

Post-exchange zooplankton in ballast water of ships entering the San Francisco Estuary

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The San Francisco Estuary in California (CA), USA, has been heavily altered by invasions of nonnative zooplankton and benthic organisms, presumably by the discharge of ships' ballast water. Since 2000, ships entering CA have been required to exchange ballast water with oceanic water during the voyage to decrease the number of organisms discharged into the Estuary that had previously been taken aboard at foreign ports. We examined abundance of zooplankton in ballast water of 18 container ships and 48 bulk carriers. Asia dominated the sources of ballast water, which contained multiple nonnative zooplankton including species that have invaded and since become common residents in the Estuary. The abundance of zooplankton was significantly lower in ballast water that had been emptied and refilled with oceanic water than those that had continuously been flushed with oceanic water (about three times the volume of ballast water), suggesting that empty-refill is more effective in removing exotic zooplankton.

INTRODUCTION

The San Francisco Estuary is among the most invaded estuarine ecosystems, harboring more than 200 nonnative species (Cohen and Carlton, 1998), which include at least nine species of zooplankton (Ferrari and Orsi, 1984; Orsi and Ohtsuka, 1999; Bollens *et al.*, 2002). Introduced zooplankton have not only become numerically dominant, but their ranges in the Estuary have also expanded (Bollens *et al.*, 2002; Kimmerer, 2002).

The invasions of zooplankton have apparently been mediated by the discharge of ships' ballast water (Cohen and Carlton, 1998). The San Francisco Estuary is one of the largest shipping ports on the west coast of North America. Between January 2000 and June 2002, for instance, the Estuary received nearly 3 million metric tons of treated (i.e. exchanged in open oceans) and untreated ballast water from foreign countries (Lion *et al.*, in preparation).

The ecosystem of the San Francisco Estuary is food-limited (Cloern, 1996; Jassby *et al.*, 2003), and the abundance of native zooplankton has been on a long-term decline (Kimmerer and Orsi, 1996; Kimmerer, 2002), partially associated with the proliferation of introduced

benthic clams feeding primarily on phytoplankton (Kimmerer *et al.*, 1994). The alteration in composition and distribution of zooplankton in the Estuary has generated concern over a shift in the function of the plankton community (e.g. decreased energy transfer; Bollens *et al.*, 2002; Hooff and Bollens, 2004).

As an initiative to stem future biological invasions through ballast water, the State of California, effective January 2000, mandated the exchange of ballast water for ships traveling outside the US Exclusive Economic Zone and entering California ports (Falkner, 2000).

To better understand the effectiveness of ballast water exchange, we need the information of the dynamics of the delivery of organisms including the source of the ballast water, efficiency of mid-ocean exchange, and the post-exchange species composition and abundance of organisms. In particular, final delivery of post-exchange organisms will represent the invasion risk of potential invaders into the Estuary. Yet, there is little information available for this invasion pressure into the Estuary. We have therefore undertaken extensive sampling of zooplankton in post-exchange ballast waters

to determine what species are being transported, and in approximately what abundance, to the San Francisco Estuary under current practices of mid-ocean exchange.

METHOD

Ship selection

Information on shipping and ballast water discharge in the San Francisco Estuary was provided from the National Ballast Information Clearinghouse (NBIC). Between January 2000 and June 2002, bulk carriers accounted for the greatest volume discharge of ballast water in the Estuary, whereas container vessels accounted for the most frequent discharge (Lion *et al.*, in preparation). Far East Asian countries, such as Japan, China, and Korea, were the major sources of ballast water prior to oceanic exchange. Most of the surveyed ballast water of foreign origin discharged into the Estuary had been exchanged in the open ocean, with a small portion of unexchanged discharge, probably because of the lack of awareness of the requirement for exchange in this early stage of implementation.

