Aquatic Invasive Species Vector Risk Assessments:
The role of fishing vessels as vectors for marine and estuarine species in California

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Background

Bays and estuaries are among the most degraded and altered ecosystems in the world. In concert with habitat loss, pollution, and over-exploitation, aquatic invasive species (AIS) have had a profound effect on the functioning of near shore systems that result in serious ecological and economic losses. The bays of California's coastline, and San Francisco Bay in particular, are globally significant hotspots of introductions caused by a variety of transfer mechanisms (vectors) that have operated in the state over centuries. For this reason, prudent and effective vector management has been a priority for the state and it is a globally recognized leader in the realm of commercial ship vector management.

There are additional vectors that have received little research and management attention, however, and their role in introductions and spread of AIS throughout California is largely unknown. This study was commissioned by California's Ocean Science Trust to characterize the role of one such vector – commercial fishing vessels.

Aim

The purpose of this study was to investigate fishing vessels as vectors of introduced species in California. The structure for characterizing the fishing vessel vector followed a science-based vector management framework in order to: (a) evaluate the invasion history of California and vector associations of species to determine the possible role of fishing vessels in the initial establishment and spread of AIS in the state; (b) characterize the vector's current standing stock of vessels, their route and tempo patterns, and the biota associated with transient coastal vessels; (c) assess the invasions impact literature as it relates to AIS in California that have fishing vessels as a possible vector; and (d) describe the critical control points to disrupt the vector, tools that can be used can be taken advantage of them, and the statewide options for generating vector management action by the fishing fleet.

Methods

We used an extensive database of California's AIS history to assess current patterns of AIS distribution, timing of detections, and vectors responsible for the introduction and spread. The primary focus was on biofouling, which is the primary mechanism of species transfers by fishing boats. Then we evaluated the arrival patterns, voyage routes, seasonal trends, and harbor connectivity of the existing fishing fleet in the state. We also examined literature records of species associated with transfers on boats and sampled coastally transient boats in California to describe the boat vector biota. Our review of impact literature focused on three species-rich AIS taxa in California (crustaceans, molluscs, and algae) to provide information about known or potential impacts by species in the state. Finally, we conducted a vector process analysis to determine the critical control points (similar to Hazard Analysis and Critical Control Points [HACCP] approach) that exist for fishing vessel AIS transfers and evaluated the vessel scale and state-scale approaches that may be utilized for effective vector management.

Findings

Fishing vessels are a possible vector for 74% of the 278 AIS known to be established in California. The accelerating invasion and spread rate in the state and the diversity of organisms that can be linked to vessels play important roles in this high vector association. However, historical and current voyage routes suggest that transoceanic and interoceanic introductions to the state are unlikely to have occurred via fishing vessels. In addition, all of the AIS that can be associated with fishing vessel transfers are polyvectic (possibly multiple vectors), with extensive overlap among commercial ships, recreational boats and fishing vessels. Nonetheless, 87% of the most recent decade of new introductions and new records of spread (133 AIS and 26 bays) have fishing vessels as a possible transfer mechanism. Also, while there is high variation in the numbers of AIS occurring among bays, fishing vessels can be linked to an average of 85% (±10%) for bays with a current standing stock of twenty or more species.

The contemporary fishing fleet in California consists of more than 2400 vessels that make at least 50,000 arrivals to harbors annually. Although a slight majority of these vessels (52%) are resident boats (reporting arrivals to just one harbor), the proportion of vessels that arrived to each harbor over a four year period was higher for transient vessels than sole-port vessels. Seasonal variation in the arrivals patterns was pronounced in some bays (e.g. San Diego), but in contrast to recreational vessels, the state wide monthly pattern of arrivals was not seasonally pronounced. Port connectivity was highest among subsets of adjacent bays and there were also transient vessels that voyaged the entire length of the state during the data period (Jan 2005 to Dec 2008). Bay connectivity for fishing vessels includes overlap with other vessel types, but also differences in pair-wise linkages and in intensity of connections (e.g. creating links between shipping and non-shipping bays). In addition, there were 356 boats that reported arrivals in California and Pacific Northwest States. Vessel sampling revealed a wide range of biofouling richness and extent among boats (n=53) but we were surprised by the proportion of vessels at the upper end of the distribution that transfer thousands of organisms and up to 80 species as ‘floating reefs’ associated with their submerged surfaces.

The impacts literature review highlighted the paucity of impacts literature that exists and the unevenness of effort among species. There were data for 22 AIS with fishing vessel biofouling as a possible vector, but few of these studies have been carried out in California. There are other highly impacting AIS in California with fishing vessels as a possible vector, but this review did not capture the full scale of these elusive data.

Finally, we identified three critical control points in the vector process (colonization prevention, transfer disruption, and release containment) for fishing vessel biofouling and the tools that can be employed on a vessel-scale to take advantage of these. We also assessed the range of options (and their likely issues and outcomes) that the state can pursue to apply a commercial fishing vector management policy in the state, from retaining the status quo to full regulation and enforcement.

Conclusions

Fishing vessels are an important maritime vector in California because they may be associated with transfers of 74% of the AIS currently established on the state’s coast. They also number in the thousands, make arrivals to harbors annually in the tens of thousands, create strong connections among harbors that other vectors do not, travel the length of the state’s coast and beyond, may play a role in AIS spread by fishing gear, and may act as an important final step in the cause of bait AIS introductions. In short, they are a part of the vector ratcheting effect that occurs when multiple vectors and AIS populations interact in space and time.

Our recommendation for a state policy would include scientifically polled outreach of the commercial fishing community to evaluate (a) vector awareness, (b) uptake of vector management, and (c) changes over time in these two metrics (a and b) after intensive outreach. The value of such an approach is that it is data driven, providing insight on the human population engaged in the vector activity, the species transfers that occur after initiation of the policy, and an evaluation over time of whether vector strength (invasions caused by the vector) has diminished.

2. INTRODUCTION

California receives marine and estuarine organisms via anthropogenic transfer mechanisms (vectors) from all over the world and contributes to the biota being transferred around the world. This interchange of biota introduces novel exotic species into native communities and habitats, with the effect of altering the ecology of the near shore environment. Because marine species are introduced into maritime hubs, bioinvasions tend to occur in bays and estuaries where human activities, man-made infrastructure, and multiple vectors interact. Thus, when we consider that species invasions affect biodiversity and environmental quality – along with habitat destruction, overexploitation, pathogens, and pollution (Wilson 1992; Wilcove et al., 1998) - it can be no surprise that bays and estuaries are among the most altered and degraded ecosystems in the world (Carlton, 1996).

California's bays and estuaries are a geographical foundation for a rich history of bioinvasion studies (Carlton, 1979), the results of which have been remarkable. San Francisco Bay may be the most invaded bay in the world (Cohen & Carlton, 1998) and the state as a whole has a regional richness of aquatic invasive species (AIS) to which only two other regions of the world can compare (Hawaii and the Eastern Mediterranean; Ruiz et al., 2011a). The number and diversity of introduced organisms is a function of the combined vector strength of transfer mechanisms that have operated in the state. The prolificacy and variety of these vectors, along with the spatial and temporal scales of their operation, have provided a rich introduced flora and fauna that the state's waters did not repel and with which its native biodiversity must coexist.

The vectors responsible for maritime AIS introductions, to California and elsewhere, are numerous (Minchin et al., 2009). They include several sub-vectors of shipping and boating, canals, aquaculture transfers, fisheries development, live bait and seafood imports, ornamental species imports, research activities, biological control efforts, habitat management, and more. The foremost vector-research focus globally has been on commercial shipping because of (a) its dominance among other vectors in creating broad-scale patterns of AIS distributions and (b) the availability of extensive, detailed, centralized records of vessel activities and routes; certainly the focus varies among regions where other vectors, like canals, predominate (Gollasch et al., 2006) or on smaller scales in which ships do not operate (Wasson et al., 2001). This spotlight on shipping has led to international, national and regional efforts to reduce the invasion footprint of ships. An equivalent management attention on other vectors has yet to emerge.

The Fishing Vessel as a Vector of AIS

One transfer mechanism that has received little attention in California and around the world is the fishing-vessel vector. The primary means of species transfers by fishing vessels is biofouling (i.e., organisms attached and associated with underwater surfaces), meaning the cause of transfers is inadvertent. Fishermen activities, such as the release of live bait from bait wells, can also provide AIS with a delivery mechanism to the marine environment, though this is largely the final step in a live bait vector process rather than a vessel transfer mechanism. Contaminated fishing gear can also transfer species, but we consider this to be a lesser sub-vector of fishing vessels (compared to biofouling) that is associated more with the localized spread of established species (e.g. Relini et al., 2000). Our focus in this study was on the vessel itself as a vector, but further work is warranted to determine if there are any special cases of species transfers associated with these sub-vectors in California.

Given the longevity of fisheries and the extent of fishing fleets around the world, it is somewhat surprising that there has not been more interest in its role in transferring AIS. This may be a function of the size of boats and an assumption of limited voyage range over which individual fishing vessels travel or its demotion under the behemoth status of commercial shipping in this field. However, it is also likely that the overriding issues of resource exploitation that are inherent in fisheries provide enough conflict with environmental protection and sustainability as to render biofouling transfers an afterthought, or no thought at all.

The existing evaluations or incidental reports of fishing vessels as vectors tend to emanate from New Zealand and Australia in recent years. Hutchings et al., (2002) linked fishing vessels from Indonesia to the arrival of the bivalve, *Mytilopsis sallei*, to Darwin, Australia. In another reported bivalve invasion mediated by fishing vessels, Hayes et al. (2005) used an example of an introduction to Cairns Seaport by *Perna viridis* as a test case to evaluate scientific and cost considerations for detection and eradication of marine pests.

A newsworthy vector event involving a Russian super trawler operating in New Zealand waters is infamous in the biofouling vector literature (Hay & Dodgshun, 1997). The vessel *Yefim Gorbenko* traveled to the southern Hemisphere after a long lay up in the Black Sea and it was discovered to have extraordinary levels of biofouling, dominated by mussels, on its hull. The discovery resulted in an eventual dry docking and removal of an estimated 90 tonnes of biofouling for land fill, after many months in New Zealand. Hay & Dodgshun (1997) reported that material was not examined fully by taxonomists, but it is likely that many nonnative species were present.

A recent comprehensive account of fishing vessel biofouling was conducted by Piola & Conwell (2010) in New Zealand. They sampled the hulls of eleven fishing vessels that had arrived from outside of the country's territorial waters as part of a vector project commissioned by Biosecurity New Zealand. Although the study found that biofouling levels were generally low among boats, they found biofouling on eight of the eleven vessels and 59 morpho-species. Among the 37 specimens identified to species level, 54% of were nonnative to New Zealand. Furthermore, nine of the AIS are not known to be established in New Zealand, and four of these species had not previously been recorded on other vectors or as failed introductions in New Zealand. The overall conclusion from this study was that biomass on fishing vessels that had traveled overseas (not solely domestic boats) was generally low, but established and novel AIS were still a part of the biofouling communities being transferred.

Accounts from elsewhere are limited, although Farrapeira et al. (2007 & 2011) did include reports of fouling sampled from fishing boats from studies in Brazil. These vessels ranged from laid-up boats confined to certain ports, through local and regionally transiting fishing boats and were sampled in conjunction with other vessel types. The differences between vessel types were not considered important relative to lay-up history and range of voyage activity.

We know of no evaluation of fishing vessels from California or the West Coast of North America.

California Commercial Fishing

California's marine fisheries are an important economic, cultural and social component of coastal life in the state dating back millennia. Archaeological evidence suggests this history extends back at least 8000 years, and site excavations provide evidence not only of social organization in pre-historic communities, but the types (and species) of fish exploited (Noah, 1998). These included pelagic species, such as sardines, anchovies, mackerel, and tuna which suggests early people may have traveled some distance from the coast to catch fish (Noah, 1998). There was no suggestion that people traveled any great distance by boat to fish along the coast, however.

The idea of historic fishing communities exploiting fisheries at local sites rather than traveling along the coast is reinforced by Native American maritime fishing described by Arthur McEvoy (1986). McEvoy reported that life for California hunter-gatherer Indians was "sedentary" and they "generally lived and died within ten to fifteen miles of their birthplaces." Furthermore, their "economies were first and foremost the products of local resources." While salmon fishing was by far the most important of the aboriginal fisheries, there were two maritime cultures, the Chumash and the Gabrielino, which exploited marine fishes between Point Conception, San Pedro Bay, and the islands offshore (McEvoy, 1986). Additional features of Native American society that promoted sedentary rather than transient fishing communities, as reported by McEvoy, were a desire to under-exploit resources to ensure their longevity and to designate rights over resources such that outsiders were denied access. This latter development played a role in the commercialization of fisheries over time which ended the sustainable and sedentary nature of California's fisheries.

After the state was formed in 1850, there was a diverse immigrant fishing community with different types of vessels exploiting a variety of fish species, but remaining relatively local in range. This contrasted somewhat with the extent of fishing on the East Coast of the U.S., and it was a cause for complaint among some officials that the West Coast fishing industry consisted only of salmon harvesting on the Columbia and Sacramento Rivers and marine fishing only within close vicinity of San Francisco (McEvoy, 1986). This changed by the turn of the century, when the most readily caught inshore species (salmon, mammals, and abalone) declined and technological advances promoted the explosive growth of ocean fishing. Within 15 years, oceanic stocks of salmon, sardines and tuna were being depleted (McEvoy, 1986).

This synopsis underscores two important historical aspects of commercial fishing with respect to vector activity in California: 1) fishing vessels were relatively sedentary and unlikely to have had a major vector footprint until circa 1900, long after the age of exploration had brought ships from other continents to the coast of California; and 2) the development of fisheries on the coast of California provided rich fodder for researchers like Arthur McEvoy interested in the interaction between exploitation of ecological resources and their legal protection.

In modern times, the California Department of Fish & Game (DF&G) manages the ocean fisheries for the state, including registering and permitting issues related to vessels, catch quotas, fish sizes, and seasonal and zonal management (DF&G, 2012). There are records dating back to 1928 on fish landings and the list of species caught in the state extends to at least 336 groups (species and other divisions of commercial landings; Southwest Fisheries Science Center, 2012). The fishing fleet reports landings on a per arrival basis per vessel, and these data (defining the current fleet) were a source for one component of this vector analysis.

2.1 Aims

The purpose of this study was to investigate fishing vessels as vectors of introduced species in California. This is the first such analysis for fishing vessels in the state, to our knowledge, and one part of a broader investigation into six AIS vectors commissioned by the California Ocean Science Trust. The structure for characterizing the fishing vessel vector followed the science-based vector management framework outlined by Ruiz & Carlton (2003). This framework includes several components that contribute to vector management action and subsequent monitoring of the efficacy of that management. The steps taken in this study included evaluation of vector strength, vector analysis, and vector disruption. An additional step - examination of reported impacts of AIS already established in California and associated with fishing vessels – was also undertaken to determine the consequences of introductions linked to fishing vessel activity.

Invasion History & Vector Strength

Vector strength is a measure of the number of introductions that have resulted from a vector. Because introductions are usually not detected in real time, it is rarely possible to determine the exact time and location, or specific source (vessel or action), for an AIS being introduced and becoming established. Therefore, a broadly accepted method is to evaluate the invasion history of an area and deduce the vector or vectors responsible for incursions. This method utilizes timing, location, and life-history characteristics of species to determine vector associations with each introduction event. Our goal was to characterize California's invasion history with respect to vector patterns and the role fishing vessels may have contributed to these patterns. After briefly outlining the state invasion history, we honed in on possible vector associations of fishing vessels as a component of biofouling and non-biofouling transfers for the whole state (first records and current standing stock of AIS, as well as the differential patterns of vectors ascribed to AIS among bays). This was achieved using data from the National Exotic Marine and Estuarine Species Information System (NEMESIS) for California (provided by the Marine Invasions Lab at the Smithsonian Environmental Research Center [SERC]).

Vector Analysis

Our vector analysis of current fishing vessel operations in the state consisted of two components: 1) the spatial and temporal (seasonal) patterns of fishing vessel traffic and 2) biota associated with small boats (rather than commercial ships) and coastally transiting vessels in California. Evaluations of vessel traffic and flux into and within California provide an understanding of where vessels arrive and how fishing harbors (bays) are connected to each other via transient fishing vessel voyages. The vector-associated biota component provided insight into the types of organisms that have been recorded on the submerged surfaces of boats (using a literature search) as well as a sample of biota currently transiting the state's coast as biofouling on boats (from sampling transient boats at Californian harbors).

Impacts of California AIS associated with the fishing vessel vector

Carlton & Ruiz (2003) did not include an impact component in their framework for vector analysis and management, presumably because of the indirect nature of such an analysis – species cause impacts rather than vectors. Nonetheless, we considered it instructive to examine the AIS impact literature to determine the number and nature of impact studies among species associated with fishing vessels. It was not possible to undertake an impact evaluation of all AIS currently established in California, so this component was restricted to three AIS rich groups - algae, molluscs and crustaceans.

Vector disruption

The process underlying the way in which a vector works can be broken down into subcomponents that may provide clues as to where management activities could be targeted to interrupt the transfers of species. The goal is to evaluate critical control points in the vector process and the tools that can be used to close off the movement of species. We assessed the fishing vessel vector process in this manner, and evaluated the costs and benefits to implementation of management actions at the vessel level. We also reported on state level vector management as it pertains to fishing vessels.

In the discussion, we evaluated all of these elements together and provide an outline of vector management strategies that could be pursued for this vector.

3. METHODS

3.1 Invasion History & Vector Strength

California's coastal marine and estuarine invasion history

A database of AIS for California was created from the National Exotic Marine and Estuarine Species Information System (NEMESIS) provided by the Marine Invasions Lab at SERC. The database has been compiled over many years and contains information on the identity, locations, population status (whether considered to have an established population), timing of first detection, and other details (life-history and impact summaries). The dataset also contains information on salinity tolerance of species and all freshwater taxa were removed for this analysis. Species of uncertain origin (may or may not be native to California) were also excluded so that only known non-native species were included.

Importantly, the invasion-history data set also contains vector information that uses the timing, location and life-history of each introduction to ascribe a vector or vectors considered responsible for transferring the species to its new non-native location. This approach is a broadly accepted one that underpins several important analyses of invasion histories from different regions around the world (Carlton 1979; Cohen and Carlton 1995; Ruiz et al., 2000; Hewitt et al, 2004). However, the vector information in this data set did not include differentiation of biofouling vectors (commercial shipping versus recreational boating versus fishing vessel) until the initiation of this project. These designations were added to the data set for California.

Several analyses were conducted to characterize the invasion history of California and the possible associations with fishing vessel vectors. The statewide taxonomic breakdown of AIS and the temporal trend of AIS detections and accumulation were plotted to provide a brief overview of the extent of the data. Vectors assigned to species first records (initial introductions) were then plotted to evaluate the role of biofouling as a vector in the state. Additional partitioning of the data by vector was used to evaluate the degree to which the current standing stock of AIS in the state can be associated with fishing vessels. We also analyzed the duration between first and most recent records as a function of vessel vectors (which provides some insight about spread of species along the coast). Finally, we evaluated the number of AIS per bay with respect to fishing vessel harbors and vector associations.

For this last comparison, it is important to note that the spatial designations in the invasion history (NEMESIS) database did not align completely with fishing vessel harbors because the database includes areas that are not fishing vessel harbors and because NEMESIS used a watershed spatial network of locations in California. Therefore, the bays used for analyses included data for AIS and fishing arrivals that overlapped exactly (e.g. San Francisco Bay), data that overlapped but for which NEMESIS included additional space outside of the relevant bay (e.g. Santa Barbara), data for which two or three distinct fishing harbors were included in one watershed, and NEMESIS locations in which no fishing harbor was present. This resulted in 32 bay designations from Tijuana estuary in the south to Crescent City in the north. These designations were used for all among-bay comparisons of AIS.

3.2 Vector Analysis

Fishing vessel traffic patterns

Patterns of fishing vessel movements in California were assessed using a data set provided by the Pacific States Marine Fisheries Commission (PSMFC). The data were obtained through the Pacific Fisheries Information Network (PacFIN) and represents a four-year interval of fishing vessel arrivals (January 2005 – December 2008). The data were compiled from fish tickets, which is the required documentation from each vessel arrival to report the type and number (or weight) of fish landed after every arrival. Therefore, each entry in the data set represents a vessel arrival that landed fish; it should be noted that additional arrivals by vessels when they did not land fish would not be captured in these data. Nonetheless, this is the most complete data set of maritime fishing vessel travel history for the state and it provides a conservative (or minimum) estimate of connectivity among bays.

PacFIN identifies and describes at least 136 different types of vessel and gear combinations (http://pacfin.psmfc.org/pacfin_pub/data_rpts_pub/code_lists/agency_gears_grid.txt), which include many sub-types of dredge vessels, line fishing vessel (e.g. long liners), netting vessels (e.g. gill nets, seiners), trollers, trawlers, and other types (e.g. diver fishery vessels). We did not have data on vessel types for our traffic analyses. While vessel type and gears may play a role in vessel behaviors that affect species transfers, the data we gathered on vessel movements was sufficient for our analyses in this report.

Each entry in the data set included the location, date, and an anonymous vessel identifier for each arrival. The anonymous identifier was consistent across locations and times such that vessel flux - arrivals among different ports by the same vessel - could be evaluated (e.g. Vessel 1 that arrived in Crescent City in 2005 was the same Vessel 1 that arrived to San Francisco Bay in 2008). There were two exceptions: PacFIN uses one identifier for certain arrivals, termed zzz vessels, which result in many different boats being assigned the same vessel identifier. The two codes in this data set assigned to zzz vessel arrivals were not included in analyses beyond the initial summary statistics of statewide spatial and temporal trends (because they could not be isolated down to individual vessels). These zzz arrivals accounted for 0.01% of the total arrivals in the data set.

Our analyses of these data focused on characterizing the spatial and temporal patterns of fishing vessel arrivals across the state. First, we examined the statewide distribution of arrivals and the temporal pattern of those arrivals. The PacFIN recording system uses 58 different harbor codes as landing (arrival) locations and we aggregated some (e.g. all harbors within San Francisco Bay) to align statewide spatial arrival patterns with bays and with our analyses of AIS invasion history data. We assessed the pattern of monthly arrivals statewide and for major focal harbors. Then, we separated the vessels that reported more than one location of arrival (transient boats) from those that reported only one location of arrival for the entire four years (solely resident boats). The solely resident boats do not carry a vector risk, at least in the context of this data set, because they have not reported a possibility of transferring biota from one harbor to another. The transient boats, however, had the potential to deliver organisms among different ports. We examined the flux of boats among harbors, port connectivity, the most transient vessels in the data set, and links between California harbors and harbors in the Pacific Northwest (Oregon & Washington).

