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NON-INDIGENOUS AQUATIC ORGANISMS IN THE COASTAL WATERS OF CALIFORNIA

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This study combined numerous field surveys with a literature review to document the location of non-indigenous aquatic species (NAS) in the estuarine and coastal waters of California. Substantial numbers of aquatic species have been introduced to the coast of California. Although all areas of the coast showed some evidence of introductions, NAS totals were generally highest in the two major commercial ports, San Francisco and Los Angeles/Long Beach. Statewide, 360 distinct non-indigenous and 247 distinct cryptogenic taxa were identified from the literature and field investigations during the course of this investigation. Annelids, primarily polychaete worms, were the dominant phylum, comprising 33 % of the NAS observed. Eleven NAS were found in the current survey that had not been reported from California in previous studies. The majority of organisms introduced to the California coast are native to the northwest Atlantic, the northwest Pacific, and the northeast Atlantic, all regions from which California receives a considerable amount of ship traffic as well as the source materials for much of its aquaculture. Shipping is the most likely vector for the majority of NAS introductions; specifically, ballast water and hull fouling were identified as the most common subvectors. We identified a number of NAS that co-occur in the major ports, which may indicate intra-coastal spread of non-indigenous taxa. However, the mechanisms of NAS movement within California are poorly understood and should be addressed in future research.

INTRODUCTION

The introduction of non-indigenous aquatic species (NAS) has created serious ecological, operational, and engineering problems worldwide, including California. Non-indigenous animals and plants are commonly reported in many of the harbors and bays of California and have had a profound impact on the ecology of the marine and estuarine regions of California (Race 1982, Alpine and Cloern 1992, Cohen and Carlton 1995, Crooks 1998, Byers 2000, Grosholz et al. 2000). NAS may out-compete or alter local habitats to such an extent that they make it impossible for native species to survive, are often predators, competitors, or parasites and some can cause or carry disease (Lambert et al. 1992, Byers 2000, Grosholz et al. 2000, Ruiz et al. 2000). Through both direct and indirect mechanisms, NAS can pose risks to human health, devastate fishery and aquaculture resources, and severely disrupt habitat and ecosystem stability (Alpine and Cloern 1992, Ruiz et al. 2000, Purcell et al. 2001).

Although several human transport vectors have been implicated in the spread of NAS, commercial shipping is the dominant vector for coastal marine and estuarine introductions around the world and on the Pacific Coast (Cohen and Carlton 1995, Ruiz et al. 2000, Fofonoff et al. 2003, Hewitt et al. 2004, Drake et al. 2005). With the development of modern long-range ships in the 20th century, ballast water, used for ship stability, emerged as an important mechanism of dispersal of marine and freshwater organisms. Today, ballast water is considered the largest single vector for the transfer and release of NAS to locations outside their native range (Carlton and Geller 1993, Ruiz et al. 1997).

Ship ballast tanks typically contain numerous species in great abundance, which are subsequently discharged at ports of call (Carlton 1985, Carlton and Geller 1993, Smith et al. 1999). Worldwide, at least 10,000 marine species are estimated to be transported daily in the ballast water of cargo ships (Carlton 1999). Large vessels can carry in excess of 200,000 m^3 of ballast (National Research Council[1] 1996) and it is estimated that tens to hundreds of millions of live organisms may be discharged on any one voyage (Lavoie et al. 1999). Greater ballast tank volumes, increasing international commerce, and shorter transit times, have combined to increase the number and diversity of viable organisms potentially invading new habitats via shipping pathways and has contributed to the increasing rate of successful invasions (Cohen and Carlton 1998). Furthermore, as source ports become increasingly invaded, the diversity of exported species may expand and increase “stepping-stone” invasions, the process whereby an invaded location serves as a source for secondary introductions (Bagley and Geller 2000).

California’s Ballast Water Management Act (Act) of 1999 established a multi-agency program to address the issue of species introductions by making ballast water management mandatory for all vessels entering California marine waters with ballast from foreign ports. The Act also provided funding for the present investigation, which entailed a biological assessment to determine the current location of non-indigenous aquatic species populations in the estuarine and coastal waters of the state. To gather this information, biological surveys were conducted in habitats where species introduced from ship’s ballast would most likely occur. In addition, the Act anticipated that the data generated by this investigation would be used in future studies, such as the determination of alternative ballast water discharge zones, the delineation of environmentally sensitive areas to be avoided for uptake or discharge of ballast, and an assessment of potential risk zones where uptake must be prohibited. Data from this study will be used as a baseline to assess the effectiveness of ballast water control measures on species introductions into California.

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[1] National Research Council. 1996. Stemming the Tide: Controlling Introductions of Nonindigenous Species by Ship’s Ballast Water. Committee on Ships’ Ballast Operations, Marine Board, Commission on Engineering and Technical Systems, U.S. Congress, Office of Technology Assessment, Harmful Non-Indigenous Species in the United States, OTA-F-565, Washington, DC.

METHODS

Data Collection

Data used in this investigation were derived from field collections directed by the California Department of Fish and Game's (CDFG) Office of Spill Prevention and Response, from comparable concurrent studies being conducted independently by other organizations, and from a comprehensive literature review. Data collection focused on suspected NAS and cryptogenic taxa only; data on native taxa were not used in this investigation, except in cases of known range extensions.