Based on the ballast water discharge information, this study was focused primarily on bulk carriers, which discharged the greatest volume of water. Container vessels were also sampled, although to a lesser extent. The San Francisco Marine Exchange provided daily reports of ship traffic in the Estuary (e.g. arrival schedule, type of vessel, ships' agent, and arrival port and time). The information on ballast water was provided by ships'

agents, and sampling was carried out with the assistance of the California State Lands Commission (CSLC), whose agents are legally authorized to board and inspect ballast water of ships entering the waters of California.

Ship sampling

Bulk carriers qualified for sampling if they arrived with foreign ballast water from beyond the exclusive economic zone, since these were subject to inspection and therefore provided opportunities for sampling. Given a limited number of qualified bulk carriers, we attempted to sample every qualified bulk carrier arriving with foreign ballast water. Between mid May 2002 and mid-June 2003, we collected 49 ballast water samples from 48 bulk carriers (one vessel had ballast water from two source regions) from various ports in the Estuary (Fig. 1). Samples were not usually taken from multiple tanks, partly because of limitations on time and labor of ships' crews, but also because of ships' operating conditions such as tilt and loading-associated activities (e.g. moving along the dock).

Vessels' crews were first interviewed for information on ballast water conditions including source region, last port of call, voyage and exchange method. Temperature and salinity of ballast water during the mid-ocean exchange was obtained from ballast water reporting forms, which were submitted by crews to the port authority. Ballast water samples for zooplankton were obtained mostly from top-side tanks which have easy access through manholes on the deck, but also from other tanks (Table I). Repeated sampling from a tank was carried out for most of the top-side tanks,

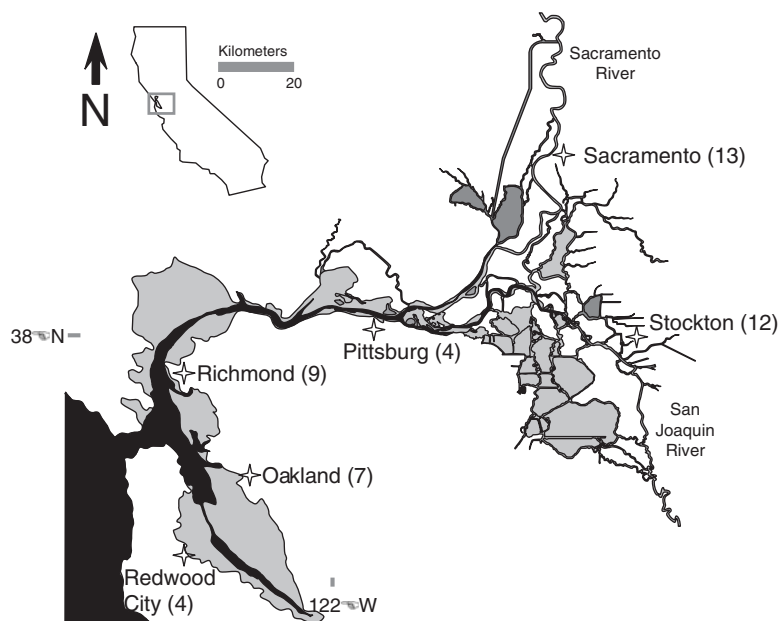


Fig. 1. Sampling ports in the San Francisco Estuary and the number of ballast water samples collected in each port (in parentheses).

Table I: The number of ballast water samples for bulk carriers and container vessels by the type of tank from which the samples were collected