Vector biota 1: organisms associated with boat fouling

We surveyed the peer-reviewed and gray literature for records of species attached to or otherwise transported by boats (anywhere in the world). These boats included fishing and recreational vessels, but not commercial ships, barges or other platforms (rigs etc). Our initial goal had been to differentiate among fishing and recreational boats, but for the most part this distinction was not made in the literature although recreational boats generally outnumbered fishing boats. We evaluated all boat data to maximize the data set and report general patterns of biota from boats.

For the peer-reviewed literature we used the search terms “invasi*” AND “boat*”, “non-native” AND “boat*” and “fouling” AND “boat” for all years in the BIOSIS search engine (Thomson Reuters). Papers that included records of named organisms (usually species level) sampled from biofouling of boats were identified and the species data within them entered into a database. Additional records were gathered from a search of the reference sections of the initial papers. Further records were gleaned from gray literature including unpublished reports, theses, and notes provided by colleagues. When possible, we included records after corresponding with authors to get further information about species sampled from boats but which were not reported in the papers or reports.

After exhausting our search for papers and reports, we entered into a database as much of the following information that was available for each species sampled: reference, species name (or taxon), location of sampling, date of sampling, life-stage, whether the species was sampled on resident or just arrived transient boats, and whether the authors provided information on whether species were native or non-native to the region where it was recorded. We used three internet sites to assist with these taxonomic classifications: AlgaeBase (http://www.algaebase.org/), Integrated Taxonomic Information System (http://www.itis.gov/), and the World Register of Marine Species (www.marinespecies.org/). Where there was disagreement between these systems, we used AlgaeBase as the authority for the algae, and for invertebrates Abbott et al. 1997 (tunicates) and Carlton (2007). Higher-level taxonomic classification was based on Pearse et al. (1987).

This data set provided a list of species that have been recorded from small boats engaged in recreational travel or fishing. The records come from all over the world and were used to assess the broad taxonomic patterns of species associated with biofouling.

Vector Biota 2: Species sampled on submerged surfaces of transient boats in California

We sampled transient boats upon arrival at dock at San Diego police dock and Santa Barbara Harbor. Our aim during sampling excursions was to sample recreational and fishing boats equally, but despite conversations with dozens of fishermen at their boats, we simply were not given permission to sample many fishing boats. The vast majority of fishermen that we have spoken to during this and other projects politely decline to answer a questionnaire, and generally rule out any possibility of providing permission to sample the undersides of their vessels. They often cite over-regulation of their livelihood as a reason to decline participation in our surveys. We did have the opportunity to sample tourist deep-sea fishing vessels in San Diego and found some to be heavily fouled. However, we declined to collect and process samples because these vessels travel only out-and-back to the same harbor in San Diego. As such, it was not useful to spend time and resources on sample processing having discovered this voyage information, because the species are not transferred to a different harbor and other transient boat sampling took precedence. Additional data for fishing vessels was gathered from Monterey Harbor for a total of 53 boats with vector biota data (49 recreational vessels and four fishing vessels).

Vessels were sampled after a brief questionnaire with the vessel owner and permission was granted to conduct an in-water survey and collection of the boat. The questionnaire was used to gather three categories of information from the boater or fisherman, following the broad outline of questions asked in prior biofouling studies (e.g. Floerl & Inglis, 2005; Davidson et al., 2010): [1] vessel information (type, length and home marina); [2] hull maintenance practices; and [3] timing and locations of transits. Additional questions for fishermen on activities with bait and gear were planned but we were unable to develop the conversations to this point simply because they preferred not to engage with us in much detail on the biofouling issue. Sampling was carried out using SCUBA, whereby two or three divers surveyed the entire length and breadth of the vessel's submerged surfaces, paying particular attention to heterogeneous niche areas (rudders, intakes, propellers, struts, thrusters).

During the surveys, one diver took photographs, video images and notes to document the extent of fouling and record whole-vessel categorical abundance. The six categories were based on a log-scale estimate of abundance ranging from 1-10 organisms through to >100,000 organisms (individuals or colonies). A seventh category of zero biota was also included. This diver also took an image of each niche area which was used to measure percent cover of biofouling per niche area. Several photo-quadrats of hull surfaces were also taken, five of which were selected at random to generate a measure of percent cover of the hull. Hull quadrat images were processed using a point-count method of 100 dots superimposed on the image.

The other diver(s) collected biota samples by carefully scraping and picking biota from the hull and niche areas and placing them in zipped plastic bags. For a majority of vessels, it was possible to collect all organisms encountered because biofouling was not so extensive as to exclude this approach. In cases where biofouling was very extensive, biota were collected from each hull location ensuring all visibly unique morphological forms were included. Samples were initially sorted into morpho-taxa shortly after collection and preserved for further processing to species level (or lowest taxa possible). Certain groups were sent to expert taxonomists for identification or confirmation.

Because of the disparity between sampling of fishing and recreational vessels, data for the few fishing vessels is presented in the text for each vessel while recreational boats were analyzed in aggregate. The overall data provides a sample of the species being transported on vessels on California's coastline (to the bays in which sampling was conducted and other bays that formed the itinerary of each transient vessel). We examined the taxonomic breakdown of species recorded on boats, the species richness among vessels, the abundance of fouling and its relationship with percent cover of hulls, and comparisons of boater reported hull maintenance and biofouling.

3.3 Impacts of California AIS with fishing vessel biofouling as a possible vector

We conducted a review of reported impacts on all species of crustacean, mollusc and algae reported as established in the NEMESIS data for California. These three taxa are species rich groups in the state. Algae and mollusc data were compiled by the UC Davis vector team (studying two different vectors) and we provided crustacean data. A standardized stepwise search was designed collaboratively among groups using the BIOSIS academic search engine.

1. We used the following search terms in BIOSIS to provide the 'first cut' of impact literature:
   Topic=(Adventive OR Alien* OR Bioinvasi* OR Biosecur* OR Exotic* OR Foreign OR Introduc* OR Incursion* OR Invad* OR Invasi* OR Nonendemic* OR Nonendemic* OR Non indigenous OR Nonindigenous OR Nonnative* OR Nuisance* OR Pest* OR Pest)
   AND
   Topic=(species name in quotes, e.g. "*Ficopomatus enigmaticus*")

AND
Timespan=1926-2011.
This timespan corresponded to the earliest records in BIOSIS to the last full year of data. Searches for species synonyms were also conducted and the number of papers returned for each species was recorded as meta-content.

2. The titles of papers were examined for relevance to impacts and all irrelevant papers were removed. The remaining number of papers was noted in meta-data.

3. For the remaining studies that were retained, abstracts were examined for relevance and those deemed to contain impacts data were downloaded. The number of articles with impact data was noted in meta-content.

4. Data for papers were entered into a formatted spread sheet. Data included reference information, the non-native species name, the name of the impacted entity (species, habitat, process involved), the type of impact, and the way impacts were measured (field studies, experiments, monitoring data etc).

These data were used to summarize existing data on impacts for species relevant to fishing vessel vectors.

3.4 Vector disruption

We examined the vector process for fishing vessel fouling (and non-fouling) to identify potential points that are conducive to vector interruption actions. In addition to this process analysis, we summarized the approaches and strategies that can be used to cause vector disruption and utilize critical control points in the process. Finally, we evaluated state wide vector control programs for vessels. The overall goal was to include an overview of management options available to reduce or prevent species transfers by fishing vessels (at the vessel and state scales).

4. RESULTS

4.1 Invasion History & Vector Strength

California's coastal marine and estuarine invasion history

The data set of California marine and estuarine AIS consisted of records for 300 species (with records dating from 1853 to 2009). Two of these species, the algae *Caulerpa taxifolia* and the polychaete worm *Terebrasabella heterouncinata*, are considered extinct from the state after apparently successful eradication efforts (Culver & Kuris, 2000; Ansderson, 2005). A further 20 species were considered to be failed introductions to the state. This resulted in 278 extant AIS in California. The statuses of these 278 species in the state included confirmed established species (based on repeated records) and unknown population status. Species populations designated as unknown may be established, but there simply haven't been follow up records to provide confidence that they persist. These unconfirmed-status species were included in analyses (n=278).

The taxonomic breakdown of statewide AIS revealed a range of organisms from bacteria to vertebrates, have been introduced and currently exist in California coastal waters (Fig. 1). Crustaceans have played a dominant role in the invasion history of the state. There were 82 introduced species of crustaceans, representing almost 30% of the state's total AIS, and amphipods, isopods, and copepods were the dominant sub-groups (Fig. 1B). Molluscs were the second largest group in the state, consisting of 27 gastropods and 19 bivalves. A further seven taxa groups contributed between ten and thirty species to the state AIS pool, while five groups contributed five or fewer species. Included in these minor groups was the bacteria, *Xenohaliotis californiensis*, a pest of abalone established in Northern California and the muskrat, *Ondatra zibethicus*, which is introduced from the eastern U.S.

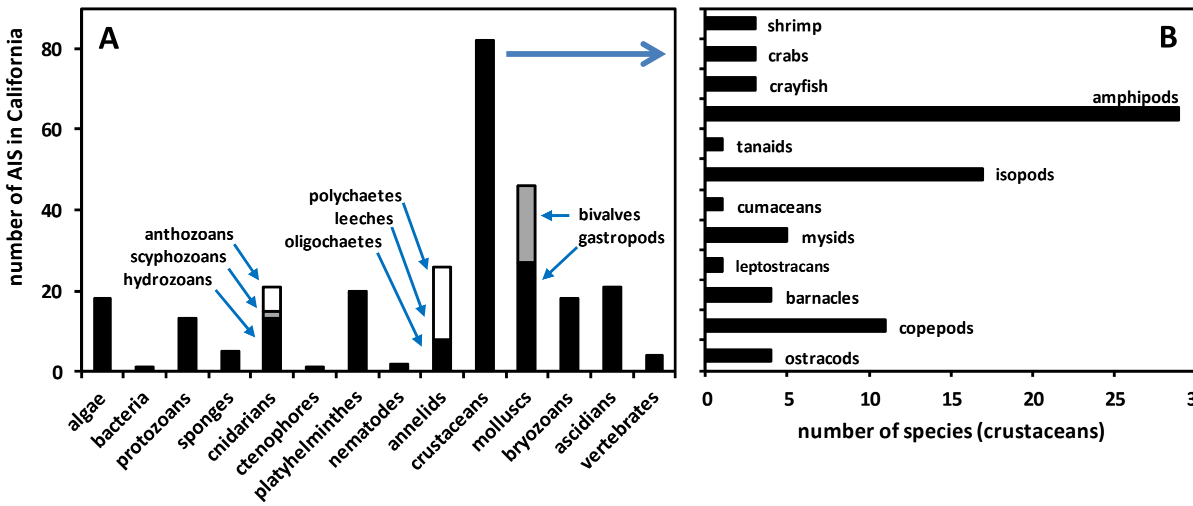

Figure 1. Taxonomic breakdown of AIS in California. The 278 marine and estuarine AIS belonged to 14 different taxonomic groups (A). This taxonomic breakdown is informal – the same hierarchy of taxonomic units are not consistent across taxa. The richness of four of the groups were further sub-divided these are indicated in the plot for cnidarians, annelids, and molluscs. The crustaceans were the richest group of AIS with 82 different species and the sub-division of this taxon is shown in panel B, which shows amphipods to be the richest of the non-native crustaceans in the state.

The years of first detection, or recording of an introduction, for the 278 California AIS ranged from 1853 to 2007. The earliest record is for the barnacle, *Amphibalanus improvisus*, collected from San Francisco Bay, while the most recent is for a ctenophore, *Vallicula multiformis*, in San Diego Bay. Although introductions earlier than 1853 are likely, such species may currently be classified as cryptogenic (unknown origin) and require further work to reconstruct their invasion history. The dataset also included first records for species in certain bays after 2007 (the most recent in 2009), but these recent records were for species that had already established populations elsewhere in the state. There have doubtless been new invasions to the state since 2007 that have yet to be reported or confirmed.

The rate of new AIS introductions has been growing exponentially since the 1850s, undergirding an exponential accumulation of AIS in the state (Fig. 2). The most recent 25-year period has seen prolific numbers of new AIS enter the state, compared to prior time intervals, with almost 40% of the state's total AIS being detected since 1983 (the most recent interval in Fig. 2). The overall trend of introductions is driven by a swathe of anthropogenic vectors that have been operating in the state for centuries and provides the foundation for the overall invasion history of the broader NE Pacific region (Ruiz et al., 2011a).

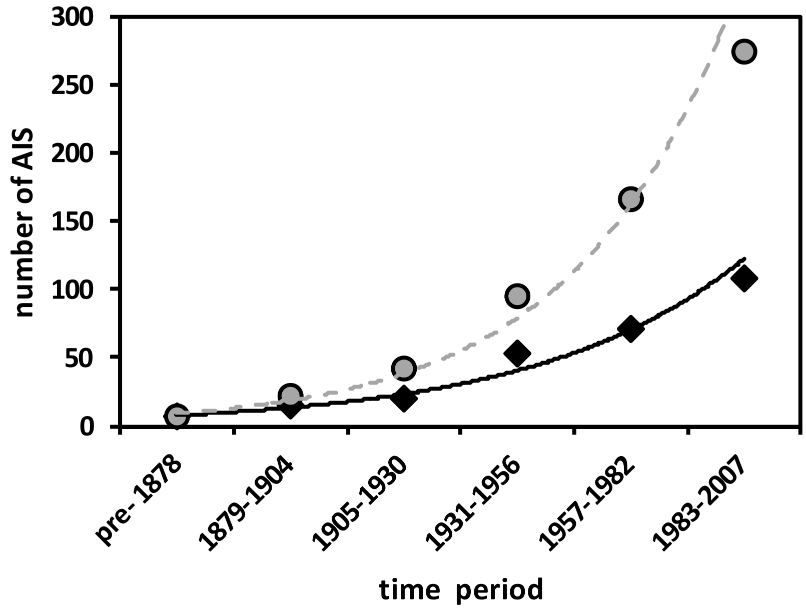

Figure 2. Temporal pattern of AIS introductions to California. The plot shows first detections or reporting of new AIS (black diamonds, solid line, r^2=0.98,p<0.01) and the accumulation of AIS (grey circles, dashed line, r^2=0.98, p<0.01) for California. Nearly 40% of the state's AIS have been detected since 1983. (n=274 species for this plot because of absent temporal data for four AIS).

Vessel vectors of California's AIS

To evaluate the role of vectors in creating California's AIS history, we first examined the vector associations for first records of species to the state. This 'first cut' of vector strength analysis focused on biofouling of all types of vessels (Fig. 3). For 274 species for which there were year × vector data, 54 AIS were attributed exclusively to vessel biofouling. A further 106 AIS were associated with vessel biofouling in combination with other vector possibilities, which meant that the biofouling vector could be linked to between 20% and 59% of the state's initial AIS incursions. The remaining non-biofouling transferred species included 28 (10%) that may be associated with fishing vessel activity (e.g. related to transfers of bait by fishermen on boats) and 86 (31%) that were neither linked to biofouling of vessels nor any sort of fishing vessel activity.

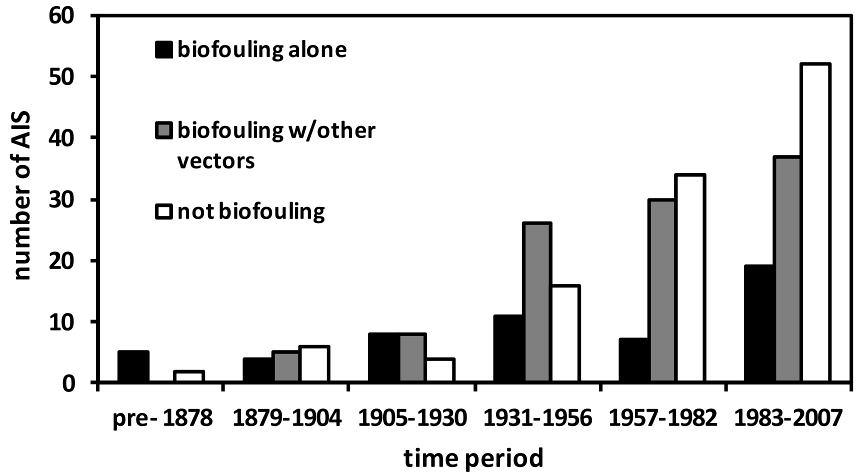

Figure 3. Biofouling vector associations with initial records of AIS in California. The plot shows the extent to which biofouling, the main vector for fishing vessels, is associated with California AIS. These data are for first records only (n=274 species). The legend is included in this plot and bars represent 1) species considered to have been introduced via biofouling alone, 2) biofouling as a possible vector in combination with other vectors, 3) species not associated with biofouling-mediated introduction. The high number of non-biofouling species since 1983 is largely a result of initial incursions via ballast and aquaculture.

It is difficult after this first classification of species × vector data to directly associate biofouling with different categories of vessels (commercial, recreational, fishing, military, rigs/platforms). This is not surprising since there is already significant overlap between biofouling and non-biofouling vectors that creates a range of possible vector strengths. From the first records for the state, species that were introduced from afar (transoceanic or interoceanic) via biofouling are very unlikely to have been brought to the state by active (in-service) fishing vessels because California's fishing industry is domestic. In modern times, national or international fishing boats are not arriving from outside of adjacent coastal areas, and a majority operates within state waters only (see below). Similarly, historical accounts of marine fishing on the coast do not highlight any long-distance arrivals of fishing boats to the state, or even describe extended coastwise voyages by fishing vessels. Fishing communities in California tended to develop along the coast rather than outsiders transiting longer distances (by boat) to exploit fisheries. Therefore, initial introductions to the state from fishing vessels appear likely to be rare in cases where the species is a first record for the NE Pacific. Only cases of coastwise source-to-destination introductions may be common for fishing boats.

To illustrate this, consider the case of *Amphibalanus improvisus*. This barnacle was recorded in San Francisco Bay in 1853 and is the initial record for not only the state, but the entire NE Pacific region. Our review dataset states that it is thought to have arrived from its native range in the north Atlantic as fouling on ships' hulls. It is almost certain that fishing vessels were not implicated in this initial biofouling-mediated arrival because of the timing and probable distance from the source population. Subsequently, it has persisted for well over a century in the state and been recorded in five other locations, most recently Elkhorn Slough and Tijuana Estuary (1998 and 2003, respectively). After its initial incursion, it is likely to be associated with coastwise fishing vessel biofouling transfers. However, the example in San Francisco Bay cannot be included in fishing vessels' vector strength measurements, even though the species is now linked to the fishing vessel vector in the state.

Of course, this is true of many species that can interact with vectors other than the one that was responsible for their initial incursion. Thus, when we consider vectors for the 278 AIS across all bays in the state, 207 of the 278 were associated with fishing vessels, including 175 linked to biofouling and a further 32 linked to fishing vessel activity but not biofouling (Table 1). These numbers refer to the current standing stock of AIS in the state and not just first records (i.e. *A. improvisus* is included on the basis that detections subsequent to its first may have involved fishing vessel transfers). All of the species with fishing vessels as possible vectors can be considered polyvectic with other vectors, particularly other biofouling transfer mechanisms.

Table 1. Numbers of California AIS associated with fishing vessel vectors. The table shows five ways of categorizing species (n=278), with the top three linked to fishing vessels and the fourth one not associated with fishing boats. In comparison to initial incursions (Fig. 3), there was an overall increase in the numbers of AIS that could be linked to fishing vessels because 15 of 86 first records of non-fishing vessel species could subsequently be coupled with fishing vessel vectors after their initial incursion to the state. In total, fishing vessels can be implicated in transferring 74% of the standing stock of California AIS (maximum possible), although all of these species can also be linked to other vessel types and/or other non-vessel transfer mechanisms. See Supplementary material for details (Appendix 1).

Vector association	Number of AIS (all state records)
Biofouling alone	46
Biofouling with other vectors	129
Non-fouling fishing vessel with other vectors	32
Not associated with biofouling or fishing vessel	71
Number of species associated with fishing boats	207

For the standing stock of AIS in the state, the fishing vessel vector is associated with all major taxonomic groups (Fig. 4). Fishing vessels can be linked to 100% of the algae, cnidarian, bryozoan, and ascidian species (78 species combined). Biofouling as a sole vector (including fishing vessels) or in combination with other non-fouling vectors plays an important role in transferring these four taxa. The vector was not linked to a significant proportion of platyhelminth species, many of which are parasitic of fish, although the non-fouling component of fishing vector activity was linked to 50% of these species. The only taxonomic group that did not have one representative transferred by biofouling alone was the annelids, but fishing vessels were still associated with transfers of 92% of these polyvectic species (species with more than one possible vector).

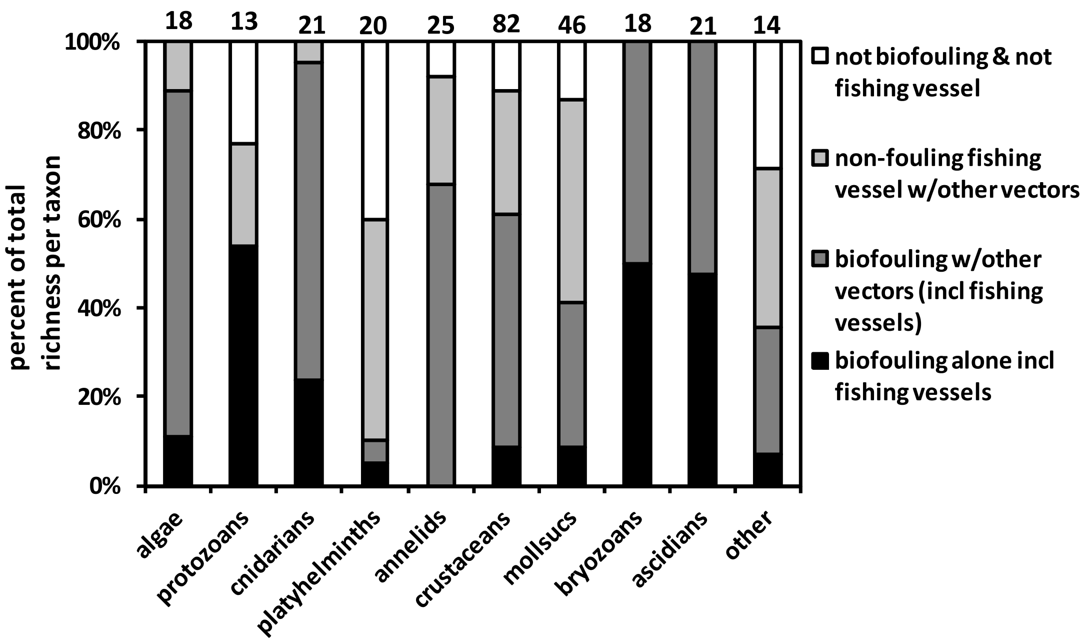

Figure 4. Differences among taxa in the proportion of species linked to fishing vessels and biofouling. The percentage bar chart shows proportions of species among taxa for 1) species vectored by biofouling alone, 2) biofouling as a possible vector in combination with other vectors, 3) species linked to fishing vessels (but not biofouling), and 4) species not associated with vessels or biofouling. Categories 1-3 include fishing vessels as vectors. The legend reflects the shading for each of these categories and the number of species for each taxon is at the top of each bar. The 'other' category included bacteria, sponges, ctenophores, nematodes, vertebrates (see Fig. 1).

