# CHAPTER 1. INTRODUCTION

Over the past four centuries thousands of species of fresh water, brackish water and salt water animals and plants have been introduced to the United States (Elton, 1958; Carlton, 1979a, 1989, 1992b; Moyle, 1986; Hickman, 1993; Carlton & Geller, 1993). In some regions, such as the Hawaiian Islands, aboriginal introductions date back more than two millennia (Mooney & Drake, 1986). The taxonomic, habitat and trophic range of this vast nonindigenous biota is impressive—ranging from exotic flatworms (*Rectocephala exotica*) in the lily ponds of Washington, D. C., to Mexican crabs (*Platychirograpsus spectabilis* ) in Florida rivers, to aquatic rodents such as the South American nutria (*Myocaster coypu*) in the southern United States.

The human role in changing the face of North America, in terms of the abundance and diversity of the animals and plants of lakes, rivers, estuaries, marshes, and coastlines, has been demonstratively profound:

- Sea lampreys (*Petromyzon marinus*) invaded the Great Lakes, destroying extensive native fisheries; the Eurasian carp (*Cyprinus carpio*), released in New York in 1831, is now a national pest; Nevada's Ash Meadows killifish (*Empetrichthys merriami*) became extinct at the hands of introduced mosquitofish, mollies, crayfish, and bullfrogs; and scores of exotic fish species now dominate aquatic habitats from Florida to New York and from the Atlantic drainage to California.
- Asian clams (*Corbicula fluminea*) spread across all of North America in only 40 years, moving from west to east—from the Columbia River to California and then quickly across the southern United States to the Atlantic seaboard, a dramatic and startling invasion of this canal- and pipe-fouling clam (McMahon, 1982). Fifty years later, European zebra mussels (*Dreissena polymorpha* and *Dreissena bugensis*) are similarly spreading across North America—this time from east to west, from the Great Lakes to the Mississippi and into Oklahoma.
- Alien plants—including the spectacularly successful purple loosestrife (*Lythrum salicaria*), Eurasian watermilfoil (*Myriophyllum spicatum*) and water chestnut (*Trapa natans*)—are now the dominant, and at times the only, vegetation, for hundreds of square miles of aquatic and marsh habitats in North America.

Despite these many invasions, there are with rare exception no syntheses of the spatial and temporal patterns, mechanisms or impacts of these nonindigenous aquatic and estuarine organisms. For the great majority of invasions, records are scattered among thousands of scientific papers and buried in general monographs, student theses, government reports, consultant studies and anecdotal accounts. While a comprehensive review of freshwater and marine invasions would be extraordinarily useful, an initial approach to understanding the ecological and economic impacts of nonindigenous animals and plants in U. S. aquatic and marine environments may be attained through case studies: the assessment of the role of invasions in defined geographic regions, focusing on historical and modern-day

dispersal pathways, on the biological, ecological and economic consequences of invasions, and on prospects for future invasions.

We present here such a regional study, focusing on one of the largest freshwater and estuarine ecosystems of the United States: the San Francisco Bay and Delta region, a region known to have sustained numerous invasions for over a century.

## (A) PRIOR STATE OF KNOWLEDGE

At the time of our study there was no synthesis available of the diversity and impacts of the nonindigenous aquatic and estuarine species of the San Francisco Bay and Delta region, an area that extends from the inland port cities of the Central Valley to the coastal waters of the Pacific Ocean at the Golden Gate.

This region includes examples of most of the common aquatic habitats found throughout the warm and cool temperate climates of the United States and, as such, represents an ideal theater for assessing the diversity and range of effects of aquatic invasions. Within the Bay-Delta Region are fresh, brackish, and salt water marshes, sandflats and mudflats, rocky shores, benthic sublittoral habitats of a wide sediment range, eelgrass beds, emergent aquatic macrophyte communities, planktonic, nektonic, and neustonic communities, extensive fouling assemblages, and communities of burrowing and boring organisms in clays and wood. Also represented is a vast range of habitat disturbance regimes. Over a 140-year period of substantial human commercial and other activities—since about 1850—a minimum of more than 200 plants, protists and animals from the aquatic and coastal habitats of eastern North America, Europe, Asia, Australia, and South America have invaded these ecosystems.

