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Intra-coastal ballast water flux and the potential for secondary spread of non-native species on the US West Coast

Christina Simkanin [a,*], Ian Davidson [a], Maurya Falkner [b], Mark Sytsma [a], Gregory Ruiz [a,c]

[a] Aquatic Bioinvasion Research and Policy Institute, Environmental Sciences and Resources, Portland State University, Portland, Oregon 97207, USA
[b] California State Lands Commission, Marine Facilities Division, Sacramento, California 95825, USA
[c] Smithsonian Environmental Research Center, Edgewater, Maryland 21037, USA

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ABSTRACT

Ballast water is a dominant mechanism for the interoceanic and transoceanic dispersal of aquatic non-native species (ANS), but few studies have addressed ANS transfers via smaller scale vessel movements. We analyzed ballast water reporting records and ANS occurrence data from four US West Coast port systems to examine patterns of intra-coastal ballast water transfer, and assess how ballast transfers may have influenced the secondary spread of ANS. In 2005, one third of the vessels arriving to the US West Coast originated at one of four West Coast port systems (intra-coastal traffic). These vessels transported and discharged 27% (5,987,588 MT) of the total ballast water volume discharged at these ports that year. The overlap of ANS (shared species) among port systems varied between 3% and 80%, with the largest overlap occurring between San Francisco Bay and LA/Long Beach. Our results suggest that intra-coastal ballast water needs further consideration as an invasion pathway, especially as efforts to promote short-sea shipping are being developed.

1. Introduction

Driven largely by the commercial shipping vector, the observed rate of coastal aquatic non-native species (ANS) establishment has increased rapidly throughout the past two centuries (Cohen and Carlton, 1998; Ruiz et al., 2000; Ricciardi, 2006). In particular, the transfer of ships' ballast water is widely recognized as a primary mechanism for the introduction and spread of ANS (Carlton, 1985; Ruiz et al., 2000; Fofonoff et al., 2003). On a daily basis, thousands of species are entrained in ballast tanks and transported within and across biogeographical boundaries (Carlton and Geller, 1993; Carlton, 1996b; Gollasch, 2007). Species that survive transport may proliferate, freed from the biotic and abiotic controls of their native range, causing potentially widespread and long-lasting ecological and economic damage (Elton, 1958; Wilcove et al., 1998; Pimentel et al., 2005).

The successful establishment and spread of ANS can be affected by variations in the frequency and magnitude of the dispersal mechanism (Carlton, 1996b; Ruiz and Carlton, 2003). As the extent of commercial vessel traffic varies considerably among ports (Carlton et al., 1995; Ruiz et al., 1997; Drake and Lodge, 2004; Verling et al., 2005), a port's risk of invasion can fluctuate depending on the frequency and volume of ballast water it receives (Carlton, 1996b; Smith et al., 1999). In addition, variability among vessel types, source regions, voyage season, routes and durations can alter the types, numbers and viability of organisms being transported (*i.e.* propagule supply; Verling et al., 2005). Once a non-native population is successfully established within a port, the system itself may become a source for subsequent introductions through passive range expansion or secondary spread through further human transfer (Wasson et al., 2001; Ruiz et al., 2006).

To reduce the risk of transporting ANS in ballast water, management strategies were developed at international, national, state and local levels. Currently, the only method approved for large scale use is open-ocean ballast water exchange, which replaces coastal water (and associated organisms) with oceanic water (Locke et al., 1993; Wonham et al., 2001). Exchange can effectively reduce the number of coastal organisms in tanks; however it is reported to be highly variable, generally removing 67–99% of coastal zooplankton, depending on ship type, tank configuration, exchange method and salinity of the source and receiving ports (Locke et al., 1993; Rigby and Hallegraeff, 1994; Wonham et al., 2001; Levings et al., 2004; Gray et al., 2007). In addition, it is not always possible to perform due to ship safety and operational constraints (Endresen et al., 2004).