There are 129 AIS in California known from just one location (bay) but additional species with more than one record (species from two bays or more) from the same year mean that 133 have first detections form just one year (no additional detections after their initial documented presence). All other taxa have more than one year of detection and it underscores the role of vectors in general, and fishing vessels as a component of this, that many species continue to be recorded in new locations many years after their initial discovery in the state (Fig. 5). In contrast to the single year and single location species, the mussel *Mytilus galloprovincialis* is known from at least 24 different locations with first records in each location spanning the years between 1987 and 2000. Self-dispersal and hybridization is thought to play an important role in this species' spread, along with ready association with biofouling of vessels.

Amphibalanus improvisus does not have such a prolific spread among locations, but it is the species with the longest time span between first detections in different bays (150 years), and can also be linked to fishing vessels as a vector. Indeed, San Francisco Bay is a hub for the earliest AIS records in the state. Like *A. improvisus*, the hydroid *Pinauay crocea* was discovered in the 1850s and has continued to be dispersed to several other bays in the state since that time, including possibly by fishing vessels. Its most recent 'new' distribution data is for Humboldt Bay in 2003. Other species that were recorded over 100 years ago and still persist in San Francisco Bay have not been recorded elsewhere in the state, including the isopod *Synidotea laevidorsalis* and the hydroid *Clava multicornis*. Their apparent confinement to the Bay places them among a group with seven other species that have not had a new distribution record in over 70 years since they were first detected.

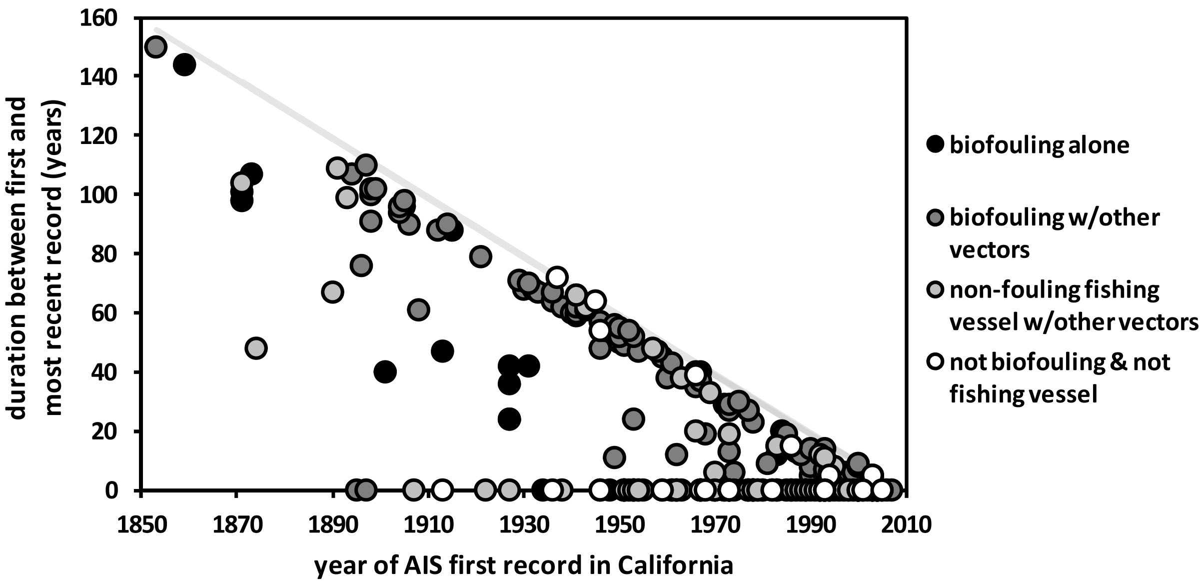

Figure 5. Duration between first and subsequent records (spread among bays) for California AIS. For four different categories of vector association (legend), the plot shows the duration between first and most recent record of AIS detection in different bays in California (n=268*). The first three categories (black & grey symbols) include fishing vessels as possible vectors. The plot forms a characteristic wedge. All species on the x-axis are those known to only occur in one location (133 species with just one record in the state). The feint grey line represents the maximum time possible between first and most recent records of detection for all species (105 species approach this line). The remaining species occur between the lines (30 species), having been recorded subsequent to their first records, but not recorded recently (in the last 13 years). The upper most data point (top left of the plot) represents *Amphibalanus improvisus*, whose first record for the state occurred in San Francisco Bay in 1853 and most recent record in a 'new' different location occurred 150 years later in Elkhorn Slough.
***the total is 268 species because ten require further analysis of timing data.**

San Francisco is one of the most invaded Bays in the world, and is the most invaded in the NE Pacific. It dominates California's invasion history (Fig. 6) and fishing vessels can be associated with 67% of initial incursions for San Francisco Bay's extant AIS. The other central California bays with substantial numbers of known AIS included Elkhorn Slough (Moss Landing in Fig. 6), Bodega Bay, and Tomales Bay. Biofouling was considered a sole vector for between 16% and 26% of AIS among these four bays, although fishing vessels could be associated with between 67% and 82% of their invasions. The role of biofouling as a sole vector was elevated in southern California (LA/Long Beach to Tijuana Estuary) relative to the rest of the state. Seven southern California bays had 20 or more AIS and biofouling was considered a sole vector for 54% of these for each bay (on average). In comparison, the same sole-vector category was linked to an average of 33% of AIS among the nine bays in the remainder of the state with 20 or more AIS. Northern California has just one bay with more than ten known AIS – Humboldt Bay with 70 species. Eighty-one percent of these 70 introductions included fishing vessels as a possible vector.

Overall, there is wide variation in the numbers of known AIS among bays within the state and the fishing vessel was a possible vector for an average of 85% of AIS (± 10% and in combination with other vectors) for bays that had 20 or more species across the whole state (Fig. 6). It is important to underscore the point that we cannot distinguish the relative contribution of fishing versus recreational versus shipping for the overall spread pattern as these are all possible vectors in many locations (especially major bays).

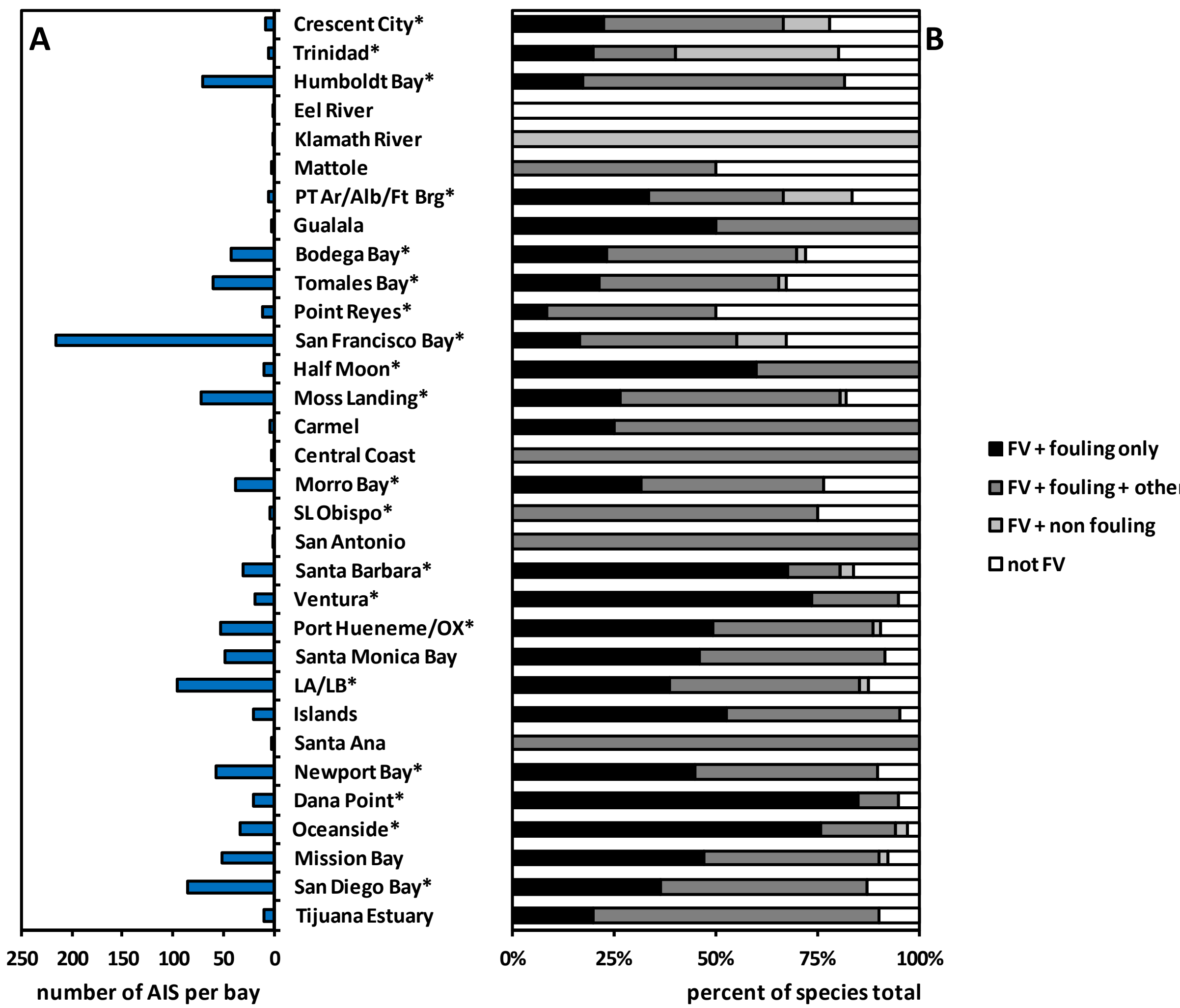

Figure 6. Differential AIS distributions among bays and the role of fishing vessels as vectors. The numbers of AIS per bay/location shows that San Francisco Bay dwarfs all others in terms of AIS numbers present (A). The bay-level was determined using NEMESIS location data overlapped with PacFIN ports where appropriate. In some cases, the NEMESIS location includes additional space outside of a bay (adjacent coastline). Bays are listed from north to south and those with an asterisk are locations that receive fishing vessels (according to the fishing traffic dataset; below). Panel B shows the proportion of AIS in each bay that were associated with fishing vessels. All non-white portions of bars relate to fishing vessels (see legend where FV is Fishing vessel) and there are four levels vector association in the legend: 1) fishing vessels and other fouling vectors only; 2) fishing vessels with fouling vectors AND other vectors; 3) non-fouling vectors, including fishing vessels; 4) non-fishing vessel introductions.

4.2 Vector Analysis

Having evaluated the invasion history of California with respect to fishing vessel vectors, our next step was to characterize present-day fishing vessel traffic in order to understand their spatial and temporal (seasonal) patterns of arrivals, voyage routes, port connectivity, and interactions among bays within and outside of the state. We then evaluated vector biota using a literature search and direct sampling of coastal transient vessels in California.

Statewide spatial and temporal patterns of fishing vessel arrivals

There were 2464 fishing boats that reported arrivals to California harbors with fish tickets during the four year period of January 2005 to December 2008. The 2464 distinct vessels accounted for 204,488 arrivals. Additional zzz-labeled boats also contributed 2262 arrivals, but we do not know how many boats were included in this designation. The port of LA/Long Beach, including the combined PacFIN landing sites of San Pedro, LA, Long Beach and Terminal Island, was ranked highest for fishing vessel arrivals and accounted for 15.4% of the total for the state (31,498 arrivals). The ports of Santa Barbara (22,193 arrivals) and San Diego (16,388) had the second and third highest numbers of arrivals in the state. These three Southern California ports accounted for over one-third (34.3%) of the fishing vessel arrivals over four years. San Francisco Bay (13,070 arrivals) and Half-Moon Bay (10,077) were the highest ranked Central California fishing ports, while Crescent City, Fort Bragg, and Humboldt Bay on the northern coast of the state rounded out the top eight ports for fishing vessel arrivals (Fig. 7).

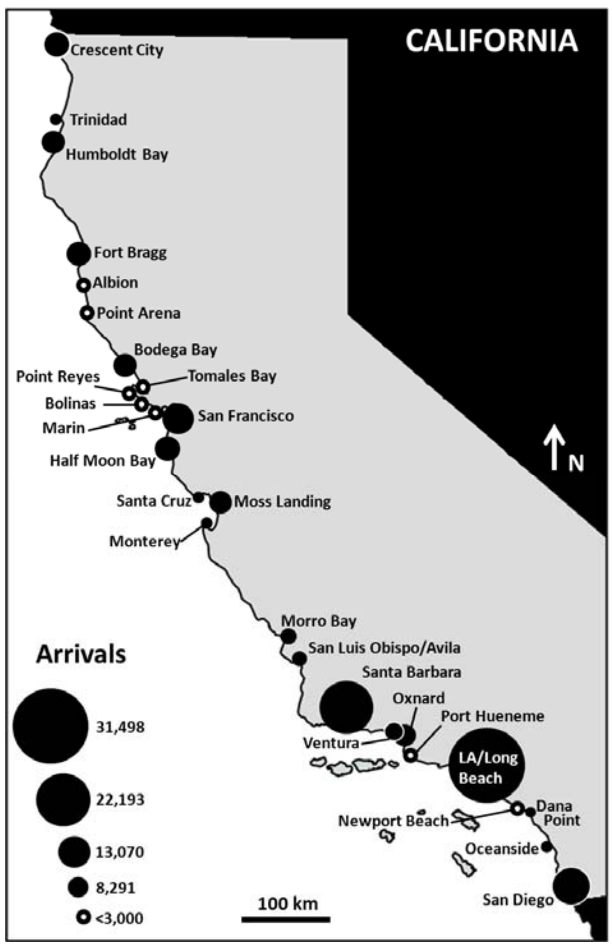

Figure 7. Numbers of fishing vessel arrivals among Californian bays. This bubble plot shows the numbers of fishing vessels that reported arrivals to each harbor in California over four years. Bubble sizes are scaled to reflect arrival numbers and the scale is provided in the bottom left. LA/Long Beach, with 31,498 arrivals, was the highest ranked bay.

The statewide temporal trend revealed there was a monthly average of 4000 to 5000 arrivals for nine months each year. The average numbers of arrivals dropped below 4000 during March, April, and June (Fig. 8). From January to April, there was a decline from the yearly peak of 4,880 arrivals across the state to the yearly trough of 2,915 arrivals. This was followed by an increase in May and another decline in June to 3,545 arrivals. The second half of the year was characterized by a steady arrivals rate of approximately 4,500 per month (Fig. 8).

Three of the four highest ranked bays for vessel arrivals (Santa Barbara, San Diego, San Francisco) each had their annual minimum in April, underlying the statewide temporal trend for lower arrivals in that month. The temporal trends for each major port (Fig. 8) revealed varying extents of seasonality of arrivals. The most striking trend occurred in San Diego, whereby a spike in arrivals in October, that continued for three months, represented an increase of over two-and-a-half times (x2.6) the numbers of arrivals for the other nine months of the year. This spike in arrivals coincides with the fish landings data reported by the California Department of Fish & Game (DF&G) for this location. For the four years of our vessel traffic data, landings jumped from 142,000 pounds on average between February and September to 309,417 between October and December. It appears landings of spiny lobster and swordfish were the fisheries that underlie the pattern. Santa Barbara also had its peak arrivals in October and November, but the increase wasn't as striking as San Diego's because of a comparatively high rate of arrivals throughout the year in Santa Barbara.

In San Francisco Bay and Half Moon Bay, there was no notable spike or trough in fishing vessel arrivals throughout the year. In Northern California, there were notable increases in arrivals in August and September at Fort Bragg and in the winter months at Crescent City (Fig. 8). The variation in these months was also substantial at both harbors. At Fort Bragg, there were 601 reported arrivals in August 2007, but only 147 in August 2008. It isn't entirely clear why such a disparity occurred between both years because DF&G reported fish landings for those times differed by less than 200,000 pounds, but some of the variation may be explained by Chinook Salmon landings which were 231,086 pounds in August 2007 but not listed (and presumably zero) in August 2008. Similarly, in Crescent City, there were 1017 arrivals in February 2006 but only 249 in the same month of 2008 (Fig. 8). The Dungeness crab fishery likely explains some of this variation; DF&G data from nearby Eureka showed that crab landings were over 7,000,000 pounds in February 2006 but less than 250,000 pounds in February 2008.

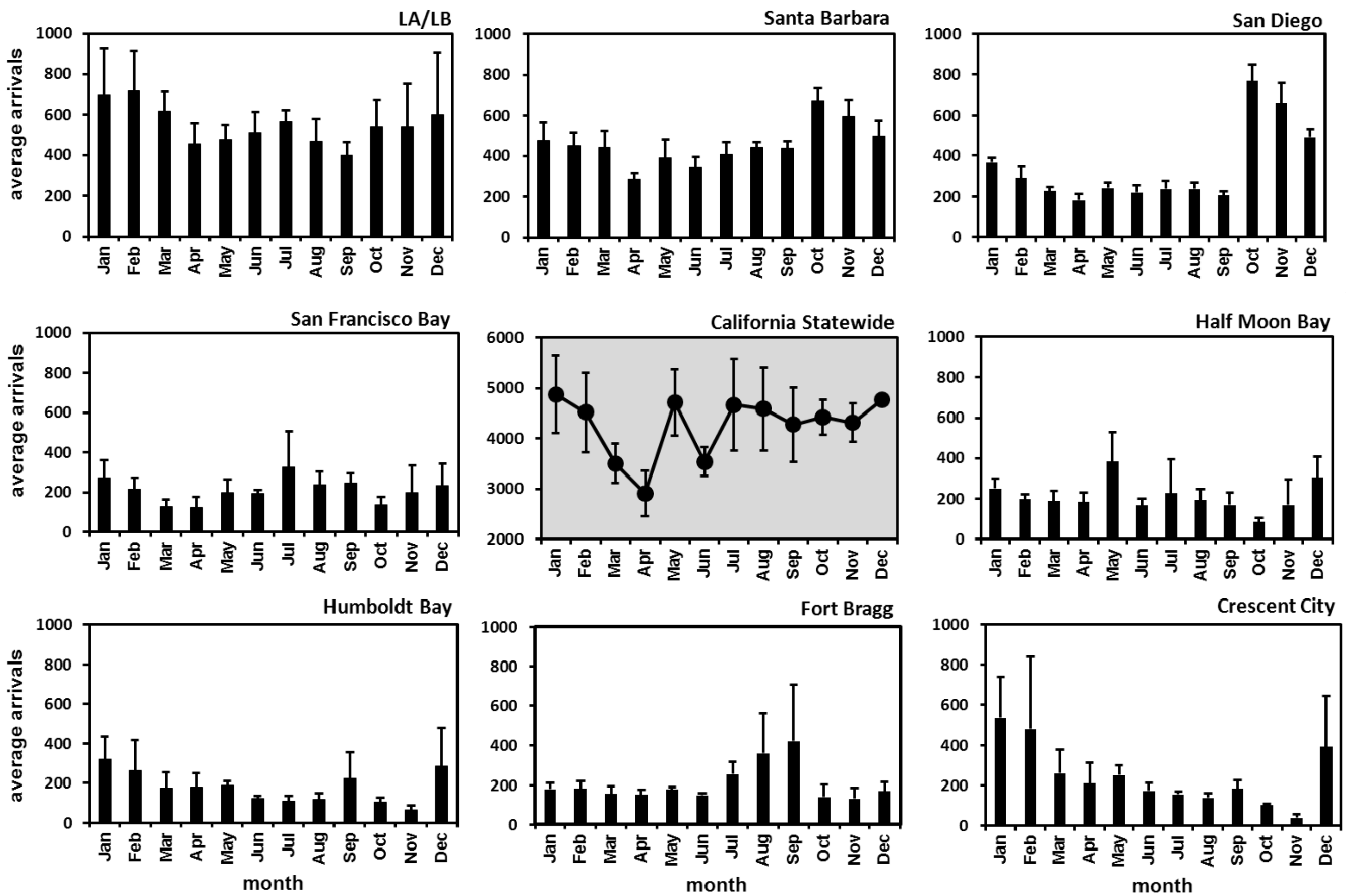

Figure 8. Temporal trends of fishing vessel arrivals for California and the top eight ranked bays. These plots show the monthly average (and SD) across four years of fishing vessel arrivals data. The center panel shows the statewide trend and has a different scale on the y-axis to the other eight panels. The names of the top eight ranked bays are provided above each panel, with harbors in Southern California, Central California and Northern California shown on the top, middle and bottom rows, respectively. The y-axis scale is the same for each bay plot.

Transient vessels and port connectivity within California

A majority of fishing vessels in California (52.8%) were resident boats that did not report arrivals to any other bay outside of their home harbor (Fig. 9). There were 1162 fishing boats that were transient during the sample period and 45% of these vessels reported transits to two ports only. The most transient vessel visited 12 different harbors (see below) and there were five vessels that visited nine different bays and one other that visited ten different bays.

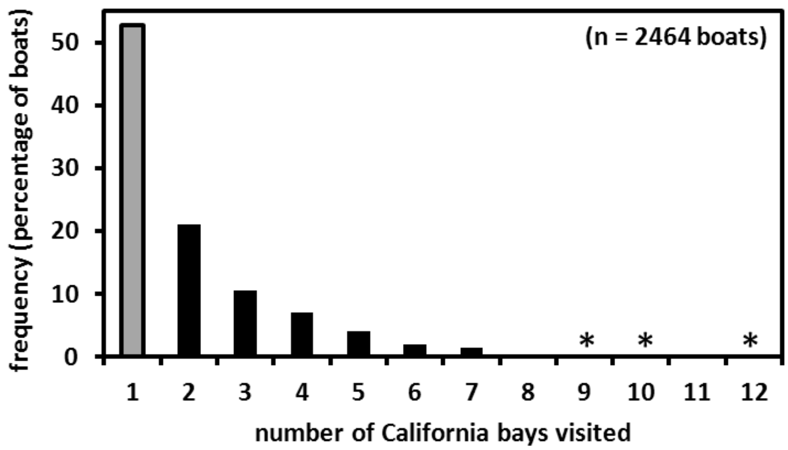

Figure 9. The frequency of fishing boats and the number of different ports they visited in California over four years. The plot shows that 52.8% of California's fishing fleet (n=2464 boats) reported arrivals to just one bay between Jan 2005 and Dec 2008 (grey bar). The remaining vessels (black bars) were transient, having reported arrivals to more than one bay. The asterisk indicates arrivals by less than 0.5% of boats to nine, ten and twelve different harbors.