Tank type	Bulk carriers	Containers
Top-side	30	2
Cargo hold	11	
Fore-peak	4	2
Top-bottom connected	3	
After-peak	1	
Bottom-side		14

which are relatively shallow. For cargo holds, vertical tows of 10–20 m depth were possible. Salinity and water temperature were measured on board with a refractometer calibrated with a SCT meter (model YSI 33) and a thermometer. Zooplankton samples were collected with an 80- μm net 30 cm in diameter, deployed to sample at least 0.5 m³ of water. Samples were preserved with formaldehyde (final concentration of 5–10%). In the laboratory we subsampled to get at least 50 individuals of each identifiable species. Subsamples were examined with a dissecting microscope, and zooplankton were identified to species whenever possible. We also collected 18 ballast water samples from container vessels at the Port of Oakland in August 2001 (3 samples) and July 2002 (15 samples). Ballast water was collected using a pump operated by air pressure for 10 min at a pumping rate of 60 L min⁻¹ (sampling volume of approximately 0.6 m³) and was discharged into an 80- μm net. Samples were then treated as for the bulk carriers. All of the statistical analysis was performed with Splus 6.1 (Insightful Inc., Seattle, USA). Zooplankton abundance was occasionally transformed log₁₀(abundance + 1). Nonparametric tests were used to compare the abundance as the errors of the abundance data were not normally distributed.

RESULTS

Ballast water

Japan dominated the source regions of initial ballast water prior to exchange, comprising nearly half of the total surveyed bulk carriers, followed by other Asian countries, with few vessels from Europe (Table II). Among container vessels, China dominated the source regions, followed by open oceans (i.e. some vessels had taken oceanic water before exchange or had taken additional ballast in the ocean). The samples overall reflected the pattern of ballast

Table II: The number of ballast water samples for bulk carriers and container vessels by source region where the water was initially taken before exchange in the open ocean occurred

Country	Bulk carriers	Containers
Japan	24	1
Korea	8	1
China	6	8
Thailand	3	
Taiwan	2	
New Zealand/Australia		3
The Netherlands		3
Mid-ocean	5	
Other countries	3	

water discharge by source region for both types of vessel into the San Francisco Estuary (Lion *et al.*, in preparation).

The voyage duration of the bulk carriers since initial loading of ballast water varied with port of origin. The voyages from Asia took approximately 20 days on average, compared to 40 days from Australia/New Zealand and 60 days from other countries. The exchange of ballast water in the ocean was done half-way the journeys on average regardless of the port of origin. Ballast waters of the container ships showed a similar pattern of voyage duration, although two ships had ballast water that was nearly 1 year old.

All of the surveyed bulk carriers and container ships reported that they had exchanged the ballast water in the open ocean before arriving in the ports of the San Francisco area. This was consistent with the high salinity (25–37) of the ballast water samples, although not all of the Asian ports are in estuaries. Nearly two-thirds of the bulk carriers and all of the surveyed container ships used the empty–refill method for ballast water exchange. Temperature of ballast water showed a seasonal pattern, with stronger variation in the mid-ocean upon exchange (2–28°C) than in samples on arrival (11–25°C).

Zooplankton in ballast water

Copepods were the most abundant zooplankton in both bulk carriers and container ships (Fig. 2). Species composition was generally similar between bulk carriers and container ships coming from the same source region (e.g. Asia, Table III). Only a few species occurred repeatedly (>3 times), with *Oithona similis* being the most frequently occurring species in both types of vessel.