Primary Studies

The CDFG field studies focused on those areas of the coast that had not been surveyed specifically for NAS in past investigations, specifically targeting regions most likely to be impacted by ballast introductions. The study initially targeted the seven major ports along the California coast: Humboldt Bay, San Francisco Bay, Stockton, Sacramento, Port Hueneme, Los Angeles/Long Beach (LA/LB), and San Diego (Figure 1). These sites are the primary locations where ocean-going vessels enter state waters, thus were the most likely places for ballast-related introductions to occur. NAS were sampled and identified in all these port areas except San Francisco Bay, which had already been extensively studied in recent years, most notably by Cohen and Carlton (1995), whose data is included in our summaries. Most of the sampling in the major port areas was conducted in 2000. Subsequent to the survey of the major ports, additional sampling was done in many of the smaller marinas and bays along the coast during the summer of 2001 (Figure 1).

CDFG contracted with three scientific research groups to assist with sample collection and literature review. With minor overlap, each group was responsible for collection and identification of organisms in different geographic areas: Moss Landing Marine Laboratories' Marine Pollution Studies Lab (MLML) sampled harbors, marinas, and bays statewide; Humboldt State University Foundation (HSUF) sampled Humboldt Bay; and San Francisco Estuary Institute (SFEI) sampled the major ports of southern California. All began their research with a comprehensive literature review of non-indigenous organisms in the marine and estuarine waters of their respective study areas. The literature review was based on both published and unpublished information, including scientific papers, graduate theses, government reports, regional monographic studies, keys, floras, field guides, check lists, as well as museum and personal collections and records. Sampling encompassed a variety of habitats, methods, and locations (Table 1).

The majority of the sampling for this survey was done by MLML and was designed to supplement existing information and data being collected by other researchers. Samples were collected at over 450 stations in 21 harbors, marinas, and bays; epifaunal samples were taken in all locations, infaunal communities were sampled in 4 harbors, zooplankton were identified from samples taken in Humboldt Bay, Port Hueneme, LA/

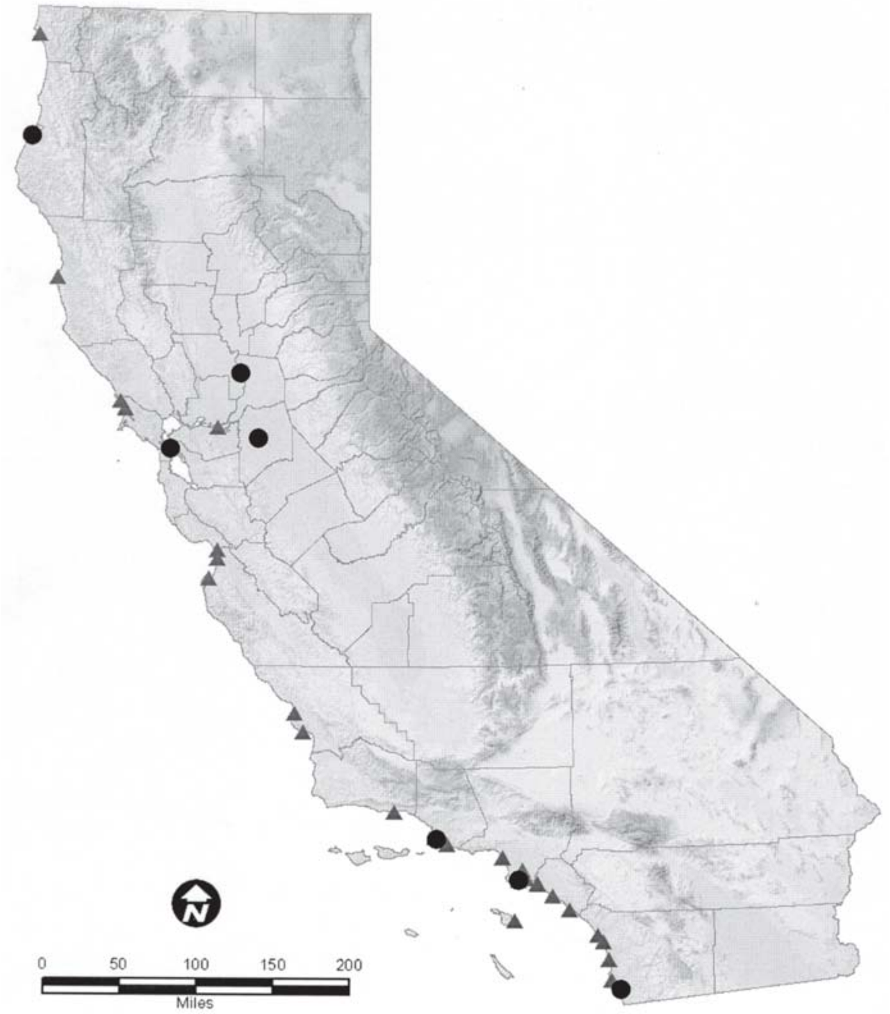

Figure 1. California major harbors and minor bays and ports sampled for non-indigenous taxa.

LB Harbor and San Diego Bay, and fish surveys were conducted in the ports of Sacramento and Stockton (CDFG[2] 2002). Benthic infaunal samples (sediment grabs) were collected at 77 stations in 4 harbors. Zooplankton samples were collected quarterly in San Diego Bay, LA/LB Harbors, and Port Hueneme. Voucher specimens of all identified NAS and cryptogenic taxa were maintained by MLML.

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[2] California Department of Fish and Game (CDFG). 2002. A Survey of Non-Indigenous Species in the Coastal and Estuarine Waters of California. California Department of Fish and Game. Sacramento, California. Report to the California State Legislature. pp116.

Table 1. Types of sampling conducted at key coastal California sites. Includes field sampling conducted between 1998 and 2001 by Moss Landing Marine Laboratories, Humboldt State University Foundation, San Francisco Estuary Institute, and the Southern California Coastal Water Research Project Authority.

