions (7 species) are linked to this mechanism (Figure 7). It is probable that this is an underestimate, and that with further studies more species (especially among non-crustacean arthropods, such as coastal insects and spiders) will be found to have been ballast-transported, similar to the studies of Lindroth (1957) on North Atlantic beetles.

(c) In ballast water or in a ship's seawater system (BW)

Ballast water may have been released into San Francisco Bay as early as the 1880s-1890s, but, as with solid ballast, the early history of ballast water in the Estuary remains to be studied. Of particular interest would be data on the timing of increased pulses of ballast water release into the Estuary. Modem ballast patterns for selected ports within San Francisco Bay have been investigated by Carlton et al. (1995). In the Ports of Oakland and San Francisco alone there were more than 2,000 arrivals of bulk cargo vessels and petroleum product tankers in 1991. "Acknowledged" ballast water released from those vessels in these two ports exceeded 130,000 metric tons (approximately 34,000,000 gallons) of water. "Unacknowledged" ballast water (water that is on board but not recorded because the vessel is classified as being "in cargo" rather than "in ballast") arriving in these two ports is estimated at approximately an additional 130,000 metric tons (34,000,000 gallons) (Carlton et al., 1995). Thus, more than 68 million gallons of ballast water per year are released by bulkers and tankers alone in the Central Bay area. Additional ports in the Bay system receiving large volumes of water include Sacramento and Stockton.

In 1991 the Ports of Oakland and San Francisco primarily received shipping from other North Pacific ports. Shipping from Asia accounted for 26 percent of ship arrivals in San Francisco and 48 percent in Oakland. Ships (and thus water) also arrived from Central Pacific and South Pacific ports and, to a smaller extent, from the Atlantic and Indian oceans (Carlton et al., 1995).

While some species may have been brought to the Estuary in the first half of the 20th century by ballast water (Table 1), the first reasonably unambiguous signal of the role of ballast water was the arrival of two Asian species, the shrimp *Palaemon macrodactylus* (first collected in 1957) and the Japanese goby *Tridentiger trigonocephalus* (first collected in 1962). The arrival of both may have been associated with increased transpacific shipping related to the Korean War. Twenty-three percent (48 species) of the Estuary's nonindigenous species are now linked to ballast water transport, with a greatly increasing number of these apparently having arrived since the 1960s (Figure 5). The pulse of recent ballast invaders into the Estuary is particularly evident in the discovery, since the 1970s, of 15 species of small Asian crustaceans (copepods, one cumacean, one isopod, 3 mysids, and 2 amphipods), and, since the 1980s, of two Asian clams (*Potamocorbula* and *Theora*), one Japanese fish (*Tridentiger bifasciatus*), and a New Zealand carnivorous sea slug (*Philine*). The appearance of the Chinese mitten crab *Eriocheir sinensis* in the Bay may also be linked to ballast water (but see mechanism 11, below).

2. Fisheries, Marsh Restoration and Biocontrol Activities

(a) Shipments of Atlantic oysters (*Crassostrea virginica*) (OA) and Pacific (Japanese) oysters (*Crassostrea gigas*) (OJ)

The first Atlantic oysters were planted in San Francisco Bay in 1869, the year of the completion of the Transcontinental Railroad. Early shipments were largely from New York and New Jersey and occasionally from Chesapeake Bay. The industry grew and flourished in the 1890s, tapering off sharply after 1900 (for reasons variously cited as increases in pollution and changes in the Bay's hydrology and flushing dynamics; see Carlton, 1979a). The last oyster seed shipments occurred about 1910, and adult oysters continued to be received for holding in the Bay until the 1930s. Barrett (1963) and Carlton (1979a) review the history of Atlantic oystering in the Bay in detail.

The first Japanese oysters were planted out in the Bay in 1932, with plantings continuing until 1939. Occasional plantings for "experimental" purposes were started in the 1950s. Carlton (1979a) reviews this brief and little-known history.