In the US, federal regulation requires that international vessel arrivals intending to discharge ballast water in a US port exchange

* Corresponding author. Present address: Department of Biology, University of Victoria, P.O. Box 3020 STN CSC, Victoria, British Columbia, Canada V8W 3N5. Tel.: +250 472 5098; fax: +250 756 7138.
E-mail address: simkanin@uvic.ca (C. Simkanin).

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their ballast water beyond 200 nautical miles (nm) from shore. Vessels that travel the comparatively shorter distances between US coastal ports are not similarly regulated at the federal level. The lack of ballast water management on intra-coastal voyages represents a sizeable loophole in the framework established to protect against the transfer and spread of ANS (Ruiz and Reid, 2007). Intra-coastal ballast water transport can increase the spread of ANS by expanding the range of established invaders through secondary spread (Lavoie et al., 1999; Hines et al., 2004; Niimi, 2004). Coastal voyages are favorable for the spread of ANS because ballast organism survivorship is higher for shorter voyage durations (Carlton, 1996b; Lavoie et al., 1999; Verling et al., 2005). To address the federal loophole on the US West Coast, state regulations were adopted in 2002 in Washington and Oregon, and 2006 in California, which require most vessels traveling coastally to exchange their ballast 50 nm from shore (exemptions remain for certain voyage routes).

To date, the coastal flux of ballast water and its potential significance for spreading ANS has been largely unexplored, relative to the transoceanic and interoceanic delivery of ballast that have been the primary focus of national and international regulations (Lavoie et al., 1999; Hines et al., 2004). Several studies over recent decades, since Carlton's initial work in the mid-eighties (Carlton, 1985), have analyzed propagule supply from ballast water, but assessments of long-distance oceanic voyages dominate overwhelmingly (Williams et al., 1988; Carlton et al., 1995; Smith et al., 1999; Grigorovich et al., 2003; Verling et al., 2005). Here, we provide the first quantitative assessment of ballast water flux (amounts received and donated) among ports within the same region or contiguous stretch of coastline, using four major port systems on the US West Coast. Specifically, data on shipping arrivals, ballast water operations and established non-native invertebrate taxa were analyzed to examine the potential for ballast-mediated secondary spread of ANS between Pacific Coast port systems. Firstly, we characterized the magnitude, frequencies, ship type variation and port system variation of overseas and coastal ballast water delivery. Then, we analyzed intra-coastal ballast water patterns to quantify variability in ballast water flux between port systems. Finally, we analyzed records of the established invertebrate ANS within each port system to determine (a) the current overlap of non-native taxa between systems, (b) the prevalence of ballast water as a vector, and (c) the potential for future secondary introductions of West Coast ANS among port systems.

2. Materials and methods

2.1. Characterization of vessel traffic at port systems

We analyzed the commercial vessel arrivals and ballast water discharge volumes of vessels arriving at four US Pacific Coast port systems (from North to South): Puget Sound, WA (PS), Lower Columbia River, OR (LCR), San Francisco Bay, CA (SFB), and Los Angeles/Long Beach, CA (LA/LB) (see Fig. 1). Arrivals to these four port systems represent 95% of all the incoming commercial vessel traffic along the US West Coast. Because PS, LCR and SFB are semi-enclosed systems (*i.e.* estuaries or bays), data from all commercial shipping ports located within these systems were used. Included in the LA/LB port system were the ports of Los Angeles, Long Beach, Port Hueneme and El Segundo. Analyses include data from a one year period: January 1, 2005 to December 31, 2005. Data were self-reported by ships to state regulatory agencies and were acquired from the Washington Department of Fish and Wildlife, Portland State University, Oregon, and the California State Lands Commission. These data are the most complete data available for these port systems over this time period, and represent 87% of PS (Anderson et al., 2007), 95% of LCR (Simkanin and Sytsma, 2006), and >94% of SFB and LA/LB arrivals (Falkner et al., 2007).