Water Body	Epifaunal	Benthic	Fish	Plankton	Algae	Fouling Plate
Humboldt Bay	X	X	X	X	X	X
Port Hueneme	X	X	X	X		
Port of Sacramento	X	X	X			
Port Of Stockton	X	X	X			
LA/LB Harbors	X	X	X	X		
San Diego Harbor	X	X		X		
Fort Bragg	X					
Tomales Bay	X	X				
Bodega Bay	X					
Elkhorn Slough	X					
Moss Landing Harbor	X					
Monterey Harbor	X					
Morro Bay	X					
Santa Barbara	X					
Channel Islands Harbor	X	X				
Marina Del Rey	X	X				
Huntington Harbor	X	X				
Anaheim Bay	X	X				
Newport Harbor	X	X				
Dana Point	X	X				
Oceanside	X	X				
Agua Hedionda Lagoon	X					
Mission Bay	X	X				
Avalon Harbor	X					

MLML sampling protocols were designed to maximize the probability that NAS would be detected by directing effort to locations and habitats most likely to have been colonized by these organisms. Sampling focused on areas within harbors and bays that had a high potential for ballast water release, on calm backwaters where species could collect and flourish, on recently established docks which could provide a comparison to growth on older docks, and on habitats at harbor entrances. Within these general areas, priority was given to active and inactive shipping berths, fishing vessel docks, recreational marinas, aquaculture facilities, and newly constructed structures. Sample sites were spread throughout each port, harbor, or bay to give spatial representation and to accommodate differences in tidal flushing and mixing. Because habitat differences can influence larval recruitment and subsequent colonization, the sampling strategy also encompassed multiple depths, substrates, and light exposure conditions.

The HSUF conducted sampling in Humboldt Bay, focusing on the fish, benthic, and fouling communities. Beginning in July 2000, HSUF researchers collected benthic samples at 87 sites, epifaunal samples at 21 intertidal and 5 marina locations, and fish samples at over 300 locations throughout the Bay. Samples were collected during the mid- to late summer to minimize the collection of large numbers of juvenile specimens which occur in the spring months and are often difficult to identify. Sampling for algae occurred at 58 sites with hard substrata where green, red, and brown algae might grow. Several soft-bottom sites were selected as potential locations where the flowering plant *Zostera japonica*, a suspected invader in the Bay, could thrive. In addition, settling plates, made of standardized PVC panels (National Research Council[1] 1996), were used to collect fouling organisms. All specimens were sorted and identified in the laboratory by taxonomic specialists with expertise in the marine invertebrate species of Humboldt Bay, as well as the benthic species of the Bay and adjacent outer coast. HSUF sampling in Humboldt Bay was supplemented by collection of zooplankton samples by CDFG on a quarterly basis over the course of one year beginning in spring 2001.

SFEI conducted a Rapid Assessment Survey in Southern California, focusing primarily on the fouling community in selected sheltered waters from San Diego to Oxnard, with sampling sites chosen to represent conditions in the three major port areas of the region, San Diego, LA/LB, and Port Hueneme (Cohen et al. 2005). The Rapid Assessment Surveys were intended to supplement other sampling surveys in these areas. A team of taxonomic experts was assembled to conduct the sampling and identification of organisms at 22 sites in the study area. Samples were collected primarily from the fouling community on docks and pilings, with some additional samples from the adjacent soft benthos, nearby intertidal and selected subtidal habitats. Specimens were identified in the field followed by confirmation in the laboratory by the expedition team, as well as taxonomic specialists at the Los Angeles County Museum of Natural History and the San Diego Ocean Monitoring Laboratory.

Supplemental Studies

To maximize the resources available to collect data and complete the picture of NAS invasions along the California coast we incorporated the results of three other recent or concurrent surveys: the Los Angeles/Long Beach Baseline Study, the Southern California Bight 1998 Regional Marine Monitoring Survey (Bight 98), and the U.S. Environmental Protection Agency's Western Environmental Monitoring and Assessment Program (WEMAP).

The Los Angeles/Long Beach Baseline Study was an environmental study conducted in the ports of Long Beach and Los Angeles in 2000, which was intended to establish a baseline for the benthic invertebrate community and the larval, juvenile, and adult fish populations, and to update knowledge of the fouling communities attached to rocky rip-rap habitats (MEC[3] 2002). The Southern California Coastal Water Research Project Authority (SCCWRP) embarked on a project to assess the nature and

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[3] MEC Analytical Systems, Inc. Ports of Long Beach and Los Angeles Year 2000 Baseline Study. ORTEP Association, "Pathways of Introduction and the Ecological and Economic Impacts of Invasive Species", http://www.ortepa.org/pages/ei26.htm , accessed May 2002.

relative magnitude of seasonal and climatic variation in benthic invertebrate populations as part of the Bight 98 Survey (Ranasinghe et al. 2005). Coastal WEMAP was a regional program to collect coastal and estuarine infaunal samples from California, Oregon, and Washington during 1999 (US EPA[4] 2001).

Introduction Status, Vectors, and Origin

We categorized the introduction status of taxa as non-indigenous, cryptogenic, or "nativeX". Non-indigenous species are those plants and animals that are living outside their natural geographic boundaries. Cryptogenic taxa are those that are neither demonstrably native or introduced (Cohen and Carlton 1995, Carlton 1996). These taxa have been identified but their native range or region is unknown. In some cases, taxa could not be resolved to species level, so were conservatively assigned "cryptogenic" or "unknown" introduction status. For these unresolved taxa, introduction status was determined on a case-by-case basis. In some instances, if we were confident that all the species from a particular genus were non-indigenous to California, we assumed that any species from that genus found in California was introduced. The introduction status of each taxon was based on documented research and personal communication with taxonomic experts. NativeX is a term that describes species that have been classified as native to California, but were found outside their previously known geographic range. The nativeX designation connotes a possible range extension for these species, which may or may not have been facilitated by human action.