Although LA/Long Beach received the highest number of arrivals among all bays, San Francisco Bay received the highest number of different vessels (589 compared to 441 unique vessels that arrived to LA/Long Beach). Transient boats were outnumbered statewide by resident (sole-port) boats, the effect of transiency meant that the number of transient boats exceeded the number of resident boats for every bay in the state (because transient boats count more than once among bays; Fig. 10). Indeed, there were 12 bays for which the ratio of transient to sole-port boats was more than 4:1, including relatively minor fishing ports of Port Hueneme and Bolinas and major fishing boat harbors like Half-Moon Bay and Bodega Bay. San Diego ranked highest for percentage of sole-port boats with 46% of vessels reporting arrivals only at San Diego. This explained why San Diego ranked third, out of 27 bays, for total arrivals but only 14th for number of different boats that arrived.

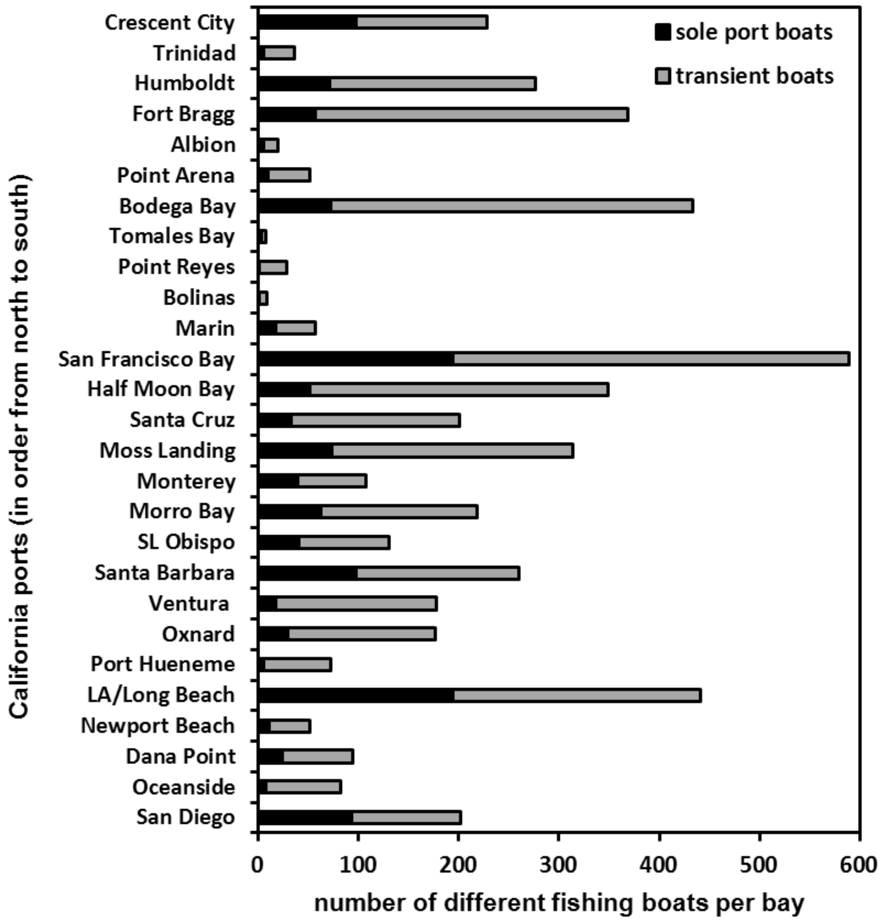

Figure 10. Numbers of different transient and resident boats per bay. This plot shows the total number of different vessels that arrived to each bay over four years, with the grey portion of each bar representing transient boats and the black portion representing sole-port (resident) boats. Although sole-port boats outnumbered transients across the state as a whole, each port had more transient boats than residents because transient boats get counted several times in this plot (between 2 and 12 depending on the number of bays visited by each boat). In comparison to the statewide pattern of arrivals (Fig. 7), this plot shows that San Francisco Bay received more vessels rather than LA/Long Beach, which received more arrivals.

On average over the four year time period, each of the 27 bays with fishing boat arrivals was connected directly or indirectly to 18 other bays (± 5.6 bays) by fishing boats. That is, each bay tended to have boats that reported arrivals to a further 18 bays (on average) during the course of their fishing operations. The least linked bays, with connections to seven other bays via fishing vessels, were among those that had fewest arrivals – Albion, Tomales Bay, and Bolinas. The most connected bays were San Francisco and Bodega Harbor with links, through fishing boats, to 25 of the other 26 bays. There were 13 bays that had connections to more than 20 other bays.

While San Francisco Bay was connected to 25 other bays, the strength of those connections, based on the numbers of boats that created the links, varied substantially among bays. There were 206 fishing boats that reported arrivals to both San Francisco Bay and Bodega Bay. A further five bays had pair-wise connection strengths with San Francisco Bay of more than 80 boats (Humboldt Bay, Fort Bragg, Half Moon Bay, Santa Cruz, and Moss Landing). In contrast, just one boat (per bay) formed the pair-wise links between San Francisco and Dana Point, Newport Bay, Albion, and Trinidad. Among all ports, there was a tendency for transient vessels to report arrivals to a core group of adjacent bays rather than a widely dispersed geographic range of arrivals (Fig. 11). Figure 11 shows that the strongest links between bays occurred far more often among adjacent bays than for distantly separated ones. This is also reflected in a mutli-dimensional scaling plot of bays (not shown) that had significant differences among clusters of bays grouped into four categories - north, central, south central, and south. The Analysis of similarities for this plot (ANOSIM) showed that clusters of harbors based on geography were significantly different in terms of their visiting boats ($R=0.504$, $p<0.001$). A result of zero would represent clusters of ports that did not differ in their vessel visitors (most similar), while an $R=1$ result would mean all clusters shared no arrivals of boats (most dissimilar). The pair-wise comparison of clusters revealed that the farthest apart clusters (south and north) had the highest R value (0.751) indicating little overlap in vessel traffic. In comparison, adjacent clusters had R-values of 0.273, 0.384, and 0.668 (from north to south respectively, all $p<0.05$).

A notable feature of the color intensity plot (Fig. 11) showing connection strengths between bays, based on shared boat arrivals, was the connections that existed for bays without commercial shipping (non-commercial bays). Locations such as Fort Bragg and Bodega Bay had strong links to each other and San Francisco Bay. These three bays in turn appeared to have a wider (geographic) range of strong connections than other bays. Even relatively minor fishing harbors had strong links to commercial bays; 30 of the 36 different vessels that called on Trinidad in Northern California also reported landings at Humboldt Bay. High proportions of the vessels that visited Southern California non-commercial bays – Ventura, Newport Beach, Dana Point, and Oceanside - also reported arrivals to LA/Long Beach (Fig. 11).

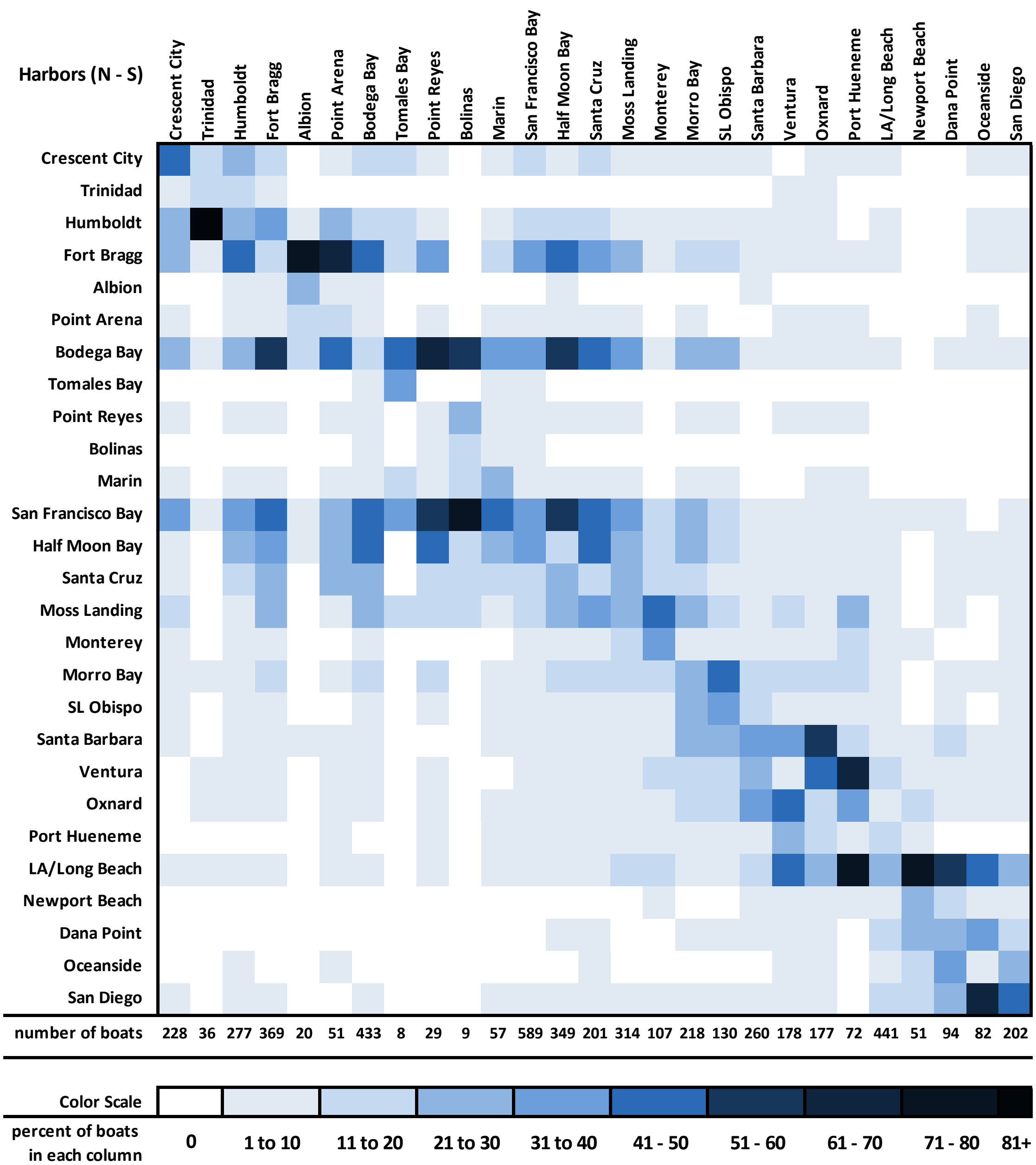

Figure 11. Color intensity plot reflecting the number of vessels that visited each pairwise comparison of California harbors. Each cell in the grid represents the proportion of vessels that reported visiting a pair of harbors , which are listed for columns and rows with both axes arranged from north to south. The darker the shade, the higher the proportion of vessels shared between two harbors (as a function of the total visits to each column harbor). For example, the bottom left cell reflects the three boats that visited the most northerly (Crescent City) and southerly (San Diego) harbors during the four year analysis period (the shade intensity denotes that this represents 1.3% of Crescent City's total distinct visiting vessels). The diagonal from top left to bottom right shows the proportion of each harbor's solely resident vessels (i.e. vessels that only reported visiting one port). The tendency towards darker cells near this diagonal and lighter cells at the opposite corners shows that most transient vessels do not voyage to opposite ends of the state very often, but tend to visit a core range of adjacent harbors. The number of different vessels that arrived to each port (against which the color scale is measured) is shown along the bottom of each column and the scale bar is provided below. See Supplementary Material, Appendix 2 for underlying data)

The most transient fishing vessel

The most transient vessel in the California fishing fleet between 2005 and 2008 was vessel 701, which visited 12 different harbors during 543 reported arrivals. The network of bays connected by this vessel ranged from San Francisco Bay to the north and LA/Long Beach to the south (Fig. 12). The record showed that this vessel had a 'home' range of Santa Barbara, Ventura and Oxnard, which accounted for 87% of the distinct arrivals and a majority of these were uninterrupted return visits (out-and-back to the same port). For example, there were 204 out-and-back visits to Santa Barbara out of 263 visits in total to that port. The connection strength between the three core ports was the highest in this vessel's larger port network, with 146 direct transits among them. Across the four year period, Santa Barbara's role as a hub for this vessel was underscored by direct outward connections to ten harbors and direct incoming transits from nine different harbors.

Overall, 34% of the total arrivals for this vessel involved distinct transits from one port to another (187 transits). It was notable that this vessel's network of bays was largely called upon in 2006, when it visited 11 different harbors (Fig. 12). This contrasted with the other three years when the port network for this vessel contracted to four (in 2007) or five bays (in 2005 and 2008), all but one of which had been visited in 2006 (Morro Bay). The vessel had significantly different numbers of arrivals ($\chi^2 = 10.63$, $p<0.05$, df=3) and numbers of transits between ports ($\chi^2 = 19.9$, $p<0.001$, df=3) among years, with higher numbers of each for 2006, as well as higher numbers of harbors visited that year. The underlying cause of the additional activity in 2006 is unknown, but it highlights the variation in voyage patterns that can occur for fishing vessels.

The consequence of this vessel's movements for introductions is difficult to ascertain without knowing the status of the vessel's submerged surfaces throughout this four year operational window. The strong connections between its core sites (Santa Barbara, Ventura, and Oxnard) certainly provided a means for organisms to be intermixed among those bays, while the longer distance transits connected these core bays with other sites up to 500km away. Voyages from San Francisco connected other sites in this vessel's network to the most heavily invaded bay in the state.

Furthermore, biofouling is a concatenation of biota and the port-to-port aspect of transits is not as important for introductions as it is for other vectors (ballast water, for instance). Ballast water acts predominantly as a point-to-point source of species delivery whereas biofouling continues to operate as a 'diffuse' vector with continuous transfers of the same community over time. Any organisms attached to vessel 701 may have been transported throughout the network, with transit tolerance, breeding times and local recipient-port conditions providing opportunities and barriers to introduction across the 12-bay network. This is true for all vessels that visited more than one port, but a high degree of transiency, exemplified by vessel 701, provides more opportunities across a broader range for introductions to occur.

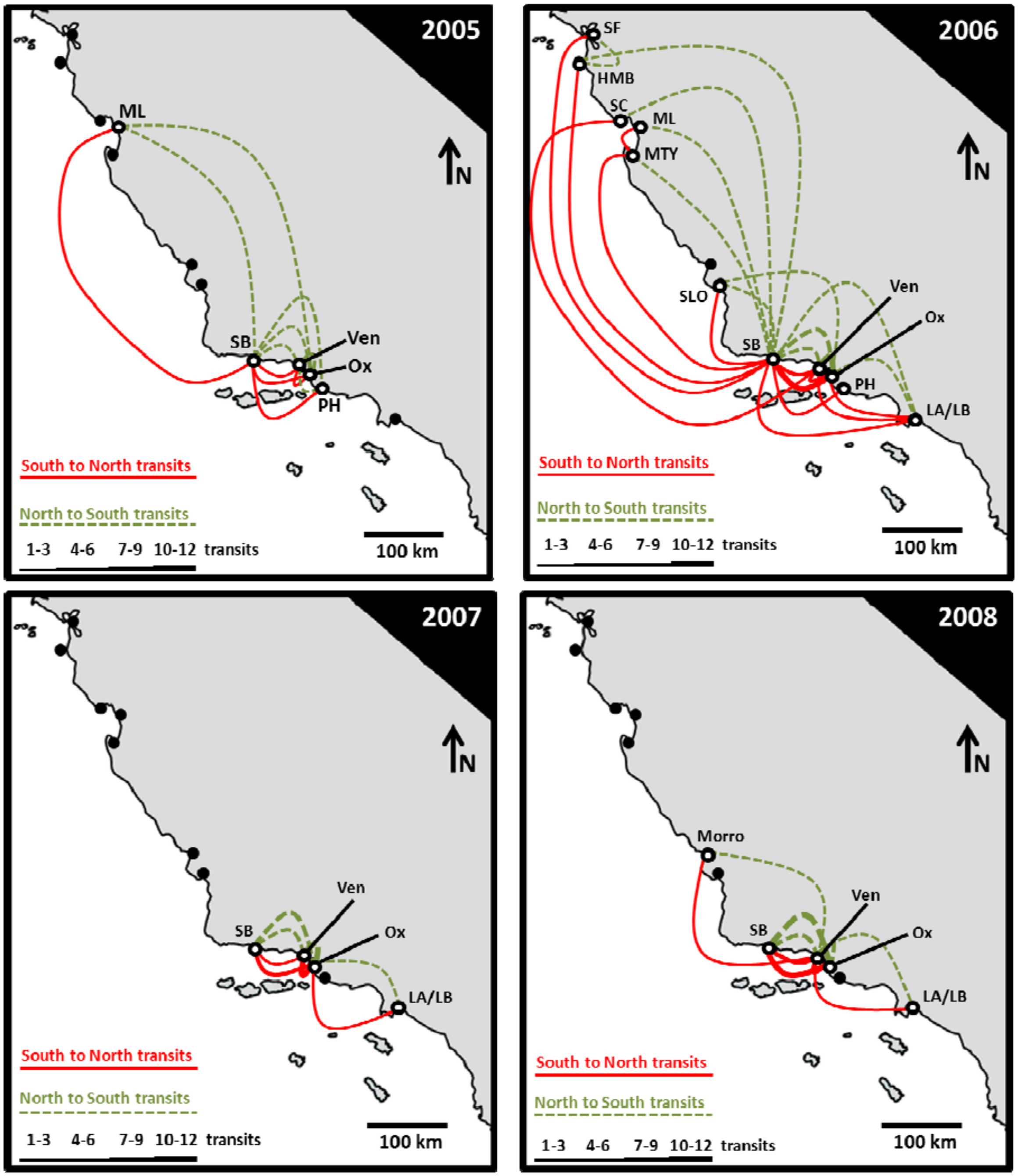

Figure 12. Voyage patterns of the most transient fishing vessel. The four panels show the year-by-year transits for a fishing vessel that called on 12 different bays. Red lines (solid) represent south to north transits and green (dashed) lines represent north to south voyages. The thickness of each connection differs based on the number of transits that occurred (scale bar in the bottom left of each panel). The plots show how voyage patterns can differ from year-to-year for fishing vessels. This vessel's port network was much larger in 2006, in terms of numbers of ports visited, the numbers of transits made, and the geographic distances covered. Not represented in these plots are the numbers of uninterrupted return (out-and-back) transits by this vessel to the same port; for example, this vessel reported 44 uninterrupted returns to Moss Landing in the summer of 2005. Active ports in each year have abbreviated names. From north to south, these are: SF– San Francisco Bay, HMB– Half Moon Bay, SC- Santa Cruz, ML- Moss Landing, MTY- Monterey, Morro – Morro Bay, SLO- San Luis Obispo/Avila, SB- Santa Barbara, Ven- Ventura, Ox- Oxnard, PH- Port Hueneme, LA/LB- LA/Long Beach.

Three vessels reported arrivals to the two bays farthest apart in the state, Crescent City and San Diego. The first of these vessels registered 132 arrivals in the most northerly bay and two in the most southerly, as well as calls to six other bays for a total of 159 arrivals over four years. In 2005, this vessel reported a landing in mid-September in Crescent City and did not report another arrival until landing in San Diego one month later. It is likely that the vessel visited other ports in between without catching or landing fish (thereby not having to report those arrivals). However, after moving from San Diego to Oceanside in January 2006, it reported another arrival two days after Oceanside back in Crescent City. This probably required a non-stop voyage from one end of the state to the other.

The second vessel to visit the state's most northerly and southerly bays reported just 39 arrivals over four years. It reported arrivals to Crescent City, Moss Landing, San Luis Obispo, and San Diego, with at least one month between transfers to different harbors. This vessel did not report direct transit between San Diego and Crescent City, though it did report sequential arrivals to and from those bays and Moss Landing. The third vessel also reported a relatively modest number of arrivals across four years (47), with month-long or longer time gaps between arrivals at non-adjacent bays. As well as Crescent City and San Diego, this vessel called on San Francisco, Half Moon Bay, and LA/Long Beach.

Transient fishing vessels connected to California from out-of-state

Our request for data on transient boat arrivals from a foreign last-port-of-call yielded initial summary data of 2535 arrivals over a 14 month period from January 2009 to May 2011. Just over 95% of the arrivals in the summary data were recorded in San Diego, which presumably came from Mexico and other countries to the south, but the last port visited prior to U.S. entry or re-entry was not part of the CBP data collection available to us. Other foreign last-port vessels arrived at San Francisco and LA/Long Beach. The records showed that arrivals from foreign sources into the State had a seasonal pattern of initial entry, with peaks of arrivals in May and June (140-175 arrivals) and troughs in December and January (25-45 arrivals). The request for more detailed information on boat arrivals to the state from outside the U.S. remains in processing at the CBP.

The PacFIN data on fishing vessel traffic revealed that there were 356 fishing boats that traveled between California and the Pacific Northwest states between 2005 and 2008. Vessel flux between California and Oregon included 190 boats and there were 39 that transited between California and Washington (the remaining 127 reported arrivals to all three West Coast states). Twenty-two of the 27 bays with fishing vessel arrivals in California had a direct or indirect connection with the Pacific Northwest through fishing vessel flux; the exceptions were Albion, Tomales Bay, Bolinas, Newport Beach, and Dana Point. For vessels that traveled out of state, 73% called on three of fewer Pacific Northwest bays (Fig. 13A), although one vessel reported arrivals to ten Northwest harbors. Similarly, the numbers of Californian bays visited by vessels that had spent time in the Northwest tended to be low; 34% of these inter-state boats visited just one bay in California (Fig. 13B).