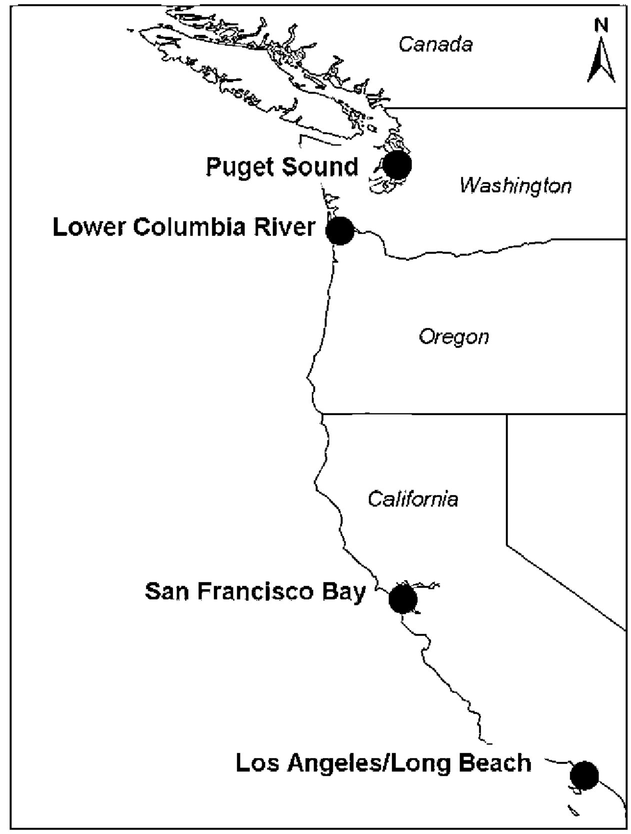

Fig. 1. Map of West Coast port systems.

For each port system, we determined the number of arrivals, the proportion of vessels that discharged ballast water, and the source of that ballast water. Because ships may carry ballast from more than one port at any given time, we used the source port of water in each ballast tank, which directly reflects where the ballast water in each tank originated (see Carlton et al., 1995 and Noble, 2006 for discussion). For the purposes of this paper, 'overseas' arrivals were defined as vessels that arrived from outside of the US exclusive economic zone, and therefore included all vessels that arrived from a port outside the mainland West Coast. 'Coastal' arrivals refer to vessels whose voyages originated within California, Oregon or Washington. Vessels were divided into seven different ship types that reflect different types of trade (cargo), and included: barge, bulk carrier, container, general cargo, ro-ro (*i.e.* auto carrier), tanker and other. The 'other' category included vessels such as military vessels, dredges and research vessels that did not characteristically fit into a specific type.

All statistical analyses were carried out using SPSS 13.0. The Kolmogorov–Smirnov goodness of fit test was used to assess normality and Levene's test was used to determine if sample variances were homogeneous. A chi square goodness of fit test was used to assess differences in the frequency of bulk carriers arriving at the four port systems. Data on the volume of water discharged per ship for each vessel reporting discharge was used to determine the effect of vessel type and voyage route on ballast discharge amounts. Despite transformations, these data did not meet the assumptions of ANOVA, so non-parametric Kruskal–Wallis tests were used to test for differences between the median volumes of ballast water discharged per vessel type. Non-parametric Mann–Whitney U tests were used to assess the effect of voyage route (*i.e.* overseas or coastal based on the vessels last port-of-call) on ballast water discharge patterns.

2.2. Ballast water flux between port systems

We used the 'coastal' subset of the entire data set to quantify the frequency of vessel movements and the flux of ballast water between and within port systems. Specifically, we analyzed the volumes of water ballasted by vessels in one of the four port systems and transported to another. Source port data for each tank discharged were analyzed to determine the volumes of ballast water received and donated by each port system. The same ship type categories (as above) were used to characterize port system to port system traffic and ballast operations, with the exception that general cargo and ro-ro vessels were included in the 'other' category. General cargo and ro–ro's were lumped into the 'other' category because their frequency of port system transfers was lowest (4% and 7% of the total, respectively). Chi square goodness of fit tests were used to test for differences between arrival frequency and discharge volumes per vessel type involved in port system to port system trade.