We labeled taxa that could not be identified unambiguously as "non-distinct" and used the term "distinct" to indicate taxa that unambiguously represent a unique taxon. Many genera identified in the study have at least one species that is indigenous to California. Thus, it was often unclear whether an organism identified as "*Genus sp.*" represents a unique (distinct) species and/or whether that species is native or introduced. Unless otherwise noted, we have reported only "distinct" taxa in the summary figures, which results in a somewhat conservative listing of introduced and cryptogenic species, but avoids the problems associated with counting a genus as a distinct taxon when it may not be.

Many of the species included were collected from more than one site within the specified harbor areas but, unless otherwise noted, were counted only once in the summaries. However, all summaries of introduction vectors include species in more than one category if the literature indicated that they were polyvectic (having multiple potential vectors). Non-distinct taxa and cryptogenic taxa were not included in vector summaries.

The regions of origin of NAS were classified into eight major oceanic quadrants: northeast Atlantic, northwest Atlantic, southwest Atlantic, northeast Pacific, northwest

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[4] U.S. EPA. 2001. National Coastal Assessment: Field Operations Manual. U. S. Environmental Protection Agency, Office of Research and Development, National Health and Environmental Effects Research Laboratory, Gulf Ecology Division, Gulf Breeze, FL. EPA 620/R-01/003. pp72.

Pacific, southwest Pacific, and Indian Ocean. Some records from the literature regarding the nation or region of origin for NAS were either speculative or very general. Some data sources listed very generic possible origins, such as "Atlantic" or "Asia" or listed a number of potential native ranges that spanned most of the globe (so-called "cosmopolitan" species). Such species were included in each of the regions of possible origin identified in the literature.

RESULTS

State-Wide Totals

A total of 352 distinct non-indigenous taxa was identified from the literature and field surveys during the course of this investigation. In addition to these introductions, 393 other taxa were either of uncertain origin (cryptogenic, 246), represented range extensions within California (nativeX, 11), or could not be identified to the required taxonomic level (non-distinct, 136) (Figure 2).

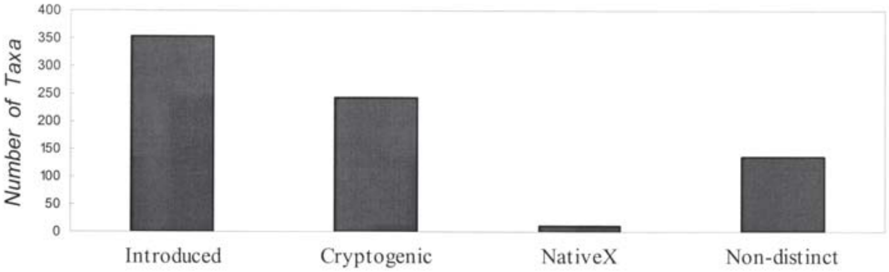

Figure 2. Numbers of non-indigenous taxa in coastal California waters by introduction status category.

Distinct non-indigenous taxa represented 24 phyla, but 4 phyla accounted for greater than 75% of non-indigenous taxa: Annelida, Arthropoda, Chordata, and Mollusca (Figure 3). Annelids, primarily polychaete worms, were the dominant phylum, comprising 33% of the non-indigenous taxa identified (52 introduced and 147 cryptogenic). Arthropods were the second most abundant phylum identified, comprising 22% of non-indigenous taxa (89 introduced and 41 cryptogenic). Amphipods were the most common group of arthropods identified. Chordates (primarily fish and tunicates) accounted for 13% of non-indigenous taxa and molluscs made up 10% of the total. Although most non-indigenous organisms were found in marine habitats, the vast majority of the fish species identified were from fresh and brackish water habitats, including the Sacramento-San Joaquin Delta and the location of two primary study sites, the ports of Sacramento and Stockton.

Eleven new NAS were identified in this study that had not been found in previous

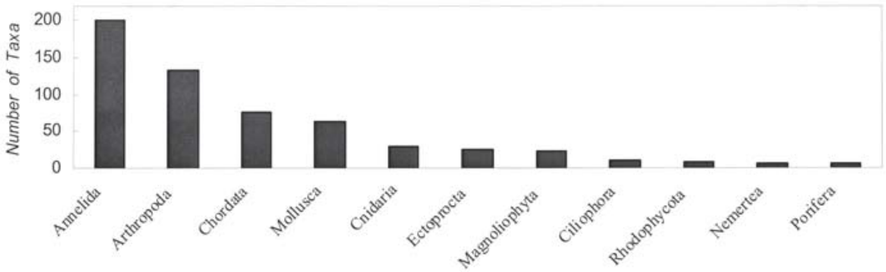

Figure 3. Non-indigenous taxa in coastal California waters by phyla.

studies. In Humboldt Bay, newly found taxa included three polychaetes, *Boccardiella hamata, Euchone limnicola,* and *Fabricia sabella*, an amphipod, *Incisocalliope nipponennis,* and the eelgrass, *Zostera japonica. Alderia modesta*, a gastropod, was observed in northern California. Newly observed taxa in southern California included the amphipod, *Phtisica marina,* in Port Hueneme; the isopod, *Munnogonium wilsoni,* in LA/LB Harbor; the isopod, *Pleurocope floridensis,* in Avalon Harbor; the green alga, *Caulerpa taxifolia*, in San Diego County; and the branchiopod, *Eulimnadia texana,* along the coast.