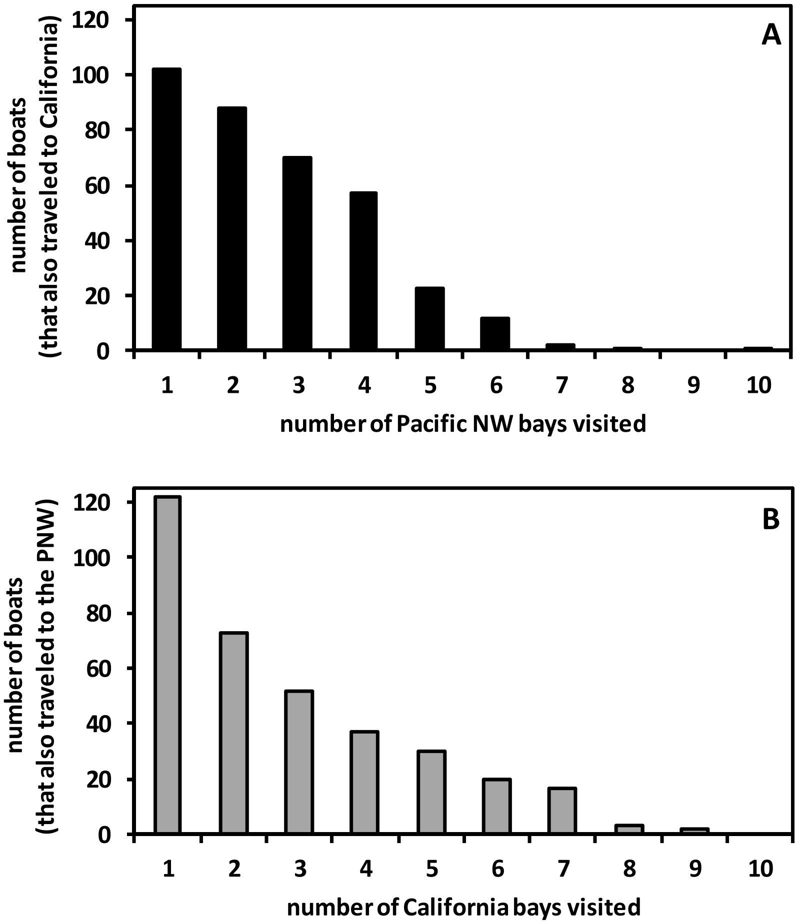

Figure 13. Number of bays visited by vessels that reported arrivals in California and the Pacific Northwest states. The plots show the decreasing frequency with which vessels visited multiple bays in the Pacific Northwest (A) and in California (B). There were 102 vessels that called on just one port in the Pacific Northwest having also operated in California. Similarly, 122 vessels that had been in the Northwest States visited one California port, although one vessel reported arrivals and nine California bays in addition to its

The ports of the NW that had the greatest traffic flux in terms of numbers of boats that visited California were Newport (196 boats called at Newport and a California port), Coos Bay (195), Astoria (99), and Brookings (90) in Oregon and Ilwaco (124) and Westport (72) in Washington. Conversely, the ports in California that had shared vessels' arrivals with the NW were unsurprisingly from the north and central parts for the state: San Francisco Bay (150 boats), Crescent City (143), Fort Bragg (117), Humboldt Bay (108), Bodega Bay (96), Half Moon Bay (73) and Moss Landing (84). There were, however, 19 fishing vessels that operated in San Diego and the Pacific Northwest states, again demonstrating the long-distance ranges that these boats can cover during the course of their operations. Among the 19 boats that had visited San Diego and the Northwest were three, mentioned previously, that visited Crescent City. Nine vessels reported calls to San Diego and Westport, Washington, which, at a distance of more than 1750km by coastal voyage, represented the most distant pair-wise port comparison in the vessel flux data set. Unfortunately, data from ports further north in British Columbia and Alaska that may also have operated in California were not available because of differences in data collection by the relevant fishing authorities.

Vector biota 1: Species associated with biofouling of boats

There have been relatively few studies conducted on the boat fouling vector, with many remaining in gray literature, despite the prevalence of incidental mentions about the vector throughout the literature. There are doubtless many more records of species from boat hulls than we encountered, but these are not easily extracted from taxonomic accounts, museum literature, and other sources. There have also been studies of the vector that do not report species lists or identifications in the text. We did find 23 papers or reports (Supplementary material, Appendix 3) recording 455 marine or brackish water organisms sampled directly from small vessels. These studies emanated from 12 countries from studies published since 2000.

As a group, fouling species represent a broad spectrum of life forms and trophic levels, including both sessile (attached) and mobile taxa. In some cases, organisms were identified to species level, in other cases descriptive terms such as "green macroalgae" or "fish" were used. Taking a conservative approach, this appears to represent 243 distinct animal, protist, and plant species or taxa in 15 phyla (Fig. 14).

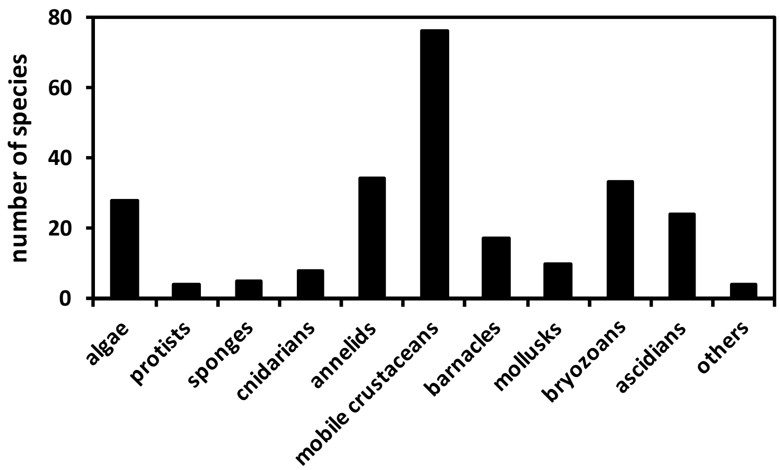

Figure 14. Taxonomic breakdown of species recorded from boat hulls in the literature. The plot shows the number of species per taxon that have been recorded on the hulls and niches areas of boats (n=243) reported from 23 different studies.

Mobile arthropods were by far the richest taxonomic group, with at least 76 distinct taxa reported. Over half of these species were amphipods, with smaller numbers of isopods, decapods (exclusively crabs) and copepods. The second largest group, Annelids, comprised almost entirely of polychaetes and consisted of 34 distinct taxa. There were 33 bryozoan species and 24 ascidians. Barnacles made up a significant group with 17 species reported, while the combined richness of green, brown and red algae totaled 24 distinct taxa.

The most-reported taxon was a foliose form of the green alga *Enteromorpha* (formerly *Ulva*), which was recorded six times. The arborescent bryozoan *Bugula neritina* was reported five times. Each of these may actually represent multiple species, as *B. neritina* is now recognized as a species complex, and there are several species of foliose *Enteromorpha*. The tunicates *Botrylloides violaceus, Botryllus schlosseri* and *Diplosoma listerianum,* the barnacle *Amphibalanus amphitrite,* and the bryozoan *Watersipora subtorquata* were each reported four times.

We suspect that the numbers of species known from boat hulls and niche areas of boats are vastly underreported, even though the numbers of explicit studies of this vector appear to be accounted for in this review. The available data does show how diverse the boat biofouling community can be. There have also been accounts of very high abundance of organisms on resident and transient boats, highlighting the high doses of organisms that can be transferred in one vector event. No reports evaluated the condition of the species reported from hulls, although some noted the presence of gravid individuals, eggs, larvae, and juveniles, indicating that at least some of the species present were capable of reproducing and dispersing into the environment.

Vector Biota 2: Species sampled on submerged surfaces of transient boats in California

Our limited number of fishing vessels sampled yielded the following information:

Vessel A: This fishing boat was sampled in Monterey harbor and did not have any accompanying questionnaire data. It had just two species attached to niche area surfaces, the introduced Bryozoan *Watersipora subtorquata* and an unidentified Caprellid amphipod (though confirmed that it was not the introduced *Caprella mutica*).

Vessel B: This vessel was also sampled in Monterey harbor and the limited data provided by an operator suggested that it had not had hull maintenance in the last 15 months (paint application or cleaning). It had also been quite stationary in the past 12 months but the respondent could not provide details on where it had been. We recorded five species on this vessel, three native to California (the bryozoan *Cellaporaria brunnea*, the colonial ascidian *Diplosoma* sp, and the amphipod *Caprella californica*) and two non-native to the state (the bryozoan *Bugula neritina* and the amphipod *Caprella mutica*).

Vessel C: This fishing boat was sampled in Santa Barbara and the underwater sampling resulted in the collection of one or two individuals of the stalked *Lepas* barnacle at the bow end of the vessel. The operator reported that the vessel had been fishing out of Santa Barbara for the past three months, but had visited no other harbors in that time. The vessel had also had a reapplication of antifouling paint one month prior to sampling, which explained the flawless nature of the underwater surfaces of this vessel. The operator also reported that the vessel was about to embark on a trip to Oregon related to the Albacore fishery.

Vessel D: The owner of this boat provided detailed information on his recent voyage and maintenance history and consented to an underwater survey of his boat. The vessel had not had a new coat of antifouling paint applied for over 30 months and cleaning was done cursorily by the operator with a brush (with a focus on the propeller). The most recent cleaning had occurred six months prior to sampling. It had been in Santa Barbara (sampling location) for just over one month, and arrived from fishing trips in Mexico and San Diego. Underwater sampling revealed this transient boat had almost 100% cover of biofouling across hull and niche area surfaces. This was evident from the waterline, and our initial impression was of a resident non-moving vessel rather than an active transient fishing vessel. We recorded at least 81 different morpho-taxa on this vessel, including sponges, mobile crustaceans, polychaetes, bryozoans, bivalves, barnacles, hydroids, ascidians, and algae. We are endeavoring to get identifications for these species completed, but the non-native species among this boat's fouling community included the solitary ascidians *Ciona intestinalis* and *Styela clava,* the amphipod *Caprella mutica,* and the bryozoans *Watersipora subtorquata* and *Bugula neritina*. A notable record was also made for the colonial ascidian *Botrylloides perspicuum*, which is not known to be established in Santa Barbara as yet.

For the 49 other vessels sampled, we encountered a range of zero to 72 different taxa on vessels (Fig. 15). Ten vessels had more than 30 species in their biofouling communities, while the average was 16 taxa. Bryozoans, mobile crustaceans (including isopods and amphipods), and ascidians were the most frequently sampled taxonomic groups (Fig. 16) while polychaetes and barnacles were also relatively well represented among samples.

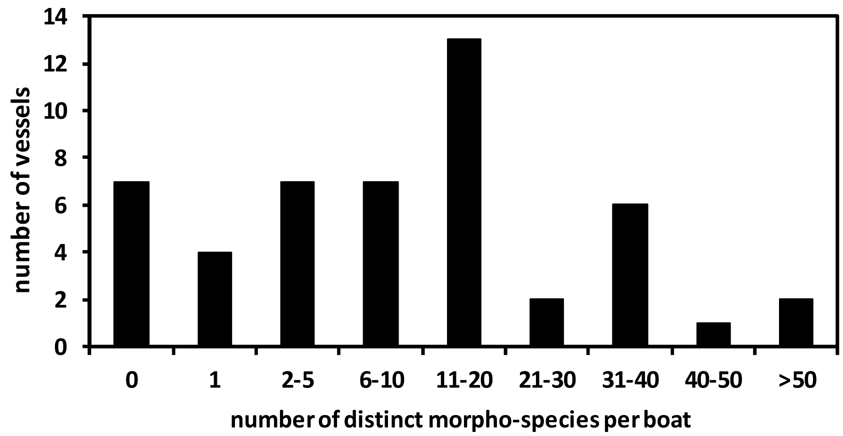

Figure 15. Initial estimates of species richness on 49 transient boats sampled in San Diego and Santa Barbara. These estimates are based on distinct morpho-taxa and show that 7 vessels had sero biota, two had more than 50 morpho-species, and the highest frequency was for 11-20 species.

The current list of 119 species identified by our group and by taxonomists for these vessels is shown in supplementary material (Appendix 4). Among these species, 37% were native to California and 29% were non-native but have been described from bays along the coast previously. A further 26% could only be identified to genus level because they were juveniles or lacking taxonomic characters to identify further, and other members of these genera are known to be present in California. The biogeography of seven species (6%) is undetermined at present and these species were considered to be cryptogenic for now.

A notable record was the bryozoan *Hippoporina indica,* which has not been identified from the west coast of North America previously. A taxonomic expert provided details of a new species within the polychaete genus *Branchioma*, which has only recently been described from the west coast(since 2008) and is listed as *Branchiomma* sp. 2 Harris (the taxonomy of this genus needs revision and no species names are provided as yet; L. Harris, pers. comm.). Another potentially new record is for the polychaete *Syllis* sp. 37 Harris, which exhibited a novel combination of pigment pattern and morphological features that suggests it may be a new record for the region. Other species that are of interest include the ascidian *Botrylloides perspicuum* and polychaete *Pileolaria tiarata* which have only been described from limited ranges in Southern California to date. A small blade of *Undaria pinnatifida,* a large kelp that has invaded numerous locations in California and around the world, was also found on a boat hull in San Diego, a location in which it is not yet reported to be established.

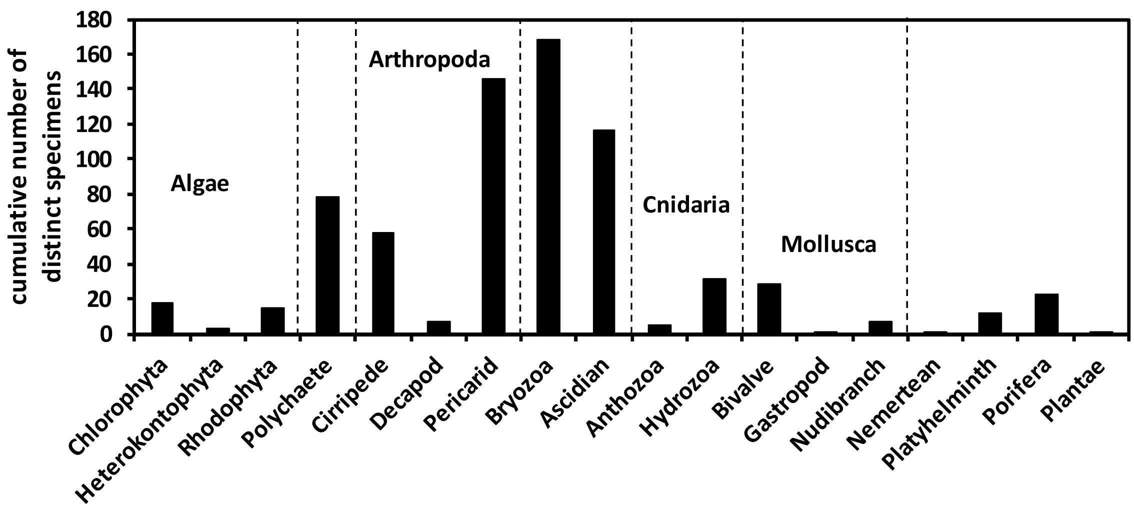

Figure 16. Numbers of specimens within broader taxonomic groups sampled from hull fouling of 49 boats in Santa Barbara and San Diego. These data reflect the total numbers of specimens collected from 49 vessels (n=718). The same species can be counted several times in these data based on the number of vessels they were collected from. Almost 120 different species have been identified to date.

A minority of just over 14% of the 49 transient vessels sampled during this project had no detectable macro-fauna or macro-algae (Fig. 17). Using categorical abundance estimates, we found that 22% of vessels had only isolated individuals on their submerged surfaces, while a further 12% had between eleven and 100 organisms. The most common extent category recorded comprised of boats with between 101 and 1000 organisms (26.5% of vessels). We found it somewhat surprising that nearly 25% of transient vessels sampled had more than 1000 organisms, especially the vessels at the upper end of the distribution that had hundreds-of-thousands of individuals and colonies (Fig. 17). These extensive biofouling assemblages are more often associated with resident or laid up vessels, but we observed five vessels with over 10,000 organisms each, suggesting that a significant minority of vessels transport very large quantities of biota from harbor to harbor on their coastal journeys. One of the transient fishing boats had a similar level of biofouling cover.

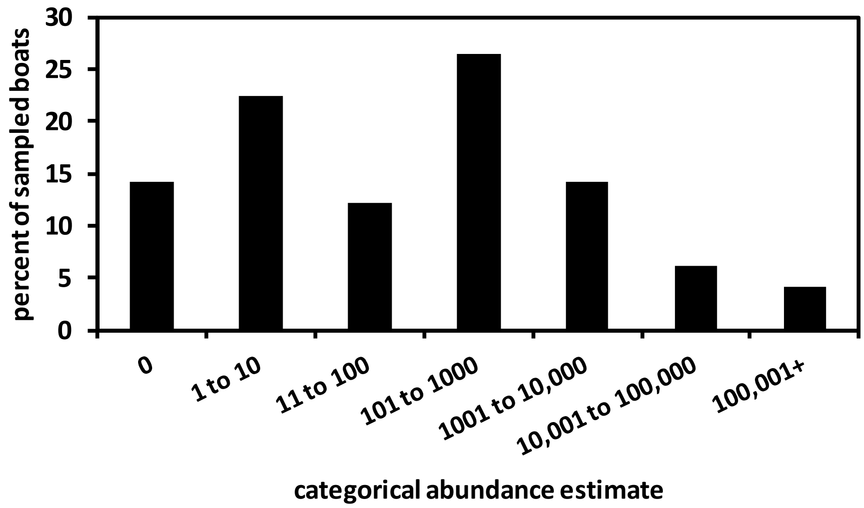

Figure 17. Frequency of transient vessels with different biota abundance categories. This plot shows the proportion of sampled boats that were assigned to one of seven abundance categories. Underwater observations and subsequent assessments of images were used to assign each boat into a log-scale category of organism abundance.

As recorded in ours and others' previous studies, biofouling tended to occur more often on niche areas of vessels rather than hull surfaces. This was certainly true for vessels that were recorded in the lower abundance categories (1-10, 11-100, 101-1000 organisms; Fig. 18). Vessels in the higher abundance categories, however, tended to have fouling on both hull and non-hull surfaces. On the most heavily fouled vessels, there was an increase in the average percent cover of fouling on hulls, but also a wide variability in fouling on hulls (Fig. 18), reflecting the patchy nature of fouling cover on laminar surfaces of heavily fouled boats.

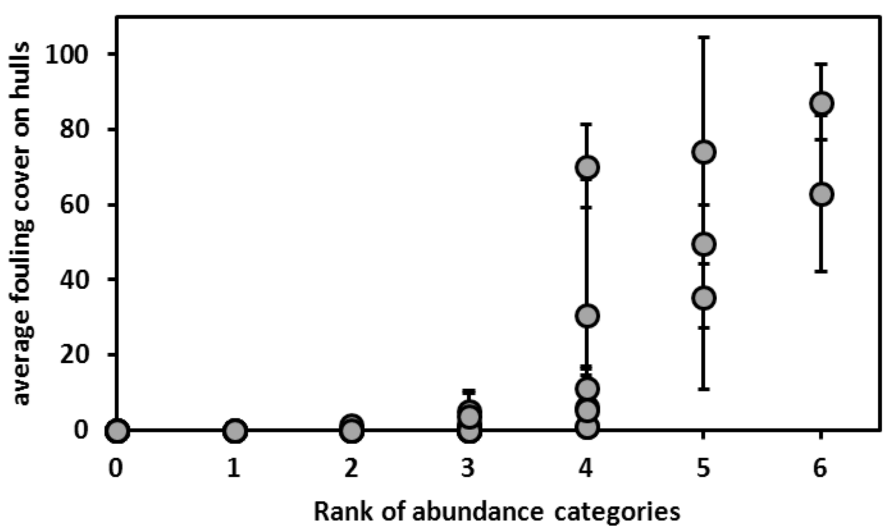

Figure 18. Comparison of biofouling percent cover on hulls with whole vessel biofouling extent. The categories of fouling abundance correspond to the seven categories outlined in figure 17 (where rank 1 corresponds to abundance 1 to 10, 11 to 100, and so on). The percent over of biofouling on hulls tends to increase on extensively fouled vessels, but variation in percent cover also increases.

For 46 of the 49 sampled vessels, we had corresponding questionnaire data with responses on antifouling paint age. Antifouling paint had been applied within three years of sampling for a majority of vessels (87%). There was a significant correlation between antifouling paint age and abundance of fouling organisms on hulls (Pearson correlation $r=0.514$, $p<0.001$; Fig. 19). There was also a majority of vessel operators reporting some maintenance activity (hull cleaning or paint application) within 12 months of sampling (90%), but the correlation between biofouling extent and duration since last maintenance was not significant ($r=0.265$, $p>0.05$).

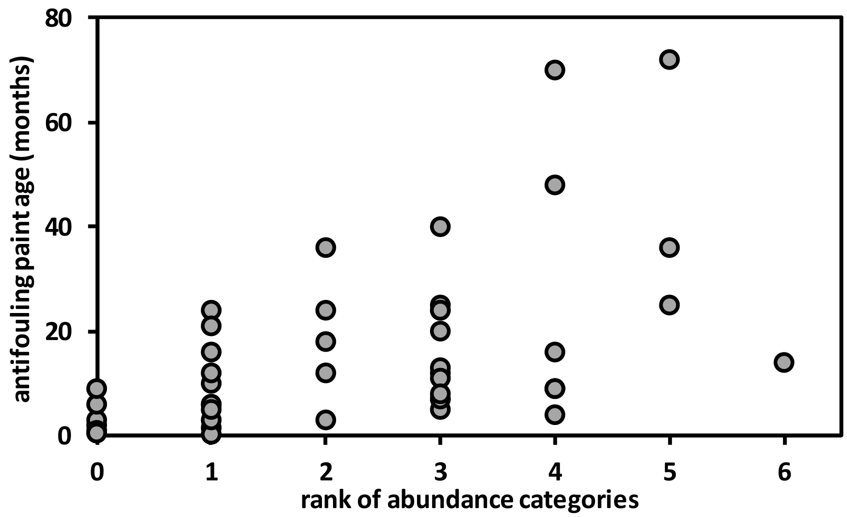

Figure 19. Comparison of biofouling abundance with reported age of antifouling paint. The categories of fouling abundance correspond to the seven categories outlined in Figure17 and 18 (where rank 1 corresponds to abundance 1 to 10 and so on). There was a significant correlation between paint age and extent of fouling (see text).

4.3 Impacts of California AIS with fishing vessel biofouling as a possible vector

The literature searches for impacts studies were conducted for 95 biofouling species (that are associated with fishing vessels and other biofouling vectors). This included 53 crustaceans, 22 molluscs, and 20 algae. After the stepwise process of eliminating irrelevant papers, there were 134 papers with impact information (from around the world, not just California) for 22 of the initial 95 species. The 22 species included 7 algae, 9 crustacea and 6 molluscs (Table 2). The earliest study retrieved was published in 1926 (Miller, 1926) but almost 60% of the impact studies (n=80) were published since 2006.

The number of relevant papers per species ranged from 1 to 30 with algae, *Sargassum muticum,* having the most. Other species with a large number of impact papers included the alga *Codium fragile* ssp *fragile* (n=25), the green crab *Carcinus maenas* (n=24) and the (shipworm) mollusc *Teredo bartschi* (n=17). One-third (34%) of impact papers described studies conducted in the USA, and 14 of these were conducted in California.

The most common type of impact reported in these studies described impacts of non-native species on native species (56%). Impacts to native communities (12%), ecosystem processes (7%), and the whole community (native/non-native not specified, 5%) were also reported in these papers. Almost half of the studies (48%) were based on experimental analyses, including field and laboratory experiments, while many of the remaining studies measured impacts without manipulations (40%) or reported simple observations (11%).

Different types of impacts were recorded within and among AIS. For example, the impacts of the algae *Sargassum muticum*, the fouling species for which the greatest number of studies were retrieved, were first studied in 1982 in California (Ambrose & Nelson, 1982). This was 38 years after the species had been first recorded outside of its native range, in British Columbia (Wallentinus, 1999). Further studies of this species have been conducted from several coastlines in Europe (including Atlantic coastlines and the North Sea) and both coasts of North America. The articles range from describing a single impact on a single species, mainly the AIS's impact on native species (e.g., Ambrose & Nelson, 1982), to multifaceted evaluations of abundance, species richness, diversity, evenness and composition of different components of the impacted community (e.g., mobile epifauna, sessile epifauna, epibiota; Harries et al., 2007). While most studies on the impacts of *S. muticum* were focused on a numerical effect on native species populations, others included effects on biogeochemistry, physical habitat and non-numerical native species responses (e.g. a behavioral or physiological responses).