2.3. Biological comparison between port systems

We used the National Exotic Marine and Estuarine Species Information System (NEMESIS), developed by the Smithsonian Environmental Research Center, to compile a list of aquatic non-native invertebrate taxa recorded from each port system. The numbers of ANS recorded from the four port systems are underestimates of the true numbers because the search effort for ANS can be unevenly distributed spatially, temporally and taxonomically (Ruiz et al., 2000); and the knowledge about biogeography and historical spread of some species is unknown leading to many species being 'cryptogenic' or not demonstrably native or introduced (see Carlton, 1996a for discussion). Our analysis focused on invertebrate taxa that were recorded as established from subtidal and intertidal habitats. We focused on this well known and relatively large group of taxa because they are associated with maritime shipping and have been well-studied along the western US compared to other taxonomic groups and regions.

Additional data provided by NEMESIS for each ANS listed included the potential vector of introduction, the date of first record, and the native range of the species. Potential vectors were assigned based on the taxa's life history characteristics (*e.g.* larval phase, larval duration *etc.*), invasion history and habitat utilization (Fofonoff et al., 2003). Date of first record was determined using the first date of collection, sighting or documented deliberate release. If these were not reported, dates of written documents or publications were used (Ruiz et al., 2000). These data should be interpreted with caution, as it is possible that species may have been discovered considerably after the date they were truly introduced (Costello and Solow, 2003). There were no records of introduced taxa from before 1850 for the western US in the NEMESIS database. This reflects the limited amount of Pacific trade and biological surveys, prior to 1849, when gold was found in California and European settlement and Pacific trade expanded (Carlton, 1987; Ruiz et al., 2000). Because only taxa which are known to be established and non-native were included, any taxa that have been recorded but are not known to be established or are cryptogenic (*sensu* Carlton, 1996a) were excluded from analysis.

For clarity of spatial boundaries, ANS recorded from PS are known to be established from US waters and the shared (US/Canada) waters of Boundary Bay. ANS known only from British Columbia locations where excluded from analysis. For the other three port systems, spatial boundaries adhered strictly to the bays, harbors and estuaries that determine each systems composition and therefore did not include ANS confined to outlying or adjacent areas.

Counts of non-native taxa present in each port system were analyzed for distributional patterns by taxonomic group and potential invasion vector. A chi square goodness of fit test was used to test for significant differences amongst the number of non-native taxa found at each port system. For many of the taxa, several mechanisms of introduction are possible and multiple vectors have been assigned to several taxa where appropriate. To analyze the importance of each pathway, instances where a vector was listed as a potential mechanism (*i.e.* either singly or one of multiple possible vectors) were noted, as were instances where the vector was the sole potential mechanism. ANS lists were also analyzed to determine the timing and overlap (*i.e.* species recorded from more than one of the port systems) of species associated with each port system and invasion vector.

3. Results

3.1. Characterization of vessel traffic at port systems

During 2005, 14,428 vessels arrived and discharged over 22.5 million Metric Tons (MT) of ballast water at the four port systems. LA/LB received the greatest proportion of arrivals (43%), followed by SFB (26%) and PS (20%); whereas LCR received the least (11%). A majority of the arrivals to the four port systems originated at an overseas port, except within SFB (35% from overseas). Although LCR received the least number of arrivals, it received the greatest volume of ballast water (6,816,653 MT), followed by PS (6,414,086 MT), LA/LB (5,050,713 MT) and SFB (4,267,984 MT). SFB was the only port system to receive a greater volume of ballast water from vessels traveling coastally, rather than from overseas sources (Fig. 2).

There were differences in the relative contribution of each vessel type to the number of arrivals and ballast discharge (Table 1). There was a significant difference between the number of bulk carriers arriving at each port system ($\chi^2 = 282.04$, d.f. = 3, $p < 0.001$). LCR received a significantly greater number of bulk carriers than the other three port systems, which were dominated by container vessel arrivals. Although PS, SFB, and LA/LB received a large number of container arrivals, this vessel type did not account for the highest proportion of ballast water discharged within these systems (Table 1). Bulk carriers discharged the greatest proportion of ballast water at PS, LCR and LA/LB; whereas tankers were responsible for over 50% of the ballast water discharged into SFB.