Across all locations, shipping was the most common probable introduction mechanism for NAS, with ballast water and hull fouling being the most common probable subvectors (Figure 4). The majority of the species introduced to California appear to be native to the northwest Atlantic, the northwest Pacific, and the northeast Atlantic (Figure 5).

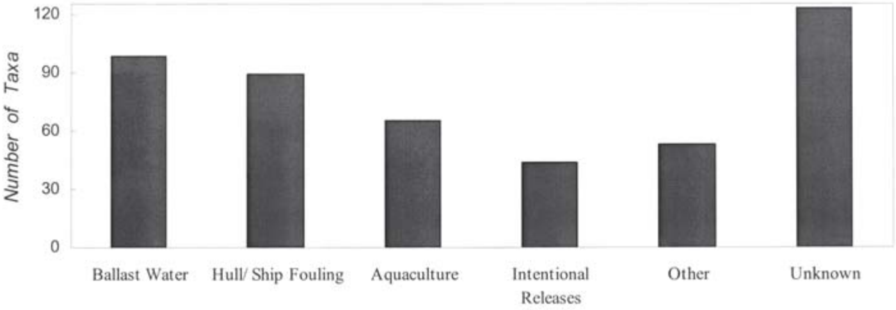

Figure 4. Introduced species in coastal California waters by vector. “Other” includes aquarium releases, fish market dumping, escape from cultivation, accidental introduction with ornamental plants or game fish, and solid ballast. Only “distinct taxa” are included. Species with multiple potential vectors have been counted in more than one category.

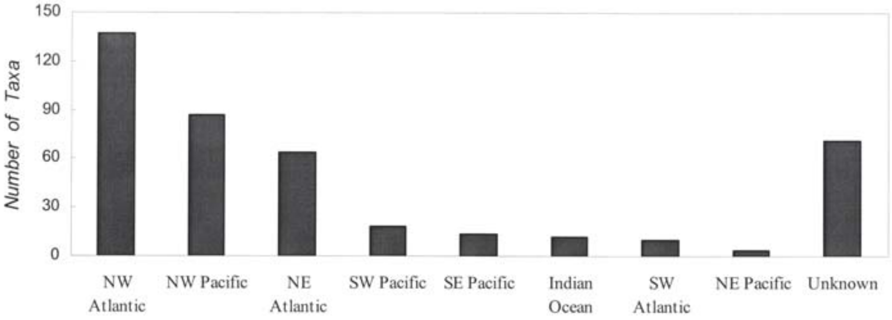

Figure 5. Non-indigenous species in coastal California waters by region of likely origin.

Major Harbor Areas

All the major harbor areas in California have received significant NAS introductions (Figure 6). Each major commercial harbor area of the state had between 50 and nearly 250 species that are either clearly non-indigenous or considered to be very likely non-indigenous. San Francisco Bay had the greatest number of NAS, but the other major port, LA/LB, had only slightly fewer NAS. The major harbor areas had a number of NAS in common; San Diego Bay and LA/LB Harbor shared 40 NAS, and 59 NAS that occur in San Francisco Bay also occur in Humboldt Bay. However, quantitative comparisons among ports or bays are difficult because sampling methods, seasons, and effort varied considerably among the different studies.

The primary introduction pathways differed somewhat for each of the major harbor areas (Figure 7) and the number of "unknown" vectors was substantial. The combination of ballast discharges and hull fouling were the primary potential mechanisms of introduction in all areas except the freshwater ports of Sacramento and Stockton (Inland Ports). Intentional introduction, primarily of fish species, was the leading probable vector in the Inland Ports and in the Delta. Hull fouling was the most common introduction probable vector in four harbors, Humboldt Bay, Port Hueneme, LA/LB,

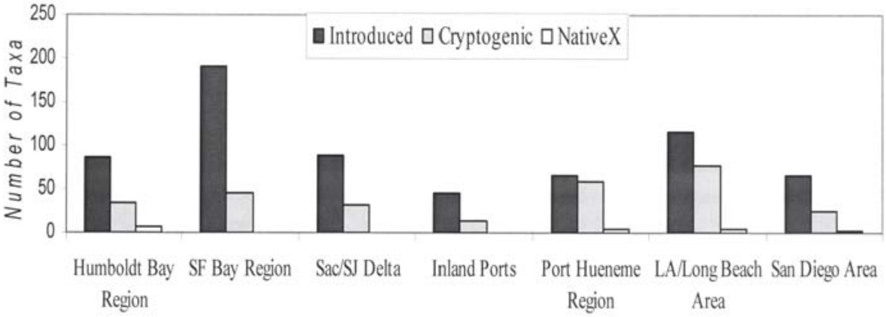

Figure 6. Non-indigenous species in major harbor areas of California.