The 14 studies of biofouling species impacts were conducted in California and involved seven species; *Sargassum muticum, Batillaria attramentaria, Musculista senhousia, Mytilus galloprovincialis, Teredo navalis, Carcinus maenas,* and *Sphaeroma quoyanum*. The studies span the coast between Bodega Bay and San Diego Bay, including San Francisco Bay, Bolinas Lagoon and Santa Catalina Island. The lag between a species being first recorded in California and the first impact study being published varied between 10 years (for *C. maenas*) and 103 years (for *Sphaeroma quoyanum*). The mean lag time was 41 years. The impacted entities included native species (most studies), ecosystem processes, and anthropogenic concerns (e.g. economic impacts). For example, the one impact study in California on the wood boring mollusc, *Teredo navalis*, examined the economic impact of the species on maritime infrastructure.

It is important to remember that these summary results reflect a standardized review approach for three taxa only. There are impacts literature for these taxa that were not returned in a search-engine based review, and there are many other species for which impact data have been reported (see discussion)

Table 2. List of biofouling AIS, with fishing vessels as a possible vector, for which impacts data were returned during a standardized literature search. The search of impacts literature yielded data for the 22 species of crustacean, mollusc, and algae. The step-by-step reduction in relevant papers is shown for the initial output result from BIOSIS (initial result), those that had relevant titles, and ultimately those from which data could be gleaned.

Taxon	Species	Initial results	Relevent titles	Articles with impacts data
Algae	*Sargassum muticum*	132	71	30
Algae	*Codium fragile ssp fragile*	137	68	25
Algae	*Undaria pinnatifida*	116	50	9
Algae	*Gracilaria vermiculophylla*	34	14	6
Algae	*Grateloupia turuturu*	32	9	2
Algae	*Neosiphonia harveyi*	18	4	2
Algae	*Dasya sessilis*	4	1	1
Molluscs	*Mytilus galloprovincialis*	278	62	17
Molluscs	*Crassostrea gigas*	415	42	12
Molluscs	*Musculista senhousia*	56	13	8
Molluscs	*Batillaria attramentaria*	14	4	4
Molluscs	*Potamopyrgus antipodarum*	136	21	2
Molluscs	*Teredo navalis*	16	7	1
Crustaceans	*Carcinus maenas*	394	149	24
Crustaceans	*Mytilicola orientalis*	10	6	5
Crustaceans	*Amphibalanus improvisus*	51	10	3
Crustaceans	*Rhithropanopeus harrisii*	74	13	3
Crustaceans	*Sphaeroma sp.*	45	6	3
Crustaceans	*Caprella mutica*	42	11	2
Crustaceans	*Sphaeroma quoianum*	14	4	2
Crustaceans	*Caprella scaura*	7	1	1
Crustaceans	*Amphibalanus amphitrite*	100	11	1

4.4 Vector disruption

In this section, we conduct an evaluation of the vector process and the tools that exist to disrupt this process. This evaluation of existing practices is split into the scale of an individual vessel and at the scale of state management policies. We discuss these management issues with respect to future prospects and recommendations in the discussion section of this report.

Critical control points in the biofouling vector process and vessel-scale management

The vector process that successfully transfers biofouling organisms from one location to another is quite straightforward when considered from the point of view of one vessel transit rather than a complex network of overlapping vectors in time and space. The straightforward vessel-level process is also the level at which management action happens, regardless of the larger scale policies governing that action (e.g. an epidemiological model of control at the state level would still result in action on the vessel level). The vector process for fishing vessels (and other biofouling vectors) has three steps and three important points where management can act to impede the progress of transferring species (Fig. 20). The critical points of interaction between organisms and the vessel occur at colonization, translocation, and release. At either end of the process, organism behavior determines the initial contact with the vector and the outcome after arrival at a recipient location. The critical control points in the process relate to colonization prevention, transfer disruption, and release containment. (Note: this is related to the Hazard Analysis & Critical Control Points Approach that is increasingly being adopted in AIS management. We did not use the explicit term HACCP in this study because we followed the vector analysis approach of Ruiz & Carlton (2003) more than any explicit HACCP approach). Each of these steps in the process is also a filter that occurs in nature without additional intervention by people (e.g. the transfer stage can exert dislodgment forces on biota). Additional disruption though management can enhance the filter and greatly reduce the numbers of successful vector events.

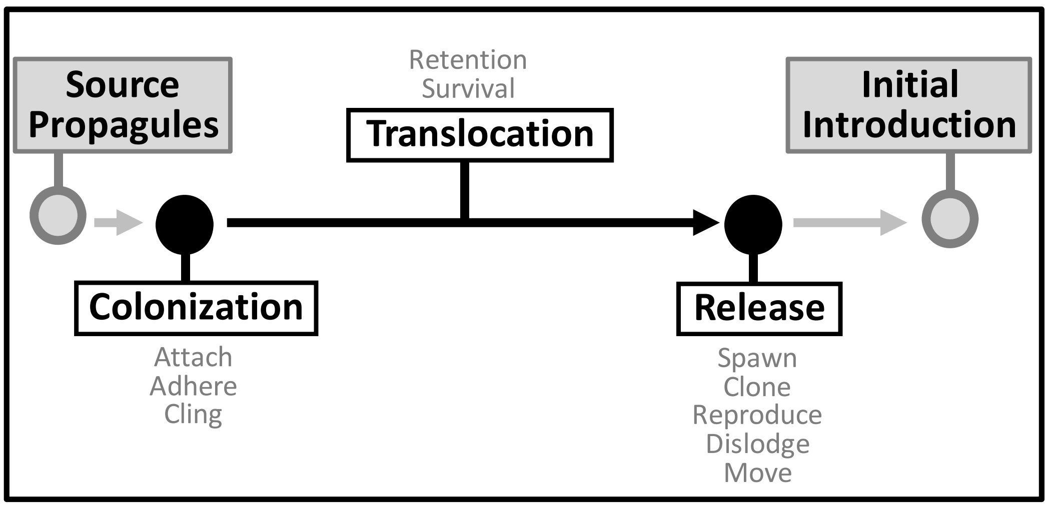

Figure 20. The biofouling vector process. There are three steps (arrows) involved in the successful transfer of organisms from one location to another. The vessel's components are in black and the organism interactions with the vessel are in gray. At the outset, source populations of organisms must interact in space and time with the vector and behave in a way that allows them to take advantage of colonizable space. Upon colonization, the organisms must attach, adhere or otherwise cling on to the vessel directly or to other organisms already attached. After colonization, organisms must withstand any disturbances that can affect a vessel prior to departure and during transit, and must be able to retain its position on the vessel. Upon arrival at a destination, the timing in relation to the species ability to release from the vessel is critical. Species can disembark themselves, through dislodgement, fragmenting, or simply moving or they must release propagules. At this point, the vector process has successfully transferred the organisms, but the organisms have additional hurdles after hereafter in order to become established.

The options for interrupting the vector event at each point of the process are numerous and summarized in Table 3. Colonization prevention methods include separating the boat from the water, separating it from propagules while it remains in water, and applying (and maintaining) an antifouling surface that allows organisms to come into contact with the vessel but prevents their attachment to it. These approaches vary in their utility for fishing boats (from basically no uptake to fleet wide application; Table 3) and vary in their convenience and expense.

Disrupting transfers after the vessel has been colonized is usually a response to a first phase failure. These include in-water cleaning by owners or professional service providers, and sometimes utilizing freshwater harbors to act as a biocide that kills marine organisms. The intensity of these applications is the key to their success; partial cleaning, or hull only cleaning, does often not disrupt niche area transfers while freshwater immersion for short durations is of little consequence. In fact, freshwater immersion is really only applicable to boats with home ports in freshwater that travel to marine waters and back, which applies to a small minority of vessels statewide, but may be significant at the local scale. In addition, there is one transfer disruptor that is designed to work with the existing vector filter at this point in the process. Foul-release coatings are not designed to prevent colonization but to allow attachment by species and provide such limited adherence force that organisms slough off a vessel almost immediately after departure. This process enhances the sloughing effect that exists for biofouling, regardless of paint application, when vessels are underway.

The final step in the process involves containment of biota after its transfer to a recipient harbor. At this point in a linear conceptualization of the steps, prevention of species releases from the vessel to surrounding habitats is largely unknown in the case of regular boating and fishing vessel activities. It has only been triggered in the event of a specific high-profile incursion that has come to the attention of concerned citizens or agencies (Hayes et al., 2005). The options are simply to clean in-water or out-of-water while ensuring to retain all propagules that are removed from the vessel and dispose of them on land. Another option for an agency with authority to prevent unwanted incursion is to demand immediate departure, although again, this is more of an emergency response than a generally applied tool (and it is not boat operator driven).

An additional consideration for vector disruption is that the biofouling vector does not act solely as a source-to-point vector, as is largely the case for ballast water (for example). Biofouling is a concatenation vector with organisms accumulating, and dispersing, over time throughout the life-cycle of an inter-dry docking period. The straight line process described in figure 20 could just as easily be presented as a loop, with the end point of one voyage acting simultaneously as the starting point of the next, and species colonization happening continuously during periods of inactivity. Because of this, applications that are available for vector disruption must be carried out fairly continuously if the efficacy of the primary method (generally antifouling paint) begins to subside. Also, disruption tools that are designed to operate in concert with the natural filtering effect of the vector process are probably more convenient and more readily maintained than ones that react to the failure of an application intended to affect a prior step in the process.

Table 3. Products, services and strategies for applying management effort to critical control points in the fishing vessel biofouling vector. The table shows the methods, benefits and issues related to applications of tools to disrupt a biofouling vector transfer by fishing vessels.

Action	Method	Benefits	Issues
Prevent species colonization	Keep the boat on a hoist or stored on land	- Separating the vessel from the water is the most effective preventative measure	- Expense - Inconvenience - Impractical for most fishing boats - In-water hoists are unheard of for large fishing vessels (recreational vessels only)
	Use a skirt or container around vessel at berth (e.g. boat bath)	- Relatively simple tool - Allows for vessels to remain in water (more convenient	- Expense - Inconvenience - This treatment is more effective if freshwater or chlorine is used inside the bath, but this has other

		than above) - Skirt also remains in water for convenient re-application after voyages	environmental implications and may be prohibited in some locations - If not maintained, the skirts become fouled on the outside, adding to the maintenance burden - If not maintained, the skirts sag and sink (become ineffective) - Unheard of for larger fishing vessels
	Maintain a pristine antifouling coating with toxic agents (including niche areas)	- Antifouling paint is the most commonly available prevention option making it readily available - Convenience	- Expense - Maintenance burden (re-applications may be necessary) - Interim measures are usually required (in-water cleaning) - Requires regular vessel usage because stationary periods can compromise efficacy - Pollution - Toxicity issues (e.g. copper) conflict with other environmental management
Disrupt a transfer after colonization has occurred	Use a non-toxic foul-release coating	- Prevents pollution - Does not conflict with other environmental regulations - Convenience	- Expense - Maintenance burden (re-applications) - Interim measures required (soft scrubs) - Partial efficacy may contribute to AIS spread (if dislodgement doesn't occur soon after departure)
	Clean hull in-water by owner	- Straightforward - Inexpensive	- Application rigor varies widely - Niche areas often ignored - Awareness/training usually needed to improve efficacy - Usually less effective than professional service - Releases species/propagules into the environment - Must be done regularly (clean-before-you-go) to ensure propagule release does not include transferred biota
	Clean hull in-water by professional service	- Convenience - Usually more effective than amateur cleaning	- Expense - Limited availability of diver services in busy harbors - Application rigor generally better than amateur cleaning but still

			varies - Niche areas not always targeted - Releases species/propagules into the environment - Must be done regularly (clean-before-you-go) to ensure propagule release does not include transferred biota
	Use freshwater harbors	- Generally inconvenient - Haphazard strategy - Usually works in concert with other methods above for boats with FW home ports	- Not practical for vessels that do not frequent FW harbors - Short term FW exposure (days) has variable efficacy - Full FW rather than low salinity is often required for efficacy - Efficacy often over-estimated by boat operators
Contain a release after transfer has occurred	Clean hull in water (by owner or professional)	- Can be effective if conducted properly - Relatively inexpensive	- The containment part of this process is generally (always?) not adopted - Cleaning in-water can cause organism releases (doing more harm than good) - Containment using non-suction devices (netting) restricts containment to larger organisms - Suction devices are expensive and not widely used - Even suction device cleaning is not 100% effective (at containment of propagules from the environment
	Clean hull out-of-water (by owner or professionally)	- Can be effective if conducted properly - Allows for other maintenance issues to be attended to (e.g. paint touch-ups)	- Expensive - Shoreline cleaning (by trailer or hoist) must also include a containment strategy - Dry docks must treat all solid and liquid effluent (treatment or land-fill) - Availability of facilities can be very limited at many harbors - Larger vessels require professional work

The range of options (in Table 3) does provide flexibility for boat owners to adapt their strategies to their preferred levels of convenience and expense. However, there is no 'silver bullet' approach that does not require upkeep and continuous re-evaluation by boat owners to maintain a pristine (un-fouled) hull and niche areas. Technological advances in antifouling paint tend to provide a range of paint types that can be tailored to vessel usage patterns, but the most commonly applied paints, using copper as an active antifouling agent, must be maintained and are increasingly coming into conflict with other environmental regulations (as occurred with tributyl tin paints in the past). The longer term efficacy of new generation foul-release paints in regards to species transfers remains an open question, even if this advance in paint technology helps to counteract the conflict between vector disruption and water/sediment quality.

Finally, there are also other non-fouling related species that can be transferred as a result of fishing, either from boats or on the shore. Fishing gear can act as a mechanism for spreading some marine AIS, as has been implied for the invasive green algae *Caulerpa taxifolia* in the Mediterranean (Relini et al., 2000) and the colonial ascidian *Didemnum vexillum* on the East Coast of the U.S. (Bullard et al., 2007). It is considered relatively minor vector but may be important for some species in certain contexts. Release of bait species is another potential vector and the final crucial step in a larger vector process whereby bait, often shipped in from outside of the state, is released to the environment by fishermen. We have not considered these sub-vectors extensively in this report because we were unable to garner data on these issues from fishermen and it is thought to be a much lesser vector than the primary biofouling mechanism. Also, in the context of bait, these species do not result from the fishing vessel vector (but the fishermen themselves) and the bait vector is the subject of another study in this overall six-vector project. However, there may be species-specific transfer associations with bait and gear that warrant further investigation because there is likely some risk attached to these sub-vectors.

State scale management

While the array of tools available to take advantage of the vector process in order to disrupt species transfers is large, it is clear from the history of AIS introductions to the state, and our sampling of vectors, that these tools are not being applied effectively over the large scale of vessels in operation. This is true of both recreational and fishing vessels. Unfortunately, the limited participation of fishing boat operators with our questionnaire and underwater surveys means we do not yet have a substantial data set on any specific differences regarding maintenance that affects fishing vessels but not recreational boats. Our conversations with some fishermen suggested that hull maintenance concerns were not more acute for fishing boat operators than for recreational boats. A few fishermen have said that hull cleaning and re-application of antifouling paint is largely based on their interpretation of need based on fuel efficiency, engine strain, or vessel speed. This suggests that action is sometimes taken re-actively rather than pro-actively, but we do not have a dataset to evaluate the extent to which this is true across a population of fish boat operators. It should also be stated that some recreational boaters apply the same 'needs-must' strategy.

The State's existing regulations for managing biofouling vectors are largely confined to commercial ships. The State Lands Commission manages commercial ship biofouling (and ballast water) through a ship-funded marine invasive species program (http://www.slc.ca.gov/spec_pub/mfd/ballast_water/Ballast_Water_Default.html). This agency makes rules regarding the required practices to reduce and prevent species transfers into and within the state, through an open process of stakeholder-driven deliberations. Existing and proposed rules include the maintenance of a biofouling management log book on each ship, the submission of a hull reporting form (annually), the duration of inter-dry docking periods, and limits on the extent to which biofouling can develop over hull and niche area surfaces. Many of these rules coincide with mandatory federal and classification society requirements. Ships that have had long lay-up periods are also subject to additional assessments because of their higher risk of transferring species into the state.

The State Lands Commission program also funds research to evaluate vector activity and management efficacy of the commercial fleet while the funding instrument also supports coastal monitoring for AIS.

The remit for this program is strictly limited to vessels over 300 gross weight tons (that can carry ballast water).

In addition to the state management of commercial ship biofouling, the U.S. Coast Guard manages ship biofouling at the federal level, focusing on hull husbandry and requiring an unspecified regularity of cleaning on hull and other surfaces (Code of Federal Regulations, Section 151.2035 (5) and (6)). The International Maritime Organization (IMO) provides best practice guidelines to the global shipping fleet that may become mandatory in future (Davidson & Simkanin, 2012).

There are no equivalent programs or policies in place in the state to manage non- large commercial ship biofouling vectors.

5. DISCUSSION

5.1 Marine introductions in California and the role of fishing vessels

Fishing vessels are an important maritime vector in California because they may be associated with transfers of 74% of the AIS currently established on the state's coast. They also number in the thousands, make arrivals to harbors annually in the tens of thousands, create strong connections among harbors that other vectors do not, travel the length of the state's coast and beyond, may play a role in AIS spread by fishing gear, and may act as an important final step in the cause of bait AIS introductions. All of the AIS that were associated with the fishing vessel vector in the state can be considered polyvectic – species that can be transferred by other fouling and non-fouling vectors – and the 'possible vector' designation is required because it is difficult to isolate a single vector for most species, especially for species linked to biofouling. Nonetheless, the overlap between existing AIS distributions and fishing vessel harbors, combined with a better understanding of voyages and biota associated with coastally transiting boats, suggests fishing vessels have transferred AIS in the past and will continue to do so.

Fishing vessels are unlikely to be responsible for long-distance trans- and inter- oceanic introductions entering the state, however, because these boats' voyages tend to be intra-coastal in nature. These include domestic vessels arriving from Mexico (and possibly farther south) and throughout the NE Pacific as far north as Alaska (Ashton et al., 2010). First records of AIS in California tend to be first records for the NE Pacific (Ruiz et al., 2011a), suggesting that long-distance primary and secondary introductions to the state are brought by other vectors, rather than fishing vessel transfers from adjacent territorial waters. The range and domestic nature of fishing vessels operating on the coast appears to be a consistent historical feature of fishing fleets in California, and certainly by 1976, with the passage of the Magnuson-Stevens Fishery Conservation and Management Act that claimed jurisdiction over fisheries extending 200miles offshore (McEvoy, 1986), California's fishing vessel traffic was exclusively American traffic. In the absence of other information regarding foreign fishing (or foreign-traveling domestic) vessels arriving on the coast, it appears that AIS associated with fishing vessels are 1) those from outside the NE Pacific brought in by other vectors, or 2) those that are transferred outside of their native NE Pacific range into a non-native NE Pacific range (intra-coastal primary invasions).

This distinction between potential sources of AIS is important because it provides a stark contrast between fishing vessel biofouling and other biofouling vectors on the coast. Commercial ships, to a large extent, involve arrivals to the state from much farther afield. They are more likely than fishing vessels to transfer AIS from the other side of the Pacific, or through the Panama Canal. Subsequent to these initial establishments in the state or adjacent coastal waters, fishing vessels can act as part of the vector ratchet effect for these AIS and cause wide ranging secondary spread (Davidson et al., 2010). The effect is a function of multiple vectors co-occurring in space and time (sharing the same bay) with AIS populations that may be brought in by one vector becoming 'available' to other vectors. From this juncture, the differential patterns of outward voyages from the focal bay multiply the opportunities for range expansion by the AIS using several different vectors. It is through this mechanism that fishing vessels are most likely to have contributed to the patterns of AIS distributions in the state.

Fishing vessels connect bays via biofouling vectors that are unconnected by commercial vessels and possibly offer unique connections relative to recreational boats too. Although resident boats outnumbered transient ones in the fishing fleet, the transient boats made up a higher proportion of vessels per harbor (across four years) than resident boats. This was the first indication of strong connectivity among bays. Bay-to-bay connections tended to be strongest for adjacent sites rather than long-distance ones, although direct and indirect links from one end of the state to another did occur. This differentiates small boat vessel flux patterns from large ship ones whereby a higher intensity of short stepwise coastal linkages develop among bays (fishing) with an overlapping longer distance connection between major bays (shipping). The lack of a standardized statewide data source for recreational vessels precludes a formal comparison with fishing vessels as yet (Ashton et al., in review), but there is likely to be significant differences in the intensity of overlap for fishing and recreational boats, ranging from zero to high similarity. This distinction would yield useful information for untangling some invasion histories and prospective management options (spatial focus) between fishing and recreational boats.

Other differences among biofouling vectors, aside from the obvious difference of vessel size (for commercial ships versus the other two vessel types), are the numerical comparisons of vessel flux. The state receives around 5,000-6,000 commercial ship arrivals per year, with twice as many overseas arrivals as coastal ones (Davidson et al 2006). More than 800,000 recreational boats were registered in California in 2010 (Ashton et al., in review). Fishing vessel landings occur at a rate of approximately 50,000 per year across the state by approximately 2400 different vessels. There is no such thing as a 'resident' commercial vessel unless it is laid-up, but this study indicated that 52%of fishing vessels tend to arrive to one home port only (resident boats). This compares to a rate of 80-50% of recreational boaters across different bays that reported no voyages to harbors outside of their home bay (Ashton et al., in review). Thus, for this triumvirate of vessel types, fishing vessels most likely rank second for arrivals (after recreational boats) and probably second for transiency rate of the fleet (after ships). Of course, a full scale comparison of all three vessel types would require a biota × vessel × voyage comparison of fleets, which is not yet possible for this coast from existing data.

Temporal variation is a part of the vessel flux pattern for California's fishing fleet, though it isn't clear how it interacts with AIS transfers or distributions. Our previous work (Ashton et al., 2010) found that long distance coastwise voyages to southeast Alaska from the south (California – British Columbia) tended to occur during a time of peak spawning for West Coast marine invertebrates (April to June, Reitzel et al., [2004]). This temporal overlap may extend to AIS, exposing these northward moving vectors to AIS propagules at the opportune time for their vector dispersal. For California's fishing fleet, there is seasonality in the arrival patterns of some harbors and not at others, and there is also inter-annual variation in the voyage patterns exhibited by individual vessels (such as the very transient boat highlighted in Fig. 12). This can be partially explained by the unpredictability of some fisheries, which is a source of worrying instability in fishing communities (Pomeroy et al., 2010). Temporal patterns in fishing vessel movements, with a general reduction in activity in April but without major seasonal fluctuations at many ports, contrasts quite starkly with recreational vessels that have a very seasonal aspect to their tempo throughout the year (Ashton et al., in review). This may be useful information for a division of effort across the year (targeting fishing boats in winter and recreational ones in summer) for any outreach campaign targeting both vessel vectors.