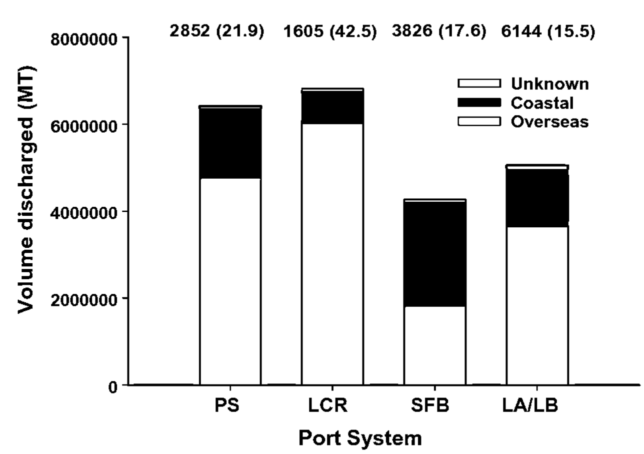

Fig. 2. Volume and origin of ballast water discharged at the four port systems. Above each bar is the total number of vessel arrivals reporting, with the percentage of arrivals discharging in parentheses.

Table 1
Number of arrivals by vessel type, including the percentage each type discharged and the percentage each type contributed to the total volume discharged at the four port systems from January 2005 through December 2005.

	PS			LCR			SFB			LA/LB		
Vessel type	Number of arrivals	(%) discharging	(%) of total volume discharged	Number of arrivals	(%) discharging	(%) of total volume discharged	Number of Arrivals	(%) discharging	(%) of total volume discharged	Number of Arrivals	(%) discharging	(%) of total volume discharged
Barges	150	86.0	17.3	62	1.6	0.3	275	27.3	6.5	223	8.6	1.7
Bulker	306	66.3	55.7	818	69.3	94.3	414	30.4	27.4	532	19.5	49.0
Container	1361	16.9	11.5	105	13.3	0.6	1803	12.5	9.8	2767	43.1	24.6
General cargo	124	20.2	3.6	205	51.2	3.8	180	23.9	2.5	484	4.4	1.6
Ro-Ro	247	3.2	0.2	261	1.9	0.1	135	0.7	0.0	527	0.6	0.1
Tanker	445	20.4	11.6	117	9.4	0.8	933	24.0	53.1	1142	16.8	22.2
Other	219	4.6	0.1	37	13.5	0.1	86	5.8	0.6	469	7.1	0.8

Of the 14,428 total vessel arrivals in 2005, 22% (3,152) reported discharging ballast water. Among the latter group of vessels, the average volume of water discharged per ship varied significantly by vessel type (Fig. 3; Kruskal–Wallis $H = 1104.4$, d.f. = 6, $p < 0.001$). Bulk carriers and tankers discharged a greater volume of water per ship than the other vessel types. Vessels arriving from overseas ports discharged a significantly greater mean volume of water than vessels from coastal ports (Fig. 3; Mann-Whitney test $Z = -6.060$, d.f. = 1, $p < 0.001$). Bulk carriers ($Z = -5.347$, d.f. = 1, $p < 0.001$), containerships ($Z = -2.842$, d.f. = 1, $p < 0.005$) and general cargo vessels ($Z = -2.302$, d.f. = 1, $p < 0.05$) arriving from overseas ports discharged greater mean volumes of ballast water compared to those that had arrived from coastal ports. In contrast, tankers that underwent coastal voyages discharged significantly greater volumes compared to tankers arriving from overseas (Fig. 3; $Z = -4.587$, d.f. = 1, $p < 0.001$). For the other three vessel types, barges, ro-ro's and others, there was no significant difference between the volumes discharged on coastal and overseas voyages.