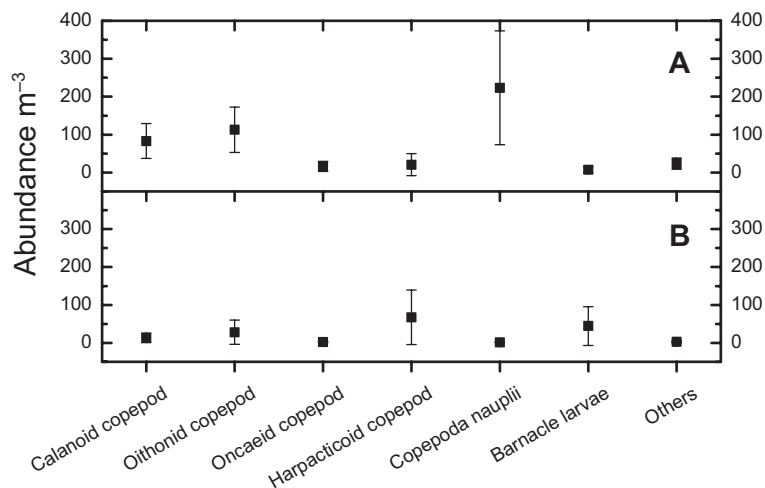


Fig. 2. Zooplankton abundance added by 1 (mean ± 95% confidence limit) by taxonomic group in the ballast waters of the bulk carriers (**A**, *n* = 49) and container vessels (**B**, *n* = 18).

Table III: Zooplankton taxa found in the ballast water, the number of vessels in which the zooplankton was found (i.e. frequency of their occurrence; B-bulk carriers, C-container vessels), status in the San Francisco Estuary and their type of habitat

	Frequency of occurrence		Status in the Bay	Taxonomic group	Type of habitat ^a
	B	C			
Holoplankton					
<i>Ceriodaphnia quadrangula</i>	2		Nonresident	Cladocera	Freshwater
<i>Daphnia parvula</i>	3		Unknown	Cladocera	Freshwater
<i>Sinobosmina freyi</i>	2		Nonresident	Cladocera	Freshwater
<i>Acartia hudsonica</i>	6		Resident	Calanoid copepoda	Estuarine
<i>Pseudodiaptomus forbesi</i>	2		Introduced	Calanoid copepoda	Estuarine
<i>Tortanus discaudatus</i>	1	2	Resident	Calanoid copepoda	Estuarine
<i>Tortanus forcipatus</i>	1		Nonresident	Calanoid copepoda	Estuarine
<i>Oithona davisae</i>	7	2	Introduced	Cyclopoid copepoda	Estuarine
<i>Penilia avirostris</i>	1		Nonresident	Cladocera	Estuarine, coastal
Podocopida		1	Unknown	Ostracoda	Estuarine, coastal
<i>Acartia longiremis</i>		1	Nonresident	Calanoid copepoda	Estuarine, coastal
<i>Acartia pacifica</i>	1		Nonresident	Calanoid copepoda	Estuarine, coastal
<i>Paracalanus parvus</i>	4	1	Nonresident	Calanoid copepoda	Estuarine, coastal
<i>Paracalanus quasimodo</i>	5	3	Resident	Calanoid copepoda	Estuarine, coastal
<i>Pseudodiaptomus marinus</i>	2	3	Introduced	Calanoid copepoda	Estuarine, coastal
<i>Oithona oswaldocruzi</i>		1	Nonresident	Cyclopoid copepoda	Estuarine, coastal
<i>Tortanus derjugini</i>		1	Nonresident	Calanoid copepoda	Estuarine, coastal
<i>Hemicyclops japonicus</i>	5	2	Nonresident	Cyclopoid copepoda	Estuarine, coastal
<i>Mysidopsis japonica</i>		1	Nonresident	Mysidacea	Estuarine, coastal
<i>Acartia tonsa</i>	1	4	Resident	Calanoid copepoda	Estuarine, coastal, oceanic
<i>Calanopia americana</i>		1	Nonresident	Calanoid copepoda	Coastal
<i>Epilabidocera longipedata</i>	1		Resident	Calanoid copepoda	Coastal
<i>Labidocera euchaeta</i>	1		Nonresident	Calanoid copepoda	Coastal
<i>Paraeuchaeta plana</i>	1		Nonresident	Calanoid copepoda	Coastal
<i>Amphiascoides subdebilis</i>	1		Nonresident	Harpacticoid copepoda	Coastal

(continued)