The high numbers of AIS in the state that have fishing vessels as a possible vector is a function of the diversity of organisms that have been introduced to the state that are also members of boat fouling communities. Species from four major groups of primarily sessile (attached) organisms – algae, cnidarians, bryozoans, and ascidians – could all be linked to transfers via fishing vessels. For example, the arborescent bryozoan, *Bugula neritina*, is one of the most commonly encountered species in our sampling of organisms on West Coast boats. It is known to occur in 19 different bays throughout the state from San Diego to Trinidad, being first recorded in Elkhorn Slough in 1905 (cited from NEMESIS data). This included 16 bays with fishing vessel landings, eleven of which did not also have commercial shipping, and two bays that had neither fishing nor commercial ship harbors but do receive recreational vessels. Given the widespread records for this species in the state, distributed among commercial shipping and non-shipping locations, it is unlikely that just one of the biofouling vectors is responsible for all of its transfers.

Mobile (unattached) species are also a component of the fishing vessel vector, included in fouling and non-fouling components. The richest group of AIS in the state is crustaceans with 82 species, only four of which are sessile (barnacles). Fishing vessels were a possible vector in part of their California range for 26 of the 29 amphipod crustaceans and for 14 of 17 isopod AIS. We have encountered situations where mobile species have outnumbered sessile ones in the biofouling communities of transient coastal vessels, but mobile taxa usually require at least some sessile biofouling cover to occur (using the matrix of biogenic surfaces created by sessile taxa). This study highlighted the sometimes extensive cover of sessile species that can occur on boats, and lead to very rich assemblages of mobile taxa. Such encounters with 'floating reefs' are not common for transient boats, but they numbered almost as many in this study as the boats recorded with zero biota.

The non-fouling component of fishing vessel transfers involves incidences where fishing vessels can be implicated in accidental fisheries-related transfers. For example, the crab *Rhithropanopeus harissii* is established in San Francisco Bay and designated polyvectic, including a non-fouling component of fishing vessels as a possible vector. It has also been recorded in Drake's Estero and has been assigned vector unknown at present.

When we consider the current status of the vector, it is useful to move from the complete historical record to examine recent years of AIS first detections among bays. NEMESIS records revealed new distribution data for 133 of the 278 species in California between years 2000-2009. These records come from 26 different locations (of the 32 analyzed, Fig. 6) and 20 of these include fishing harbors. Fishing vessels are a possible vector for 87% of the 318 species × bay detections. It is important to acknowledge that these records are based on locations where studies have occurred (rather than a standardized and even effort among bays) and Ruiz et al. (2000 & 2011a) provide an in-depth discussion of this and other potential biases in the data. Nonetheless, it appears that the role of fishing vessels as a possible vector for species re-distributions is not abating.

The richness component of AIS introductions is an important metric of invasion history, and a critical component of vector analysis, but the consequences of AIS introductions are also important to understand when considering options to manage vectors. To that end, there is a focus on impact of AIS in resource management. In California, one of the most notable impacts occurred in San Francisco Bay whereby a cascade of invasions involving the Asian clam (*Corbula amurensis*) and planktonic mysid and copepod species have altered the food web and caused or contributed to declines in striped bass and the endangered Delta Smelt (Ruiz et al., 2011b). For biofouling species, the impacts of ascidians on the East Coast of North America, including *Styela clava*, *Ciona intestinalis*, and *Didemnum vexillum* (all established in California) has been particularly acute on shellfish aquaculture operations (Arsenault et al., 2009; Edwards & Leung, 2009; Carman et al., 2010). With effects as significant as the endangerment of threatened species and the reduction of incomes that threaten livelihoods, it is clear that impact evaluations play an important role in determining how management priorities are established.

However, the impact literature is very unevenly distributed among species and tends to focus on a small subset of apparently impactful ones (e.g. the review results for *Sargassum muticum* and *Carcinus maenus* above). Our preliminary results are also confined to certain taxa and one search engine and require evaluation as to which studies were not provided in search results. Still, a literature review approach tends to be the only approach that yields data on a community of AIS in one location because there are no bays that have had multiple investigations of impacts across a range of AIS over a sustained period (the San Francisco Bay example is one of the most comprehensive). Ruiz et al. (1999) suggested that <5% of the species in most bays have had any impact evaluations whatsoever. Our review for this project did highlight four species for which several impact studies had been carried out, but few of these were from California sites. Going forward, if resource managers are to rely on impact metrics of AIS to direct management efforts, the paucity of data on impacts for most AIS will have to be addressed.

Finally, an important consideration in vector analyses is the extent to which vectors cross important biogeographic boundaries. Fishing vessels tend to engage in coastwise traffic only, but this still involves passage through different biogeographic provinces. California straddles two major marine provinces, the Californian and Oregonian, with the boundary between them generally considered to be Point Conception. These provinces have characteristic assemblages of co-evolved marine animals and plants, and it has been noted that the Oregonian province has a high degree of endemicity (Niesen, 2007). A relatively wide environmental tolerance is considered necessary for AIS to occur on either side of Point Conception boundary, and such species are prevalent in the AIS community of the state (based on their occurrence north and south of this point). Within this larger biogeographical framework, four smaller-scale sub-provinces (Ensenadian, Southern Californian, Montereyan, and Mendocinian) display affinities of species that highlight a meso-scale pattern of ecological community differences (Blanchette et al., 2008). Of course, AIS communities among bays do not belong to these provinces, and outer coast ecological communities usually form the basis for the divisions (rather than bays), but fishing boats are regularly crossing these divides with biota that lack a natural means to do so. The examples of boats travelling from southern California to northern California, Oregon and Washington exemplified the longest distance travelers in this data set. Thus, fishing vessels can engage in coastwise primary introductions of species native to one province but not others. When combined with ocean warming, the trend of apparent northward spread of AIS in California and further north can be expected to continue (Ruiz et al., 2011a).

5.2 Prospects for statewide fishing vessel vector management

As noted at the outset, the vector management framework proposed by Carlton and Ruiz (2003) was adopted where possible in this analysis of fishing vessel vectors: 1) We evaluated the invasion history of California and vector associations of species to determine the possible role of fishing vessels in the initial establishment of AIS in the state (vector strength; 74% of AIS can be considered possible fishing boat related); 2) We characterized the vector's current standing stock of vessels and their route and tempo patterns, and the biota associated with transient coastal vessels; and 3) we assessed the impact literature as it relates to AIS in California that have fishing vessels as a possible vector (not part of the framework); and 4) we assessed the critical control points (Fig. 20) to disrupt the vector and the tools Table 3) that can be used can be taken advantage of them.

It is important to note when considering management options that the fishing vessel vector of AIS is an inadvertent one. Species are moved around often without the knowledge of the vessel operator, and sometimes to their annoyance because of their impact on vessel efficiency. This contrasts with other vectors where the longer parts of the vector journey (e.g. shipments of ornamental species from another continent) are designed with the intention of bringing the species into California, and to keep it alive while doing so. Of course, in this example, the critical vector step of release in to the environment must still be achieved after arrival to the state, and this is not a step that biofouling vectors must overcome (biofouling species are already in the recipient environment). However, the point is that the cause of vector transfers (Carlton & Ruiz, 2003) is something to reflect on when designing strategies to engage with end-users – management of an inadvertent vector may be well received by the user community if the benefits to them (in addition to preventing AIS transfers) can be communicated.

Another item to note about a statewide policy or program that considers fishing vessel vector management is that the size of the fleet and the largely within-state audience may make it more tractable and enhance the possibility of success. Certainly this is true in relative terms when we compare approximately 2400 boats of the fishing fleet with the circa 800,000 of the recreational fleet. The commercial versus recreational motivation can also warrant differential strategies between both sectors, even if the prescribed disruption tools are broadly similar. Furthermore, a large proportion of fishing vessels are sole-port boats. This is beneficial in relation to invasions because there is no inter-harbor transfer for these boats, although we must remember that this data set relates to reported fish landings and not all voyages by these boats (i.e. non-fish landing trips) are included here. In any case, it would probably be impractical to further sub-divide the fleet for targeted communications on this basis.

It is clear that responsibility for boat maintenance falls on individual fishing boat owners, some of whom may not know or care about the issue of non-native species and measures they could take to prevent species transfers. Also, the history of fishing regulation in California is a case study in the tug-of-war between resource exploitation and preserving the commons (McEvoy, 1986). As such, the biofouling vector is a much lower-level concern for fishermen, if it is a concern at all, and there appears to be wide scale wariness of consenting to evaluations of their equipment and activities that may subsequently be used as supporting evidence to add to their regulatory burden.

Having described the model of vector transfers and tools that can be applied (by users) at critical control points to interrupt the vector (reduce or prevent transfers from occurring), the broader statewide strategy of persuading user uptake must be considered (Table 4). The vessel-scale management of the vector is relatively well catered to in terms of products and services that can be used to disrupt the vector. The market in each of those products and services should drive their efficacy over time, although certain issues (e.g. management of niche areas of vessels) require a management role in order to incentivize uptake. The state scale policy of ensuring management occurs at the user level is virtually non-existent. Except in regards to cross-over benefits of outreach campaigns to recreational boaters (e.g. Sea Grant), we are unaware of any fishing vessel vector initiative in the state.

Table 4 describes a range of options that could be considered for statewide management action. These range from the least onerous in terms of budget and resources needed for implementation (and effect on fishermen *status quo*), to the most onerous that would involve regulation and enforcement (and probable pushback from fishermen). Our recommendation would be for targeted outreach to occur to enhance the uptake of products and services to affect vector disruption. However, we highly recommend that this be done with scientific polling before- and periodically after- the implementation of the campaign so that efficacy of outreach can be measured. Simply conducting outreach without determining whether or not it is having the desired effect (increasing awareness and uptake of management) is a far less optimal alternative. The balanced nature of this approach, at the midpoint of options between retaining the status quo and enacting statewide enforcement of regulations, is a feature that may help reduce conflict with a user group that may be receptive to the need for action without the need for regulation. It also can be a first step toward regulation if social and biological data suggest it is required. For example, exploration of the social-policy aspects of vector management within the fishing community would provide useful insight into the likelihood of uptake of guidelines and the possible need to enforced regulation. The combined science-based design of monitoring user group response and the marine biological response mean our suggestion is adaptable to measured outcomes.

Table 4. Strategies for fishing vessel vector management of biofouling. The table describes a range of measures that could be adopted, from the least to the most resource intensive (top to bottom). While these strategies are described as independent approaches, some items could be undertaken in sequence.

Item	Action	Outcomes
Retain the status quo	- Do nothing	- Potential conflict with stakeholders concerned at the lack of action on vector management - No conflict with fishermen - Unintended consequences avoided (e.g. additional copper pollution) - Fishing vessel influence on AIS spread remains unchanged - But, the 'do nothing' option is not static and the per capita effect of AIS × Area affected will expand dramatically over time
Conduct outreach to commercial fishermen (without polling)	- Attempt to increase awareness of AIS and vector issues among commercial fishermen	- Can be scaled to suit budget and resource availability - May provide very favorable cost-benefit outcome - The effects of outreach will be largely unknowable - Fishing vessel influence on AIS spread may decline
Conduct outreach to commercial fishermen with scientific polling	- Attempt to increase awareness of AIS and vector issues <u>AND</u> determine efficacy/uptake	- Can be scaled to suit budget and resource availability - May provide very favorable

		cost-benefit outcome - The effects of outreach will be assessed with before and after polling to determine efficacy - Efficacy measures can be used in adaptive strategy and to inform future policy directions - Higher chance (than above) for beneficial effect on AIS transfers
Propose voluntary guidelines on a statewide basis	- Add guidelines regarding vector management to other permits issued by the state DF&G.	- May be inexpensive - Linking voluntary guidelines to other permitting interactions may enhance uptake of vector management - Additional monitoring required to determine uptake - Fishing vessel influence on AIS spread may decline
Propose mandatory rules governing vector management	- Create regulation and enforcement mechanism for vector management of fishing vessels	- A model of state vector management already exists in the state that can be mimicked (SLC) - An agency is already responsible for ocean fishery management (DF&G) - Highest likelihood of effective vector management - High and continuous expense - High possibility of conflict with fishermen - Possibility of unintended consequences (e.g. copper pollution or inappropriate use of foul-release coatings)

An important final step in the Carlton & Ruiz (2003) framework for vector management is the role of monitoring efficacy after management actions have been adopted. This involves a shorter time scale evaluation of vector transfers after management (preferably with a before- comparison) and a longer time scale monitoring of AIS distributions to determine if the ultimate goal of preventing new invasions is occurring. This type of action is underway for commercial vessels and the efforts to evaluate vectors and invasions through time for one vector can be undermined by a lack of action on another. To that end, there are overlapping interests and efficiencies that can be attained by working with existing vessel vector managers in the state (e.g. SLC marine invasive species program and DF&G marine invasions monitoring program).

Vector management and subsequent monitoring should also consider the role of infrastructure in providing habitat for AIS. Marinas, docks, pier walls, pilings and other anthropogenic structures are the real focal points within bays for much of the richness of AIS communities (Ruiz et al., 2009; Simkanin et al., in press). A majority of our data on AIS distributions emanates from sampling done in the built environment that supports fishing and recreational boating. To the extent possible over the longer period, design aspects of marina docks should be evaluated to determine if better materials, strategies or tools can be used to prevent the establishment of AIS in those locations, or create a barrier between them and the vectors nearby. One example would be the design of docks in which the berths have a pre-installed and easily manipulable skirt (or boat bath) to prevent colonization during stationary periods.

Finally, the value of vector management should be restated. The role of preventive rather than reactive management in regards to marine AIS is broadly accepted (Ruiz & Carlton, 2003). Vector management represents an AIS strategic action that isn't solely defensive and that works on the underlying process involved in AIS dispersal. It doesn't simply defend a territory from unwanted organisms and consequences – an approach that superimposes political boundaries that may be meaningless to the broader ecological scale of the process - but attacks the underlying mechanism of unwanted ecological change. In this sense, the beneficial effect of vector management is felt at both the enacting territory and at interacting locations downstream of the territory, which promotes a 'neither-sink-nor-source' outlook that may better serve AIS and resource management over larger scales.

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Supplementary Material

Appendix 1: 278 AIS in California and possible link to fishing vessels

taxon	species name	vector (binary for fishing vessels)
Algae	*Aglaothamnion tenuissimum*	Fishing vessel possible
Algae	*Antithamnion hubbsii*	Fishing vessel possible
Algae	*Ascophyllum nodosum*	not fishing vessels
Algae	*Asparagopsis armata*	Fishing vessel possible
Algae	*Bryopsis sp .1*	Fishing vessel possible
Algae	*Caulacanthus ustulatus*	Fishing vessel possible
Algae	*Ceramium kondoi*	Fishing vessel possible
Algae	*Codium fragile ssp .fragile*	Fishing vessel possible
Algae	*Cutleria cylindrica*	Fishing vessel possible
Algae	*Gelidium vagum*	not fishing vessels
Algae	*Gracilaria vermiculophylla*	Fishing vessel possible
Algae	*Grateloupia lanceolata*	Fishing vessel possible
Algae	*Lomentaria hakodatensis*	Fishing vessel possible
Algae	*Neosiphonia harveyi*	Fishing vessel possible
Algae	*Polysiphonia denudata*	Fishing vessel possible
Algae	*Sargassum filicinum*	Fishing vessel possible
Algae	*Sargassum muticum*	Fishing vessel possible
Algae	*Undaria pinnatifida*	Fishing vessel possible
Annelids-Leeches	*Myzobdella lugubris*	Fishing vessel possible
Annelids-Oligochaetes	*Chaetogaster diaphanus*	not fishing vessels
Annelids-Oligochaetes	*Limnodriloides monothecus*	Fishing vessel possible
Annelids-Oligochaetes	*Protodactylina pamelae*	Fishing vessel possible
Annelids-Oligochaetes	*Tubificoides apectinatus*	not fishing vessels
Annelids-Oligochaetes	*Tubificoides brownae*	Fishing vessel possible
Annelids-Oligochaetes	*Tubificoides wasselli*	Fishing vessel possible
Annelids-Oligochaetes	*Varichaetadrilus angustipenis*	Fishing vessel possible
Annelids-Polychaetes	*Alitta succinea*	Fishing vessel possible
Annelids-Polychaetes	*Amaeana sp. A .Harris*	Fishing vessel possible
Annelids-Polychaetes	*Amblyosyllis sp. A Harris*	Fishing vessel possible
Annelids-Polychaetes	*Boccardiella ligerica*	not fishing vessels
Annelids-Polychaetes	*Crucigera websteri*	Fishing vessel possible
Annelids-Polychaetes	*Ficopomatus enigmaticus*	Fishing vessel possible
Annelids-Polychaetes	*Geminosyllis ohma*	Fishing vessel possible
Annelids-Polychaetes	*Heteromastus filiformis*	Fishing vessel possible
Annelids-Polychaetes	*Hydroides diramphus*	Fishing vessel possible
Annelids-Polychaetes	*Hydroides elegans*	Fishing vessel possible
Annelids-Polychaetes	*Laonome sp SF1*	not fishing vessels

Annelids-Polychaetes	*Marenzelleria viridis*	not fishing vessels
Annelids-Polychaetes	*Myrianida pachycera*	Fishing vessel possible
Annelids-Polychaetes	*Neodexiospira brasiliensis*	Fishing vessel possible
Annelids-Polychaetes	*Nicolea sp. A. Harris*	Fishing vessel possible
Annelids-Polychaetes	*Sabaco elongatus*	not fishing vessels
Annelids-Polychaetes	*Streblospio benedicti*	Fishing vessel possible
Annelids-Polychaetes	*Typosyllis nipponica*	Fishing vessel possible
Bacteria	*Xenohaliotis californiensis*	Fishing vessel possible
Coelenterates-Anthozoan	*Bunodeopsis sp. A*	Fishing vessel possible
Coelenterates-Anthozoan	*Diadumene ?cincta*	Fishing vessel possible
Coelenterates-Anthozoan	*Diadumene franciscana*	Fishing vessel possible
Coelenterates-Anthozoan	*Diadumene leucolena*	Fishing vessel possible
Coelenterates-Anthozoan	*Diadumene lineata*	Fishing vessel possible
Coelenterates-Anthozoan	*Nematostella vectensis*	Fishing vessel possible
Coelenterates-Hydrozoans	*Amphinema sp.*	Fishing vessel possible
Coelenterates-Hydrozoans	*Bimeria vestita*	Fishing vessel possible
Coelenterates-Hydrozoans	*Blackfordia virginica*	Fishing vessel possible
Coelenterates-Hydrozoans	*Cladonema pacificum*	Fishing vessel possible
Coelenterates-Hydrozoans	*Clava multicornis*	Fishing vessel possible
Coelenterates-Hydrozoans	*Climacocodon ikarii*	not fishing vessels
Coelenterates-Hydrozoans	*Cordylophora caspia*	Fishing vessel possible
Coelenterates-Hydrozoans	*Corymorpha sp. A Carlton 1979*	Fishing vessel possible
Coelenterates-Hydrozoans	*Garveia franciscana*	Fishing vessel possible
Coelenterates-Hydrozoans	*Laomedea calceolifera*	Fishing vessel possible
Coelenterates-Hydrozoans	*Maeotias marginata*	Fishing vessel possible
Coelenterates-Hydrozoans	*Moerisia sp.*	Fishing vessel possible
Coelenterates-Hydrozoans	*Pinauay crocea*	Fishing vessel possible
Coelenterates-Scyphozoan	*Aurelia sp. 1*	Fishing vessel possible
Coelenterates-Scyphozoan	*Phyllorhiza punctata*	Fishing vessel possible
Crustaceans - Leptostracans	*Epinebalia sp A.*	not fishing vessels
Crustaceans-Amphipods	*Abludomelita rylovae*	Fishing vessel possible
Crustaceans-Amphipods	*Ampelisca abdita*	Fishing vessel possible
Crustaceans-Amphipods	*Ampithoe longimana*	Fishing vessel possible
Crustaceans-Amphipods	*Ampithoe sp.*	Fishing vessel possible
Crustaceans-Amphipods	*Ampithoe valida*	Fishing vessel possible
Crustaceans-Amphipods	*Aoroides secunda*	Fishing vessel possible
Crustaceans-Amphipods	*Calliopiella sp.*	Fishing vessel possible
Crustaceans-Amphipods	*Caprella drepanochir*	Fishing vessel possible
Crustaceans-Amphipods	*Caprella mutica*	Fishing vessel possible
Crustaceans-Amphipods	*Caprella scaura*	Fishing vessel possible
Crustaceans-Amphipods	*Caprella simia*	Fishing vessel possible
Crustaceans-Amphipods	*Chelura terebrans*	Fishing vessel possible
Crustaceans-Amphipods	*Corophium alienense*	not fishing vessels

Crustaceans-Amphipods	*Corophium heteroceratum*	Fishing vessel possible
Crustaceans-Amphipods	*Eochelidium miraculum*	Fishing vessel possible
Crustaceans-Amphipods	*Eochelidium sp. A*	Fishing vessel possible
Crustaceans-Amphipods	*Gammarus daiberi*	not fishing vessels
Crustaceans-Amphipods	*Grandidierella japonica*	Fishing vessel possible
Crustaceans-Amphipods	*Incisocalliope derzhavini*	Fishing vessel possible
Crustaceans-Amphipods	*Jassa marmorata*	Fishing vessel possible
Crustaceans-Amphipods	*Melita nitida*	Fishing vessel possible
Crustaceans-Amphipods	*Microdeutopus gryllotalpa*	Fishing vessel possible
Crustaceans-Amphipods	*Monocorophium acherusicum*	Fishing vessel possible
Crustaceans-Amphipods	*Monocorophium insidiosum*	Fishing vessel possible
Crustaceans-Amphipods	*Monocorophiun uenoi*	Fishing vessel possible
Crustaceans-Amphipods	*Paracorophium lucasi*	Fishing vessel possible
Crustaceans-Amphipods	*Paradexamine sp.*	Fishing vessel possible
Crustaceans-Amphipods	*Stenothoe valida*	Fishing vessel possible
Crustaceans-Amphipods	*Transorchestia enigmatica*	not fishing vessels
Crustaceans-Barnacles	*Amphibalanus amphitrite*	Fishing vessel possible
Crustaceans-Barnacles	*Amphibalanus eburneus*	Fishing vessel possible
Crustaceans-Barnacles	*Amphibalanus improvisus*	Fishing vessel possible
Crustaceans-Barnacles	*Amphibalanus reticulatus*	Fishing vessel possible
Crustaceans-Copepods	*Acartiella sinensis*	not fishing vessels
Crustaceans-Copepods	*Eurytemora carolleeae*	Fishing vessel possible
Crustaceans-Copepods	*Harpacticella paradoxa*	Fishing vessel possible
Crustaceans-Copepods	*Limnoithona sinensis*	not fishing vessels
Crustaceans-Copepods	*Limnoithona tetraspina*	not fishing vessels
Crustaceans-Copepods	*Mytilicola orientalis*	Fishing vessel possible
Crustaceans-Copepods	*Oithona davisae*	not fishing vessels
Crustaceans-Copepods	*Pseudodiaptomus forbesi*	not fishing vessels
Crustaceans-Copepods	*Pseudodiaptomus marinus*	Fishing vessel possible
Crustaceans-Copepods	*Sinocalanus doerrii*	not fishing vessels
Crustaceans-Copepods	*Tortanus dextrilobatus*	not fishing vessels
Crustaceans-Crabs	*Carcinus maenas*	Fishing vessel possible
Crustaceans-Crabs	*Eriocheir sinensis*	Fishing vessel possible
Crustaceans-Crabs	*Rhithropanopeus harrisii*	Fishing vessel possible
Crustaceans-Crayfish	*Orconectes virilis*	Fishing vessel possible
Crustaceans-Crayfish	*Pacifastacus leniusculus*	not fishing vessels
Crustaceans-Crayfish	*Procambarus clarkii*	Fishing vessel possible
Crustaceans-Cumaceans	*Nippoleucon hinumensis*	Fishing vessel possible
Crustaceans-Isopods	*Asellus hilgendorfi*	not fishing vessels
Crustaceans-Isopods	*Caecijaera horvathi*	Fishing vessel possible
Crustaceans-Isopods	*Dynoides dentisinus*	Fishing vessel possible
Crustaceans-Isopods	*Eurylana arcuata*	Fishing vessel possible
Crustaceans-Isopods	*Gnorimosphaeroma rayi*	not fishing vessels