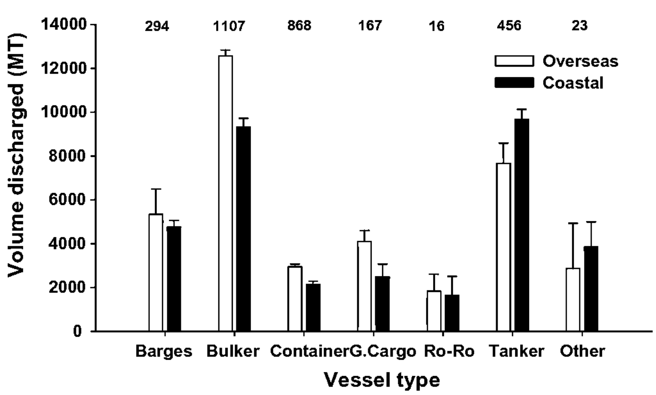

Fig. 3. The mean (±1 s.e.) volume of ballast water (MT) discharged at the four port systems by the seven vessel types. Data are divided into overseas and coastal voyages. The total number of vessels discharging water is noted above the bars.

3.2. Ballast water flux between port systems

Over the one year study period, 4,735 vessels (32% of the total) transited within and between the four focal port systems (Table 2). Of these, 1,061 loaded, transported and discharged approximately 6 million MT of ballast water, representing 27% of the total volume of ballast water discharged during this period. The greatest number of vessels transited from LA/LB to SFB (Table 2) and these vessels transported the largest volume of coastal ballast water from one port system to another; carrying over 1.2 million MT of LA/LB water to SFB ports (Table 2). The only other transits resulting in over 500,000 MT of cumulative ballast water transport and discharge were LA/LB to PS and LCR to SFB. Vessels on only one of these routes, LA/LB to PS, were required to exchange their ballast water in 2005. Transits from LCR to LA/LB and PS to SFB had the lowest frequencies of vessels discharging and the least amount of port system water being discharged (both were under 100,000 MT).

LA/LB was the origin of the greatest number of vessels transiting among the port systems (Fig. 4a). Vessels departing LA/LB also donated the greatest amount of coastal ballast water compared to the other port systems (Fig. 4b). SFB received the greatest number of

Table 2
Intra-coastal pathways for the spread of aquatic non-native species, including: the approximate distance between port systems, the average voyage duration at 24 knots (www.searates.com), the frequency of arrivals, frequency discharging and the volume discharged (MT).

Port system transits	Approximate distance (nm)	Average voyage duration	Number of vessels	Number discharging	Volume discharged
PS-LCR	350	15 h	139	20	109,734
PS-SFB[b]	800	1day 9 h	336	16	66,832
PS-LA/LB[b]	1142	2 days	188	42	175,332
LCR-PS	350	15 h	87	38	214,577
LCR-SFB[b]	641	1day 3 h	122	60	550,564
LCR-LA/LB[b]	984	1day 17 h	134	16	30,466
SFB-PS[a]	800	1day 9 h	107	64	454,520
SFB-LCR[a]	641	1day 3 h	161	40	367,597
SFB-LA/LB[b]	355	15 h	696	153	411,423
LA/LB-PS[a]	1142	2 days	376	106	687,822
LA/LB-LCR[a]	984	1day 17 h	89	39	218,751
LA/LB-SFB[b]	355	15 h	1586	285	1,230,602
Intra-port system	n/a	n/a	714	182	1,469,368

[a] Denote transits in which ballast water exchange was required in 2005.
[b] Denotes transits in which ballast water exchange is now required (starting in March 2006).