Table III: Continued

	Frequency of occurrence		Status in the Bay	Taxonomic group	Type of habitat ^a
	B	C			
<i>Schizopera grimalschii</i>	1	1	Nonresident	Harpacticoid copepoda	Coastal
<i>Euterpina acutifrons</i>	2	2	Resident	Harpacticoid copepoda	Coastal
<i>Tisbe austrina</i>	1	1	Nonresident	Harpacticoid copepoda	Coastal
<i>Tisbe ensifer</i>		1	Nonresident	Harpacticoid copepoda	Coastal
<i>Tisbe longicornis</i>		2	Nonresident	Harpacticoid copepoda	Coastal
<i>Tisbe minor</i>		3	Nonresident	Harpacticoid copepoda	Coastal
<i>Corycaeus amazonicus</i>		1	Nonresident	Poecilostomatoid copepoda	Coastal
<i>Acartia danae</i>	1		Nonresident	Calanoid copepoda	Coastal, oceanic
<i>Acartia tumida</i>	1		Nonresident	Calanoid copepoda	Coastal, oceanic
<i>Pseudocalanus newmani</i>	12	1	Nonresident	Calanoid copepoda	Coastal, oceanic
<i>Oithona oculata</i>		2	Nonresident	Cyclopoid copepoda	Coastal, oceanic
<i>Oithona similis</i>	29	5	Resident	Cyclopoid copepoda	Coastal, oceanic
<i>Microsetella norvegica</i>	1	1	Nonresident	Harpacticoid copepoda	Coastal, oceanic
<i>Nitocra bdelluræ</i>	1		Nonresident	Harpacticoid copepoda	Coastal, oceanic
<i>Nitocra malaica</i>	1		Nonresident	Harpacticoid copepoda	Coastal, oceanic
<i>Nitocra spinipes</i>	1		Nonresident	Harpacticoid copepoda	Coastal, oceanic
<i>Corycaeus affinis</i>	9	3	Resident	Poecilostomatoid copepoda	Coastal, oceanic
<i>Sagitta neglecta</i>	6	2	Nonresident	Chaetognatha	Coastal, oceanic
<i>Calanus pacificus</i>	11	5	Resident	Calanoid copepoda	Coastal, oceanic
<i>Clausocalanus furcatus</i>	1		Nonresident	Calanoid copepoda	Coastal, oceanic
<i>Ctenocalanus vanus</i>	3	1	Nonresident	Calanoid copepoda	Coastal, oceanic
<i>Oithona atlantica</i>	1		Nonresident	Cyclopoid copepoda	Coastal, oceanic
<i>Oncaea media</i>	3		Nonresident	Poecilostomatoid copepoda	Coastal, oceanic
<i>Metrida pacifica</i>	9		Nonresident	Calanoid copepoda	Oceanic
<i>Neocalanus plumchrus</i>	3		Nonresident	Calanoid copepoda	Oceanic
<i>Clytemnestra scutellata</i>	1		Nonresident	Harpacticoid copepoda	Oceanic
<i>Macrosetella gracilis</i>	1	1	Nonresident	Harpacticoid copepoda	Oceanic
<i>Microarthridion berberum</i>	1		Nonresident	Harpacticoid copepoda	Oceanic
<i>Farranula rostrata</i>	1		Nonresident	Poecilostomatoid copepoda	Oceanic
<i>Oncaea scottodicarloi</i>	3	2	Nonresident	Poecilostomatoid copepoda	Oceanic
<i>Oncaea venusta</i> f. <i>venella</i>	1		Nonresident	Poecilostomatoid copepoda	Oceanic
<i>Saphirina scarlata</i>	1		Nonresident	Poecilostomatoid copepoda	Oceanic
<i>Euphausia calyptosis</i> larva		1	Nonresident	Euphausiacea	Oceanic
Meroplankton					
Bivalve larvae ^b	9	1	Unknown		Estuarine, coastal
Barnacle larvae ^b	4	5	Unknown		Estuarine, coastal
Spionid ^b	2	2	Unknown	Polychaeta	Estuarine, coastal
<i>Nereis</i> sp.	1		Unknown	Polychaeta	Estuarine, coastal
Sphaerodoridae	1		Unknown	Polychaeta	Estuarine, coastal
Decapoda larvae	1		Unknown		Estuarine, coastal
Phoronida–Actinotroch larvae ^b	3		Unknown		Estuarine, coastal

For status: introduced, known as previously introduced and became resident; unknown, cryptogenic; resident, known as native; nonresident, known as not native and not present in the Estuary.