Crustaceans-Isopods	*Iais californica*	Fishing vessel possible
Crustaceans-Isopods	*Ianiropsis serricaudis*	Fishing vessel possible
Crustaceans-Isopods	*Limnoria quadripunctata*	Fishing vessel possible
Crustaceans-Isopods	*Limnoria tripunctata*	Fishing vessel possible
Crustaceans-Isopods	*Orthione griffenis*	not fishing vessels
Crustaceans-Isopods	*Paranthura japonica*	Fishing vessel possible
Crustaceans-Isopods	*Pseudosphaeroma sp.*	Fishing vessel possible
Crustaceans-Isopods	*Sphaeroma quoianum*	Fishing vessel possible
Crustaceans-Isopods	*Sphaeroma sp.*	Fishing vessel possible
Crustaceans-Isopods	*Sphaeroma walkeri*	Fishing vessel possible
Crustaceans-Isopods	*Synidotea laevidorsalis*	Fishing vessel possible
Crustaceans-Isopods	*Uromunna sp .A*	Fishing vessel possible
Crustaceans-Mysids	*Deltamysis holmquistae*	not fishing vessels
Crustaceans-Mysids	*Hyperacanthomysis longirostris*	not fishing vessels
Crustaceans-Mysids	*Neomysis japonica*	not fishing vessels
Crustaceans-Mysids	*Orientomysis aspera*	not fishing vessels
Crustaceans-Mysids	*Orientomysis hwanhaiensis*	not fishing vessels
Crustaceans-Ostracods	*Aspidoconcha limnoriae*	Fishing vessel possible
Crustaceans-Ostracods	*Eusarsiella zostericola*	not fishing vessels
Crustaceans-Ostracods	*Redekea californica*	Fishing vessel possible
Crustaceans-Ostracods	*Spinileberis quadriaculeata*	not fishing vessels
Crustaceans-Shrimp	*Exopalaemon carinicauda*	Fishing vessel possible
Crustaceans-Shrimp	*Exopalaemon modestus*	Fishing vessel possible
Crustaceans-Shrimp	*Palaemon macrodactylus*	not fishing vessels
Crustaceans-Tanaids	*Sinelobus cf. stanfordi*	Fishing vessel possible
Ctenophores	*Vallicula multiformis*	Fishing vessel possible
Ectoprocts	*Aeverrillia armata*	Fishing vessel possible
Ectoprocts	*Anguinella palmata*	Fishing vessel possible
Ectoprocts	*Aspidelectra melolontha*	Fishing vessel possible
Ectoprocts	*Bugula flabellata*	Fishing vessel possible
Ectoprocts	*Bugula neritina*	Fishing vessel possible
Ectoprocts	*Bugula stolonifera*	Fishing vessel possible
Ectoprocts	*Conopeum tenuissimum*	Fishing vessel possible
Ectoprocts	*Cryptosula pallasiana*	Fishing vessel possible
Ectoprocts	*Nolella stipata*	Fishing vessel possible
Ectoprocts	*Schizoporella errata*	Fishing vessel possible
Ectoprocts	*Schizoporella japonica*	Fishing vessel possible
Ectoprocts	*Schizoporella unicornis*	Fishing vessel possible
Ectoprocts	*Victorella pavida*	Fishing vessel possible
Ectoprocts	*Watersipora arcuata*	Fishing vessel possible
Ectoprocts	*Watersipora sp. A*	Fishing vessel possible
Ectoprocts	*Watersipora subtorquata*	Fishing vessel possible
Ectoprocts	*Zoobotryon verticillatum*	Fishing vessel possible

Entoprocts	*Barentsia benedeni*	Fishing vessel possible
Mollusks-Bivalves	*Corbicula fluminea*	Fishing vessel possible
Mollusks-Bivalves	*Corbula amurensis*	not fishing vessels
Mollusks-Bivalves	*Crassostrea gigas*	Fishing vessel possible
Mollusks-Bivalves	*Gemma gemma*	not fishing vessels
Mollusks-Bivalves	*Geukensia demissa*	Fishing vessel possible
Mollusks-Bivalves	*Laternula marilina*	not fishing vessels
Mollusks-Bivalves	*Lyrodus pedicellatus*	Fishing vessel possible
Mollusks-Bivalves	*Macoma petalum*	not fishing vessels
Mollusks-Bivalves	*Mercenaria mercenaria*	not fishing vessels
Mollusks-Bivalves	*Musculista senhousia*	Fishing vessel possible
Mollusks-Bivalves	*Mya arenaria*	not fishing vessels
Mollusks-Bivalves	*Mytilus galloprovincialis*	Fishing vessel possible
Mollusks-Bivalves	*Nuttallia obscurata*	Fishing vessel possible
Mollusks-Bivalves	*Petricolaria pholadiformis*	not fishing vessels
Mollusks-Bivalves	*Teredo bartschi*	Fishing vessel possible
Mollusks-Bivalves	*Teredo furcifera*	Fishing vessel possible
Mollusks-Bivalves	*Teredo navalis*	Fishing vessel possible
Mollusks-Bivalves	*Theora lubrica*	not fishing vessels
Mollusks-Bivalves	*Venerupis philippinarum*	Fishing vessel possible
Mollusks-Gastropods	*Anteaeolidiella indica*	Fishing vessel possible
Mollusks-Gastropods	*Babakina festiva*	Fishing vessel possible
Mollusks-Gastropods	*Batillaria attramentaria*	Fishing vessel possible
Mollusks-Gastropods	*Boonea bisuturalis*	not fishing vessels
Mollusks-Gastropods	*Busycotypus canaliculatus*	not fishing vessels
Mollusks-Gastropods	*Catriona rickettsi*	Fishing vessel possible
Mollusks-Gastropods	*Crepidula convexa*	Fishing vessel possible
Mollusks-Gastropods	*Crepidula plana*	Fishing vessel possible
Mollusks-Gastropods	*Cuthona perca*	Fishing vessel possible
Mollusks-Gastropods	*Eubranchus misakiensis*	Fishing vessel possible
Mollusks-Gastropods	*Haminoea japonica*	not fishing vessels
Mollusks-Gastropods	*Ilyanassa obsoleta*	not fishing vessels
Mollusks-Gastropods	*Littoridinops monroensis*	not fishing vessels
Mollusks-Gastropods	*Littorina littorea*	Fishing vessel possible
Mollusks-Gastropods	*Littorina saxatilis*	Fishing vessel possible
Mollusks-Gastropods	*Melanoides tuberculatus*	not fishing vessels
Mollusks-Gastropods	*Myosotella myosotis*	not fishing vessels
Mollusks-Gastropods	*Ocinebrellus inornatus*	not fishing vessels
Mollusks-Gastropods	*Okenia plana*	Fishing vessel possible
Mollusks-Gastropods	*Philine aperta*	not fishing vessels
Mollusks-Gastropods	*Philine auriformis*	not fishing vessels
Mollusks-Gastropods	*Philine japonica*	not fishing vessels
Mollusks-Gastropods	*Philine orientalis*	not fishing vessels

Mollusks-Gastropods	*Potamopyrgus antipodarum*	Fishing vessel possible
Mollusks-Gastropods	*Sakuraeolis enosimensis*	Fishing vessel possible
Mollusks-Gastropods	*Tenellia adspersa*	Fishing vessel possible
Mollusks-Gastropods	*Urosalpinx cinerea*	not fishing vessels
Nematodes	*Capillaria catenata*	Fishing vessel possible
Nematodes	*Hysterothylacium brachyurum*	Fishing vessel possible
Platyhelminthes	*Alloglossidium corti*	Fishing vessel possible
Platyhelminthes	*Atractolytocestus huronensis*	Fishing vessel possible
Platyhelminthes	*Austrobilharzia variglandis*	not fishing vessels
Platyhelminthes	*Bothriocephalus cuspidatus*	Fishing vessel possible
Platyhelminthes	*Cercaria batillariae*	not fishing vessels
Platyhelminthes	*Corallobothrium fimbriatum*	Fishing vessel possible
Platyhelminthes	*Dactylogyrus extensus*	Fishing vessel possible
Platyhelminthes	*Gigantobilharzia sp.*	not fishing vessels
Platyhelminthes	*Himasthla quissetensis*	not fishing vessels
Platyhelminthes	*Khawia iowensis*	Fishing vessel possible
Platyhelminthes	*Lepocreadium setiferoides*	not fishing vessels
Platyhelminthes	*Leptoplana limnoriae*	Fishing vessel possible
Platyhelminthes	*Ligictaluridus pricei*	Fishing vessel possible
Platyhelminthes	*Maritrema arenaria*	not fishing vessels
Platyhelminthes	*Megathylacoides giganteum*	Fishing vessel possible
Platyhelminthes	*Microphallus pygmaeus Group*	not fishing vessels
Platyhelminthes	*Microphallus similis*	not fishing vessels
Platyhelminthes	*Pisciamphistoma stunkardi*	Fishing vessel possible
Platyhelminthes	*Stephanostomum tenue*	not fishing vessels
Platyhelminthes	*Zoogonus lasius*	not fishing vessels
Protozoans	*Ancistrocoma pelseneeri*	Fishing vessel possible
Protozoans	*Ancistrum cyclidioides*	Fishing vessel possible
Protozoans	*Bonamia ostreae*	not fishing vessels
Protozoans	*Boveria teredinidi*	Fishing vessel possible
Protozoans	*Conidophrys pilisuctor*	Fishing vessel possible
Protozoans	*Cothurnia limnoriae*	Fishing vessel possible
Protozoans	*Haplosporidium nelsoni*	not fishing vessels
Protozoans	*Lagenophrys cochinensis*	Fishing vessel possible
Protozoans	*Lankesteria ascidiae*	Fishing vessel possible
Protozoans	*Lobochona prorates*	Fishing vessel possible
Protozoans	*Mirofolliculina limnoriae*	Fishing vessel possible
Protozoans	*Sphenophrya dosiniae*	Fishing vessel possible
Protozoans	*Trochammina hadai*	not fishing vessels
Sponges	*Chalinula loosanoffi*	Fishing vessel possible
Sponges	*Clathria prolifera*	Fishing vessel possible
Sponges	*Cliona sp.*	not fishing vessels
Sponges	*Halichondria bowerbanki*	Fishing vessel possible

Sponges	*Prosuberites sp.*	Fishing vessel possible
Tunicates	*Ascidia sp. A*	Fishing vessel possible
Tunicates	*Ascidia zara*	Fishing vessel possible
Tunicates	*Bostrichobranchus pilularis*	Fishing vessel possible
Tunicates	*Botrylloides perspicuum*	Fishing vessel possible
Tunicates	*Botrylloides violaceus*	Fishing vessel possible
Tunicates	*Botryllus schlosseri*	Fishing vessel possible
Tunicates	*Botryllus sp. A.*	Fishing vessel possible
Tunicates	*Ciona intestinalis*	Fishing vessel possible
Tunicates	*Ciona savignyi*	Fishing vessel possible
Tunicates	*Didemnum sp.*	Fishing vessel possible
Tunicates	*Didemnum vexillum*	Fishing vessel possible
Tunicates	*Diplosoma listerianum*	Fishing vessel possible
Tunicates	*Microcosmus squamiger*	Fishing vessel possible
Tunicates	*Molgula ficus*	Fishing vessel possible
Tunicates	*Molgula manhattensis*	Fishing vessel possible
Tunicates	*Perophora japonica*	Fishing vessel possible
Tunicates	*Polyandrocarpa zorritensis*	Fishing vessel possible
Tunicates	*Styela canopus*	Fishing vessel possible
Tunicates	*Styela clava*	Fishing vessel possible
Tunicates	*Styela plicata*	Fishing vessel possible
Tunicates	*Symplegma reptans*	Fishing vessel possible
Vertebrates	*Rana catesbeiana*	not fishing vessels
Vertebrates	*Xenopus laevis*	not fishing vessels
Vertebrates	*Ondatra zibethicus*	not fishing vessels
Vertebrates	*Trachemys scripta*	not fishing vessels

Appendix 2: Port connectivity (data underlying Figure 11 in report)

ports	San Diego	Oceanside	Dana Point	Newport Beach	LA/Long Beach	Port Hueneme	Oxnard	Ventura	Santa Barbara	SL Obispo	Morro Bay	Monterey	Moss Landing	Santa Cruz	Half Moon Bay	San Francisco Bay	Marin	Bolinas	Point Reyes	Tomales Bay	Bodega Bay	Point Arena	Albion	Fort Bragg	Humboldt	Trinidad	Crescent City
San Diego	46	65	26	12	11	0	7	8	6	2	7	2	4	2	2	1	2	0	0	0	1	0	0	1	1	0	1
Oceanside	26	10	32	12	8	0	2	2	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	0	1	0	0
Dana Point	12	37	26	25	11	0	4	3	5	3	2	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0
Newport Beach	3	7	14	22	8	6	4	2	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LA/Long Beach	25	45	51	71	44	75	26	48	17	5	9	13	11	3	3	3	4	0	7	0	3	2	0	1	4	6	2
Port Hueneme	0	0	0	8	12	7	13	25	5	5	5	10	5	1	1	1	2	0	3	0	0	2	0	0	0	0	0
Oxnard	6	4	7	14	10	32	17	42	35	12	15	5	4	1	3	2	2	0	3	0	2	2	0	2	1	3	0
Ventura	7	4	6	6	19	63	42	10	27	12	11	12	9	2	3	1	0	0	3	0	1	2	0	1	1	3	0
Santa Barbara	8	1	13	6	10	19	51	39	38	22	21	6	5	3	6	2	2	0	0	0	5	2	10	3	1	0	1
SL Obispo	1	0	4	0	2	10	9	8	11	31	29	8	8	4	7	3	2	0	7	0	7	0	0	4	2	0	1
Morro Bay	7	1	4	0	5	14	19	13	17	49	29	13	19	16	14	9	9	0	14	0	14	6	0	11	6	3	6
Monterey	1	0	0	2	3	15	3	7	2	7	6	36	17	7	4	2	0	0	0	0	2	0	0	2	1	0	1
Moss Landing	5	0	1	0	8	24	7	16	6	18	28	50	23	37	26	17	7	11	17	13	25	8	0	22	9	0	12
Santa Cruz	2	2	4	0	2	3	2	3	3	6	15	13	24	16	28	16	11	11	17	0	22	25	0	21	12	0	10
Half Moon Bay	3	1	3	0	2	4	7	6	8	18	22	12	29	48	15	31	25	11	48	0	43	22	10	39	21	0	7
San Francisco Bay	2	0	1	2	3	6	5	4	4	13	25	12	31	46	52	33	49	78	52	38	48	27	5	49	35	3	31
Marin	0	0	0	0	0	1	1	0	0	1	2	0	1	3	4	5	30	11	7	13	5	2	0	2	1	0	2
Bolinas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	11	7	0	1	0	0	0	0	0	0
Point Reyes	0	0	0	0	0	1	1	1	0	2	2	0	2	2	4	3	4	22	3	0	5	2	0	3	1	0	1
Tomales Bay	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	38	1	0	0	0	0	0	0
Bodega Bay	2	1	1	0	3	3	5	3	8	23	28	9	35	47	53	35	35	56	69	50	17	41	20	54	26	3	25
Point Arena	0	1	0	0	0	1	1	1	0	0	1	0	1	6	3	2	2	0	3	0	5	20	20	8	5	0	2
Albion	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	8	25	4	1	0	0
Fort Bragg	1	1	0	0	1	1	3	1	4	11	18	7	26	39	42	31	12	0	38	13	46	61	70	15	42	6	28
Humboldt	1	2	0	0	3	0	1	1	1	4	8	4	8	17	16	16	5	0	7	13	17	25	10	31	26	83	27
Trinidad	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	11	14	2
Crescent City	1	1	0	0	1	1	1	0	1	2	6	2	9	11	5	12	7	0	7	13	13	10	0	17	22	11	43
TOTAL BOATS	20	16	15	11	24	19	24	22	23	20	23	18	23	23	24	26	20	8	18	8	26	19	8	24	23	10	22

Appendix 3: Boat fouling papers in the literature (fishing and Recreational boats) with species data

References for literature search biofouling taxa reported from small craft

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Appendix 4: Specimens identified to species level from boat sampling

List of species identified from recreational vessels. Numbers indicate number of vessels that the species was sampled from. Letters indicate status of the species in California: N- Native, I- Introduced, G- could not be identified to species, but there are native members of this group. * indicates species not yet recorded from CA.

Algae

1	I	*Lomentaria hakodatensis*
1	N	*Polyneura latissima*
1	I	*Undaria pinnatifida*

Cirripeds

5	I	*Amphibalanus amphitrite*
8	I	*Amphibalanus eburneus*
5	I	*Amphibalanus improvisus*
1	G	*Amphibalanus* (blank)
11	N	*Balanus crenatus*
3	N	*Balanus glandula*
1	G	*Balanus* sp.
9	N	*Balanus trigonus*
1	N	*Conchoderma auritum*
1	G	*Conchoderma* sp.
1	N	*Lepas anatifera*
2	N	*Lepas pacifica*
2	G	*Lepas* sp.
3	?	*Megabalanus cf tanagrae*
3	?	*Megabalanus coccopoma*
1	G	*Megabalanus* sp.
1	G	*Megabalanus* sp.A
1	G	*Megabalanus* sp.B
2	N	*Megabalanus tintinnabulum*

Ascidians

6	N	*Ascidia ceratodes*
1	N	*Ascidia paratropa*
1	G	*Ascidia* sp.
2	I	*Ascidia zara*
6	N	*Botrylloides diegensis*
2	I	*Botrylloides perspicuum*
3	G	*Botrylloides* sp.
14	I	*Botrylloides violaceus*
19	I	*Botryllus schlosseri*
9	I	*Ciona intestinalis*
1	I	*Ciona savignyi*
1	I	*Molgula* cf. *manhattensis*
1	I	*Molgula ficus*
6	I	*Molgula* sp.

1 G *Riterella* sp.
4 I *Styela clava*
10 I *Styela plicata*
8 G *Styela* sp.

Hydrozoa
3 N *Aglaophenia diegensis*
1 N *Amphisbetia furcata*
2 I *Bougainvillia muscus*
1 G *Bougainvilliidae (blank)*
3 N *Campanulinidae (blank)*
2 G *Clytia* sp.
1 G *Coryne* sp.
2 N *Ectopleura* sp.
1 N *Gonothyraea loveni*
5 N *Obelia dichotoma*
8 N *Obelia longissima*
1 N *Plumularia setacea*

Bryozoans
2 G *Diaperoforma* sp.
13 G *Bowerbankia* sp.
32 I *Bugula neritina*
23 I *Bugula stolonifera*
17 N *Celleporaria brunnea*
1 N *Celleporella hyalina*
1 G *Celleporella* sp.
1 G *Celleporina* sp.
1 I *Conopeum* cf. *tenuissimum*
2 G *Conopeum* sp.
1 N *Crisia* cf. *occidentalis*
2 G *Crisia* sp.
1 G *Crisidae* sp.
3 G *Crisulipora* sp.
14 I *Cryptosula pallasiana*
1 G *Electra* cf. *crustulenta*
2 G *Electra* sp.
1 I *Hippoporina indica**
3 N *Membranipora villosa*
1 N *Microporella setiformis*
4 I *Schizoporella japonica*
2 G *Schizoporella* sp.
2 N *Scrupocellaria bertholetti*
8 N *Thalamoporella californica*
2 N *Tricellaria occidentalis*
1 N *Tubulipora* cf *pacifica*
3 I *Watersipora arcuata*
21 I *Watersipora subtorquata*
5 I *Zooobotryon* sp.

Polychaetes
5 N *Paleanotus bellis*
1 G Cirratulidae

1	C	*Dorvillea moniloceras*
1	G	Nereididae
2	I	*Alitta succinea*
1	N	*Nereis latescens*
1	N	*Nereis mediator*
1	N	*Nereis vexillosa*
6	N	*Platynereis bicanaliculata*
1	N	*Eualia quadrioculata*
3	N	*Halosydna brevisetosa*
1	N	*Halosydna johnsoni*
1	C	*Harmathoe imbricata* complex
1	C	*Thormora johnstoni*
1	C	*Bispira* sp.7 Harris
1	I	*Branchiomma* sp. 1
3	I	*Branchiomma* sp. 2 Harris
1	N	*Eudistylia polymorpha*
1	G	*Eudistylia* sp.
1	C	*Megalomma coloratum*
2	N	*Paradialychone ecaudata*
4	I	*Parasabella fullo*
2	N	*Pseudopotamilla ocellata*
1	G	Serpulidae
2	I	*Ficopomatus enigmaticus*
1	I	*Hydroides crucigera*
1	I	*Hydroides diramphus*
9	I	*Hydroides elegans*
6	N	*Hydroides gracilis*
2		*Hydroides* sp.
9	C	*Salmacina tribranchiata*
1	I	*Boccardiella hamata*
2	N	*Polydora narica*
3	G	Spirorbidae
10	N	*Pileolaria marginata*
1	N	*Pileolaria tiatara*
3	G	Autolytinae
1	C	*Syllis gracilis complex*
2	I	*Syllis* sp. 37 Harris
2	G	*Trypanosyllis* sp.
1	N	*Eupolymnia heterbranchia*