The "signal" of Atlantic oystering in terms of invasions occurred early, with the appearance of the common Atlantic soft-shelled clam *Mya arenaria* in the Bay by 1874 (it was, oddly enough, not recognized as such, and described as a new species!). The Atlantic marsh snail *Ovatella* may have also arrived with oysters, if not with ship's ballast, at this time. Coincident, however, with the greatly increased pulse of plantings in the 1890s of Atlantic oysters was the appearance in the Bay of a variety of well-known East Coast clams and snails, including the oyster drill *Urosalpinx* (1890), the tiny gem clam *Gemma* (1893), the marsh mussel *Arcuatula* (=*Ischadium*) *demissa* (1894), two species of slipper limpets *Crepidula convexa* and *plana* (1898, 1901) and the mudsnail *Ilyanassa* (1907). Similarly, the Atlantic shell-boring sponge *Cliona* (1891) and the common Atlantic pileworm *Nereis succinea* (1896) had been recorded by this time. Thirty species representing about 15% of the introduced biota are now recognized as originating from Atlantic oystering activity.

In concert with the much lower level of Japanese oystering in the Bay, only a few species in the Bay are recognized as having arrived with this industry. After the pulse of 1930 plantings, the Japanese mussel *Musculista* (1946) and the Japanese clam *Venerupis philippinarum* (=*Tapes japonica*) (1946) were collected in the Bay. The immediate role of Japanese oystering in transporting other species is not as clear, as many candidate taxa may also have entered the Bay by ship fouling or other means (Table 1). The Japanese brown seaweed *Sargassum muticum*, while apparently introduced to the Pacific coast by Japanese oystering, may have entered the Bay as drift seaweed from elsewhere on the coast or, even more likely, as fouling on coastal ship traffic. The Japanese parasitic copepod *Mytilicola* may similarly have been transported into the Bay in mussels in ship fouling from more northern stations. About 4 percent of the Bay's invasions are linked to Japanese oystering (Figure 5).

(b) Fish or shellfish stocked by the government to establish or support a fishery (FS)

We review the early attempts to move Eastern fish West, facilitated by the completion of the Transcontinental Railroad, in Chapter 3. American shad, white catfish, several species of bullhead, and striped bass were all successfully transported, released, and established in the Bay commencing in the 1870s. Intentional fish stocking by government agencies of freshwater and estuarine fish into California and the Bay region has continued to varying degrees throughout the 20th century (see discussions in Chapter 3). Nineteen species (9 percent) of the exotic biota owe their origins to this mechanism.

(c) Plantings for marsh restoration or erosion control (MR)

Plantings either for marsh restoration or possibly for erosion control were involved in the introduction of four species of the cordgrass *Spartina* in the Bay in the 1960s and 1970s. One was planted in Washington state, and then transplanted from there to San Francisco Bay; another was likely introduced to Washington in solid ballast, and later independently introduced to the Bay from the Atlantic coast for marsh restoration; the third was introduced to Humboldt Bay in solid ballast, then transplanted to San Francisco Bay; the fourth, first reported in the Bay in 1968, presumably arrived with an undocumented restoration or erosion control project (Chapter 3).

As we based our analysis on the mechanisms that brought to the northeastern Pacific the stocks of organisms introduced to the Estuary, we counted three of these cordgrasses as introduced via marsh restoration or erosion control (1.4% of the exotic biota), and one via solid ballast.

(d) Accidental release by the government with fish stocks or marsh restoration (AG)

Accidental releases of plants, fish, and invertebrates through stocking and planting programs began to be detected in the 1950s in the Bay region, although these may have occurred much earlier. Thus the rainwater killifish *Lucania parva* appeared in 1958 on the Bay's margins, apparently having been released accidentally with shipments of other fish in more eastern localities. The green sunfish and bigscale logperch, as well as the curly-leaf pondweed, are additional accidental releases. Less than 3 percent of the Estuary's invaders come under this category.

(e) Seaweed packing for live baitworms and lobsters (SW)