^aThe allocation of each species to habitat is based on Chihara and Murano (Chihara and Murano, 1997) and Bradford-Grieve *et al.* (Bradford-Grieve *et al.*, 1999).

^bThis group of zooplankton may contain several species

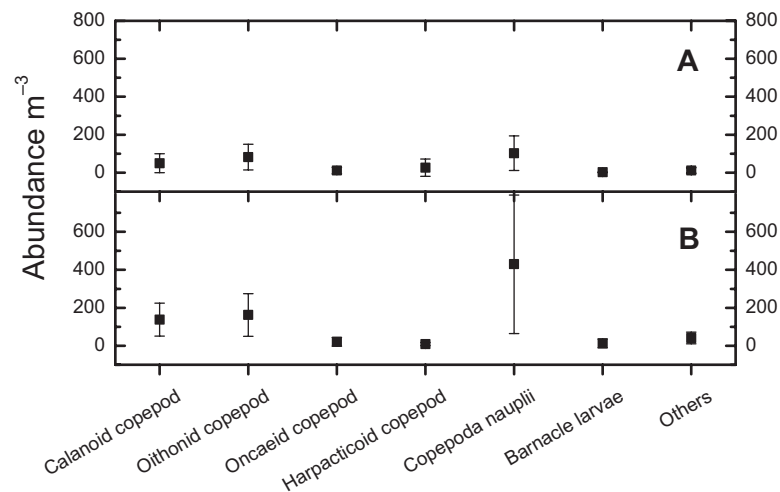


Fig. 3. Zooplankton abundance added by 1 (mean \pm 95% confidence limit) by taxonomic group in the ballast waters of the bulk carriers that had undergone empty-refill (**A**) and flow-through (**B**) exchange.

Zooplankton in ballast water contained species previously reported to have invaded the San Francisco Estuary and to have since become common residents of the Estuary (i.e. introduced species in Table III).

Average zooplankton abundance in container ships excluding copepod nauplii (115 ± 86 individuals m^{-3} ; mean \pm 95% confidence limit, $n = 18$) was not significantly different from bulk carriers when we compared the whole data set (257 ± 108 individuals m^{-3} , $n = 49$) or more comparable subset (e.g. abundance data of bulk carriers during June–September 2002 only, 374 ± 120 individuals m^{-3} , $n = 12$) or only those vessels that had exchanged with empty-refill method (162 ± 86 individuals m^{-3} , $n = 31$) ($P > .13$ for all the analyses, Wilcoxon rank-sum test).

Zooplankton abundance in bulk carriers had no temporal pattern of delivery (data not shown). Further, the variation of total zooplankton ($\log_{10}(\text{abundance} + 1)$) was not related to the duration of voyages, the duration until the exchange in mid-ocean, or the duration until arrival after the exchange (model I regression analysis, $P > .20$ for all analyses).

The average abundance of zooplankton in the bulk carriers that had undergone empty-refill exchange (162 ± 86 individuals m^{-3} , mean \pm 95% confidence limit, $n = 31$) was significantly lower ($P < 0.15$, Wilcoxon rank-sum test) than the abundance in bulk carriers that had undergone flow-through exchange (375 ± 128 individuals m^{-3} , $n = 18$, Fig. 3). Average abundance of non-native zooplankton by the source region generally was <100 individuals m^{-3} , with maximum occurrence of nonnative zooplankton in each vessel being <50 individuals m^{-3} . No comparison among the source regions was made because of differences in sample size.