Prior lists or descriptions of the introduced freshwater, anadromous and estuarine fish fauna in the San Francisco Bay-Delta region were provided by Moyle (1976b) and McGinnis (1984); of freshwater mollusks by Hanna (1966) and Taylor (1981); of marine mollusks by Nichols et al. (1986); and of introduced marine and estuarine invertebrates by Carlton (1975, 1979a,b), supplemented by Carlton et al. (1990). Silva (1979) and Josselyn & West (1985) noted some introductions of marine and brackish seaweeds, but no comprehensive assessment of possibly introduced seaweeds had been made. Atwater et al. (1979) provided a list of introduced vascular plants in San Francisco Bay salt marshes, but appear not to have distinguished between aquatic plants that are characteristically found within marshes and essentially terrestrial plants that are occasionally found at the edges of or within marshes. During our study the Bay-Delta Oversight Committee of the California Department of Water Resources produced a briefing paper summarizing some of the previously published information on introduced fish, wildlife and plants of the Bay-Delta region (BDOC, 1994), and Orsi (1995) published a list of introduced estuarine copepods and mysids.

No information had been compiled on possible introductions among freshwater invertebrates (including species of freshwater sponges, jellyfish, flatworms, oligochaete and polychaete worms, snails, clams, crustaceans, insects and

bryozoans), freshwater macroalgae, or fresh, brackish or salt water phytoplankton. Protozoan introductions had been similarly neglected.

Based on the information available prior to our study, and on consideration of extant lists of aquatic or marine introductions in other regions (Leppäkoski, 1984; den Hartog, 1987; Mills et al., 1993, 1995; Jansson, 1994), we had estimated that the number of aquatic and estuarine introductions in the Bay-Delta system could exceed 150 invertebrate species, 20 fish species, 10 algal species, and 100 vascular plant species.

## (B) CONTRIBUTIONS OF THE PRESENT STUDY

The present work is the first regional case study in the United States of the diversity and ecological and economic impacts of nonindigenous species in aquatic and estuarine habitats. Previous studies (Mills et al., 1993, for the Great Lakes; Mills et al., 1996, for the Hudson River) have largely concentrated on species check-lists with a minimal review of ecological or economic effects of the exotic biota. We intend the present study to be a comprehensive synthesis which may serve as a comparative model for other regional studies in U. S. waters.

The present study also sets forth detailed and clear criteria for determining which species are present and established within the study zone. Prior regional surveys of aquatic introductions have implied but rarely defined these criteria, a situation that impedes ready quantitative comparisons between regions. We include (Chapter 5) a supplemental list of vascular plant species based upon criteria which we judge to approximate the criteria in prior regional surveys of aquatic introductions in the USA, in order to facilitate such comparisons.

The present study is also the first regional survey of introductions to include a listing (although preliminary) of cryptogenic species—species which are neither demonstrably native or introduced (Chapter 4). As discussed by Carlton (1996a), the development of such lists is a necessary first step in correcting prior tendencies to profoundly underestimate the potential extent of biological invasions and in providing a more complete basis for understanding the sources, characteristics and frequency of success of biological invaders.

Both older (Elton, 1958) and newer (e. g. Mooney & Drake, 1986; Drake et al., 1989) reviews of biological invasions propose a number of theoretical models to explain the success of animal and plant invasions in regions where they did not evolve. However, for most such studies, comprehensive data sets on the diversity of invasions, temporal patterns of invasion, and ecological impacts have not been available by which to test the applicability or robustness of invasion theory. The present study provides an extensive review of an introduced biota exceeding 200 taxa in a defined geographic region, and thus provides a rare data set with which to test invasion models.