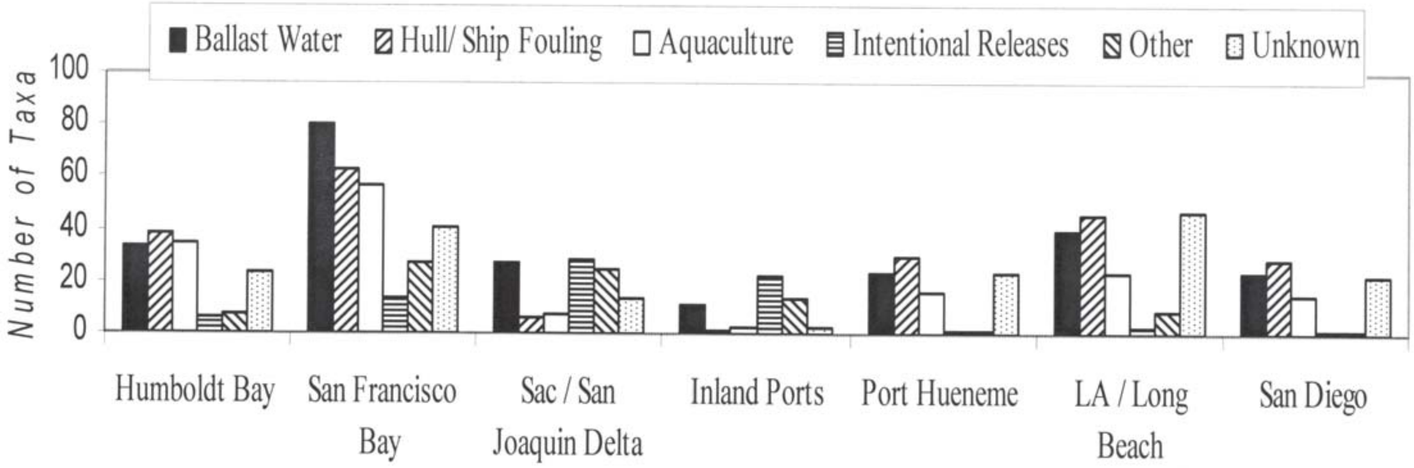

Figure 7. Primary introduction vectors in major harbor areas of California. “Other” includes aquarium releases, fish market dumping, escape from cultivation, accidental introduction with ornamental plants or game fish, and solid ballast. Only “distinct taxa” are included. Species with multiple potential vectors have been counted in more than one category.

and San Diego. Ballast water was the next most common probable vector in these regions but was not the dominant probable vector in any area except San Francisco. Aquaculture was the second most common probable vector in Humboldt Bay and the third most important source of introductions in San Francisco, Port Hueneme, LA/LB, and San Diego.

Minor Harbors

Substantial numbers of non-indigenous taxa were also found in the smaller ports and bays. Over 70 non-indigenous taxa were identified in Tomales Bay (Figure 8). Morro Bay, Bodega Bay, and Oceanside Harbor also contain high numbers of NAS.

As with the major harbors, the shipping vectors, particularly hull fouling, appear to be the primary means of introducing new species to smaller ports. Hull fouling is the leading probable vector in eight of the selected harbors and the second leading probable vector in the remaining four areas presented (Figure 9).

DISCUSSION

This study confirms that there have been a substantial number of aquatic species introduced to coastal ecosystems of California and that all areas sampled showed some evidence of introductions. NAS totals were generally highest in the two major commercial ports, San Francisco and LA/LB. These ports receive the largest amount of ship traffic and therefore have the greatest exposure to vessel-related pathways of introduction. However, the smaller commercial ports (Humboldt Bay, the Sacramento/San Joaquin Delta, the Inland Ports, Port Hueneme and San Diego) and the many small harbors, bays, and estuaries along the coast also have a substantial number of NAS.

Different methods among the major harbor areas impaired our ability to make meaningful quantitative comparisons. For example, while our data suggest that San Francisco Bay continues to be, as once described, one of the most invaded ecosystems in California, if not the world (Carlton and Cohen 1995), this conclusion may be biased by the extensive monitoring effort in this region. Drake and Lodge (2003) speculated that this reflects a greater investment of research in San Francisco Bay and that NAS in other areas may persist undetected because of a lack of search effort. They demonstrated that the San Francisco Bay and Delta, although known to have a large number of NAS (Cohen and Carlton 1998), is of relatively minor importance as a source of introduced species for other ports. Contrary to this conclusion, however, our study shows that San Francisco Bay and Humboldt Bay have a high number of NAS in common, indicating a high likelihood of cross-inoculation between California embayments. Ongoing CDFG studies should help evaluate this potential source of bias.

Vectors

Data from this study suggest that shipping is the main probable vector responsible for introductions of aquatic species in California. Ruiz and others (2000) found that