DISCUSSION

The similar level of zooplankton abundance between the two types of vessel requires more comparable studies, because in the present study the sampling method (net sampling vs. pump sampling), the number of samples, the sampling period and the type of tank from which the samples were collected were all different from each other. For instance, it is likely that some demersal zooplankton such as barnacle larvae and some harpacticoid copepods may not have been adequately sampled in bulk carriers, since bottom tanks were usually not accessible on these ships. The possible underestimation of the abundance of demersal zooplankton is indicated in the apparently greater abundance of harpacticoid copepods in container vessels where the samples were taken primarily from bottom tanks (Table I).

The variation of zooplankton abundance in ballast water of bulk carriers may have been influenced primarily by the exchange method as indicated in the significantly higher abundance in vessels that had undergone flow-through exchange. Both empty-refill and continuous flow-through methods of exchange have been widely used and have been demonstrated experimentally that these methods are capable of replacing $>95\%$ of the original ballast water (Fig. 2 in Rigby, 2001). The efficacy of removal of organisms, however, is usually lower than the proportion of water replaced (Taylor and Bruce, 2000; Bills *et al.*, 2003). The flow-through method involves flushing at least three times the volume of the ballast water by pumping ocean water into the tank, simultaneously allowing the water to overflow through deck-plates or other outlets. With flow-through

exchange, some zooplankton, because of relatively slow upward water flow, may be able to move downward and probably to the side to avoid the surface layer where turbulence would be likely to be strong (Mackas *et al.*, 1993; Lagadeuc *et al.*, 1997; Incze *et al.*, 2001), therefore the zooplankton may be less subject to being flushed out. With the empty–refill method, the tank is pumped out to the lowest level and then refilled with oceanic water, in which case zooplankton may have less opportunity to escape discharge with the ballast water.

The variation in abundance in both empty–refill and flow-through treatments is probably due both to variation in the source region and variation in efficacy of exchange. However, we were unable to stratify this analysis by source because there was mostly only one vessel for each type of exchange method from the same port.

Whether oceanic exchange will prevent future invasions into the Estuary of nonnative zooplankton (Fig. 3) depends on numerous factors associated with invasion processes of introduction, initial establishment and subsequent growth and range extension of introduced species, which will take place either by replacing existing species or by occupying available niches in the ecosystem of receiving estuaries. Oceanic exchange is aimed not only at decreasing the number of organisms of foreign origin, but also at compromising their physiological state by subjecting them to excessive environmental stress, thereby decreasing invasion risks. One key assumption for the effectiveness of the exchange practice is that any invasion requires inoculation of a sufficient number of a founding population, as a small population is more likely to be subject to extinction due to demographic and environmental stochasticity (Allee, 1931; Dennis, 1989; Courchamp *et al.*, 1999; Drake, 2004). There is a dearth of information available regarding the minimum size of founding populations of aquatic organisms.

Successful invasion of zooplankton into an estuary would likely occur either by large but infrequent inoculations of a species (e.g. ballast water discharged from bulk carriers) or by frequent delivery in small numbers of the same species (e.g. container vessels which carry less ballast water). In both scenarios, the dilution of the founder population will oppose the rate of population increase which, because it depends on finding mates (Gerritsen, 1980), although demographic and environmental stochasticity will be important for a sparse population of obligate parthenogenesis, may become negatively density-dependent at low density and result in a failure to establish a population. In the second scenario, continual reinoculation may offset dispersive losses if the reinoculation were frequent enough and dense enough to provide increased opportunities to find mates. In harbors, the organisms are further sub-

ject to extensive dilution upon discharge, which may further decrease the probability of finding mates. Population dynamics upon discharge, especially at low density and low metabolic state, therefore, is of particular importance from the perspective of bioinvasions (MacIsaac *et al.*, 2002; Drake, 2004) and may be of use in examining the effectiveness of the mid-ocean exchange and advanced treatments of ballast water.

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