Miller (1969) first described this mechanism (focusing on lobster packing) as an active vector for transporting northwestern Atlantic marine organisms to San Francisco Bay. As discussed in Chapter 3 (under the periwinkle *Littorina saxatilis*), this mechanism continues vigorously today. Large quantities of Atlantic bait worms, and with them as packing material Atlantic rocky shore seaweeds (mainly *Ascophyllum* nodosum), are air-shipped weekly to sport-fishing supply stores in the Bay Area. Investigations in progress (Lau, 1995; Cohen, Lau & Carlton, in prep.) reveal that these seaweeds support large numbers of living Atlantic coast invertebrates, including mollusks, worms, crustaceans, and insects, which are routinely released into the Bay by anglers. The apparently recent appearance of the Atlantic red alga *Callithamnion* in the Bay, the establishment of a population of the Atlantic periwinkle *Littorina saxatilis*, and perhaps even the appearance of the Atlantic green crab *Carcinus maenas* may be linked to this active and unregulated flow of New England rocky shore organisms to the Bay. To date, less than one percent of the Estuary's invaders are clearly linked to this mechanism, but the occasional appearance of other species not yet known to be established (such as the Atlantic periwinkle *Littorina littorea*; Table 8) and the continual release of living seaweeds in the Bay which could themselves become established (for example, *Ascophyllum nodosum* has now gained a foothold in the Hood Canal, Puget Sound; L. Goff, pers. comm., 1992), predictably herald the imminent establishment of yet additional Atlantic species.

(f) Biocontrol releases (BC)

Invertebrates and fish released for biocontrol in the Bay region have been few, although the release of muskellunge and sea lions in San Francisco's Lake Merced to control introduced carp is a noteworthy incident in the history of human attempts at biocontrol (Chapter 2). Two South American weevils (*Neochetina* spp.) were released in the 1980s for water hyacinth control; these became established but appear to have had little impact on these weeds (Chapter 3). An early introduction (1922) to the state was the mosquitofish *Gambusia affinis* which arrived on Bay shores at least by the 1960s if not much earlier. The inland silversides *Menidia beryllina*, brought to the state for gnat and midge control in 1967, soon entered (1971) Bay waters. These four species represent about two percent of the Estuary's exotic biota.

3. OTHER COMMERCIAL AND PRIVATE ACTIVITIES

(a) Releases by an individual, whether intentional or accidental (RI)

Under this mechanism we include non-government releases to establish food resources (the snail *Cipangopaludina*, the clam *Corbicula*, the crayfish *Procambarus clarkii*, carp, bullfrog, and perhaps the Chinese mitten crab *Eriocheir sinensis* and the pond slider turtle); releases or escapes from residential ponds and aquariums (plants (and oligochaete worms with them), possibly the snail *Melanoides*, goldfish, carp, and the turtle); escapes from commercial breeding or rearing ponds (crayfish, carp, bullfrog) and discards of market goods (the snail *Cipangopaludina* again). Fifteen species representing 7 percent of the introduced biota have been linked to this mechanism according to our data. With the possible exception of carp, water hyacinth and *Cipangopaludina*, these have all been 20th century activities.

4. SCIENTIFIC RESEARCH

(a) Releases as a result of research activities, whether intentional or accidental (RR)

Scientific research efforts have resulted in relatively few introductions to the Estuary. The bullfrog and the virile crayfish both owe their establishment, at least in part, to releases from educational and research institutions in the last half of this century. The green crab *Carcinus maenas*, as noted below, may be a further and more recent example of this vector. Less than one percent of the Estuaries nonindigenous biota has arrived via this mechanism.

The complexities and challenges in analyzing and properly weighting these many transport vectors, in terms of both developing an historical perspective and establishing effective management options, is illustrated by the many species in Table 1 for which multiple transport vectors can be assigned. The recent appearance of the Atlantic green crab *Carcinus maenas* in San Francisco Bay is a superb illustration of the analytical and managerial hurdles involved. The green crab could have arrived by at least four different mechanisms (Cohen et al., 1995), whose relative likelihood is difficult to estimate. As discussed in Chapter 3, it may have arrived in ballast water from any of several different source regions (Atlantic America, Australia, Europe or South Africa, with the first two perhaps more likely based on shipping patterns); via seaweed released from the bait worm industry; via active release from a school or research aquarium; or via a ship's sea chest or seawater pipe system. Clearly, the control of future invasions hinges on a clearer and more detailed resolution of which mechanism served to introduce *Carcinus* to the Bay. Recent collections in the Estuary of the Atlantic amphipod *Gammarus daiberi* (1983), the Atlantic worm *Marenzelleria viridis* (1991) and the Atlantic snail *Littorina saxatilis* (1993) may point to the Atlantic as the source region for *Carcinus* (1989/1990), and may further suggest the modern resurgence of an active Northwest Atlantic to San Francisco Bay transport corridor.