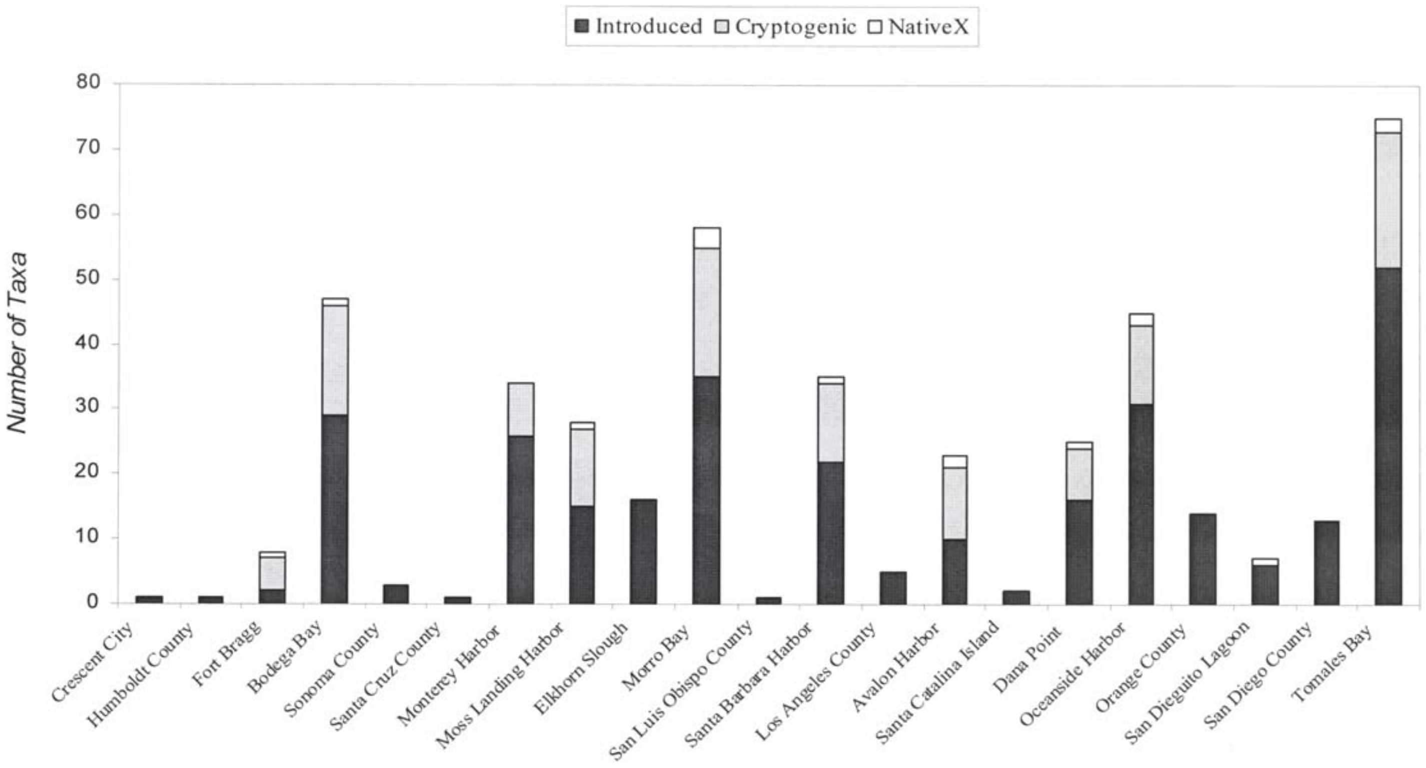

Figure 8. Non-indigenous species in minor ports and bays in California.

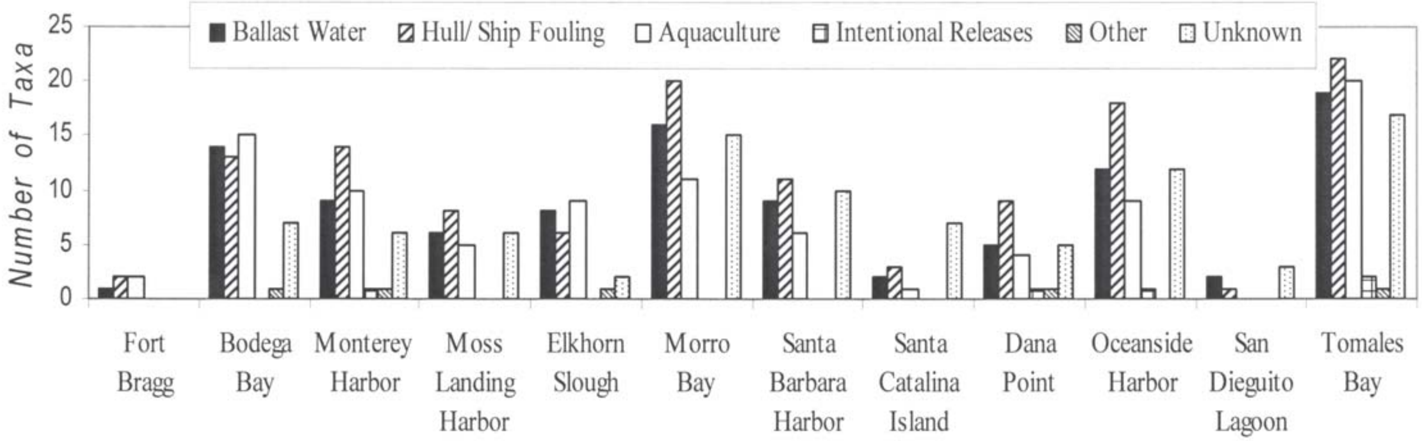

Figure 9. Primary introduction vectors in selected ports and bays of California. “Other” includes aquarium releases, fish market dumping, escape from cultivation, accidental introduction with ornamental plants or game fish, and solid ballast. Only “distinct taxa” are included. Species with multiple potential vectors have been counted in more than one category.

shipping was the sole vector for 51% of initial North American invasions and 59% of the repeat invasions. Discussion of introduction vectors is complicated by the fact that many taxa are polyvectic (Carlton and Ruiz 2005). A further complexity is that the relative contribution of the ballast water and hull fouling subvectors is extremely difficult, if not impossible to distinguish (Fofonoff et al. 2003). The field collections in our study specifically targeted areas likely to receive ballast water and, thus, may be over-estimating the importance of the shipping vector statewide. Despite these concerns, it is obvious that shipping traffic plays a significant role in dispersal of new species into California waters through a combination of ballast discharges and hull fouling.

Hull fouling, which is a dominant source of introductions in many harbors, appears to have had less of an impact in the Sacramento/San Joaquin Delta and Inland Ports. It is likely that low salinity is a limiting factor for marine fouling organisms, acting as a barrier to survival. Freshwater exposure has been used as an effective means of eliminating marine fouling organisms from ship's hulls (Brock et al. 1999).

It also appears that hull fouling may play an even more important role in the smaller harbors than in the larger ports. Wasson et al. (2001) found that 70% of NAS in Elkhorn Slough were associated with hull fouling. They noted that many resident fishing and pleasure boats frequently travel up and down the coast from port to port and that there is also an annual migration of fishing boats along the California coast, providing ample opportunity to deliver NAS to such small estuaries. However, our study disproportionately sampled fouling communities in the smaller harbors, which may have resulted in an over-estimation of the role of ship fouling.

Although many of the introductions have come by ship, aquaculture and intentional introductions (primarily of fish) were the probable vector for most of the NAS observed in freshwater and euryhaline habitats. Excluding anadromous species, no successful introductions of fish have been made to the marine waters of California (Dill and Cordone 1997). It appears that aquaculture has the same or an even greater influence than ballast water discharges outside the major harbor areas.

A substantial number of taxa had unknown vectors of introduction (~28%). It is often difficult, and in many cases impossible, to determine the mechanism of transport with even a moderate degree of certainty. Further study could reduce the unknown element of this question. Tracing invasion history using molecular techniques is one such area of research that may elucidate mechanisms of introductions.

Although this study has established some of the probable vectors of initial introduction of NAS to California from foreign ports, the mechanisms of NAS movement within California are poorly understood. Whether NAS are introduced directly to smaller bays and estuaries or spread secondarily from the larger ports is also not well understood. Initial introductions from ballast, hull fouling, or aquaculture may be exacerbated by fishing or recreational boats that move between the large harbors and smaller bays. Intra-coastal shipping may also play a key role in the spread of NAS between major ports. In this investigation, we identified a number of NAS that co-occur in the major ports, which may indicate intracoastal spread of non-indigenous taxa. Since survivorship of organisms in ballast water declines with increasing voyage duration, short domestic voyages have the potential to transfer greater abundances of organisms than longer foreign voyages (Lavoie et al. 1999). Transit time for ships between California ports can be measured in hours, enabling rapid spread of NAS along the coastline via ship traffic. The control of already established NAS populations can only be accomplished if we are able to prevent the spread to nearby ports, bays, and estuaries. Further research is needed to refine our understanding of the extent of secondary or tertiary introductions and spread of NAS both along the Northeast Pacific coast and within California.

Origins

The majority of the species introduced to California appear to have come from the northwest Atlantic, the northwest Pacific, and the northeast Atlantic. These are also the regions of the world from which California receives a considerable amount of ship traffic as well as the source materials for much of its aquaculture. Ruiz and others (2000) also found that most marine invasions to the West Coast originated from the Indo-West Pacific (including Western Pacific) and Western Atlantic and that introduction routes corresponded directly to the dominant trade corridors in historical time. Although native range information can tell us where species originate, it cannot tell us if they came to California directly from their native region or from some intermediate location. To make this determination, information on source region (the probable area from which an introduction occurred) is needed and should be included in future studies.

Sampling Limitations

This survey provides a sound baseline for future research to examine the impact that non-indigenous animals and plants may have on the health of the aquatic environment of California’s coast, but these summaries undoubtedly underestimate the true number of NAS in California because of sampling limitations that included seasonal effects, under-representation of certain habitats, and under-representation of small organisms.

The seasonal timing of sampling created the possibility that some non-indigenous taxa were not observed. Settling plates used in Humboldt Bay revealed that there are many fouling community species that establish themselves in the spring and disappear by mid to late summer; thus it is possible that due to our sampling design we may have missed some NAS whose ease of collection varies seasonally.

Although efforts were made to sample a broad range of habitats in the many areas studied, limited time and resources caused sampling in the minor ports, bays, and marinas to focus primarily on the fouling community. Since it was not possible to sample all subtidal and intertidal habitats or include all communities in the study design, the sampling effort may have under-represented the full NAS impact in some areas. Two habitats, the crevices within the rocks and rip-rap of break-waters and the hard bottom benthic substrate were not sampled successfully in this study. Attempts were made to trap fish in the rocky crevices, but no specimens were caught. The hard bottom substrate was sampled in the LA/LB Harbors but there were insufficient resources to sample this habitat in other areas of the state. As this habitat typically supports a diverse community, efforts should be made to collect samples from these areas in any future research.

We focused our sampling of the plankton community on zooplankton, to the exclusion of phytoplankton. As the phytoplankton community is easily transported by ballast water, there is a potential for introduced phytoplankton species occurring in our bays and estuaries. Phytoplankton species are the cause of some of the detrimental blooms along the east coast of the United States which have resulted in major fish kills. This community should be studied in future investigations.

Finally, there is a general pattern that smaller organisms tend to be under-sampled and the quality of systematic and biogeographic information diminishes with organism size (Ruiz et al. 2000). Therefore, the available baseline information for small organisms and microorganisms is poor relative to large invertebrates and vertebrates.

Ongoing Studies

Continued monitoring of California coastal waters is essential for determining if the rate of new introductions is changing and whether recent ballast water regulations have been successful in limiting introductions of new organisms. Also, while we did not measure relative abundance or the proportion of native to non-native taxa in this study, future monitoring will include relative abundance data, which will be used to determine the extent of impact that introduced organisms are having on the native biota and coastal ecosystems and should give us a better basis for determining the relative risk that NAS may pose should they spread to other areas of the state. Planned or ongoing monitoring for NAS in California includes re-sampling the harbors and ports, sampling along California's outer coast, and a survey of San Francisco Bay. As biological invasions of marine and estuarine habitats are increasingly studied, knowledge of the natural histories of non-native species will be vital to understanding and predicting new invasions. The present investigation should advance our knowledge of invasion vectors, sources, and impacts.

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