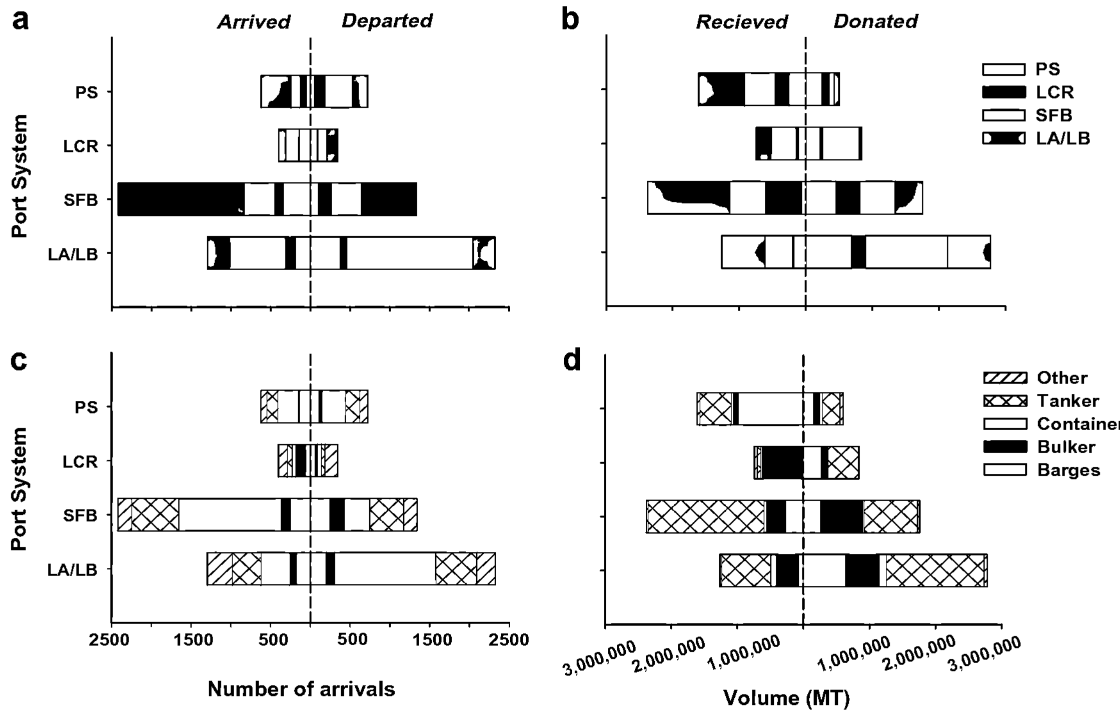

Fig. 4. Vessel arrivals and ballast water flux within and between port systems; (a) the number of vessels arriving and departing to/from the port systems, (b) the volume (MT) of ballast water received and donated by/to the port systems, (c) the number of each vessel type arriving and departing to/from the port systems, (d) the volume of ballast water received and donated by/to the port systems by different vessel types.

arrivals and volume of ballast water discharge from the other port systems (Fig. 4a, b), dominated by vessels coming from LA/LB and internal SFB vessel movements. PS received less port system arrivals then LA/LB, however, it received a larger volume of water, largely driven by the magnitude of ballast water donated by coastal barges (Figs. 4a, b, c). Significant differences existed in arrival frequency ($\chi^2 = 3323.56$, d.f. = 4, $p < 0.001$) and discharge volume per vessel type ($\chi^2 = 9190806.47$, d.f. = 4, $p < 0.001$) involved in the coastal port to port traffic. Containerships transited between the four port systems more frequently than the other vessel types (Fig. 4c) but tankers transported and discharged the largest volumes of ballast water among port systems (Fig. 4d).

3.3. Biological comparison between port systems

A total of 222 different invertebrate ANS were reported as established in tidally influenced habitats of the four port systems. There were significant differences in ANS numbers between port systems ($\chi^2 = 157.67$, d.f. 3, $p < 0.001$) with the highest number of taxa reported from SFB (182), followed by LA/LB (65), PS (62) and LCR (30) (Table 3). Overall these taxa included ten groups with the most abundant being Arthropods ($n = 84$; 38%), Mollusks ($n = 43$; 19%) and Annelids ($n = 28$; 13%). The other seven groups recorded were: Ascidians (16), Bryozoans (16), Cnidarians (15), Platyhelminthes (12), Porifera (5), Nematoda (3) and Entoprocta (2). Only one port system, SFB, had non-native invertebrate taxa recorded from all ten groups; whereas PS had nine (missing Nematoda), LA/LB had eight (missing Nematoda and Entoprocta), and LCR had six (missing Ascidians, Platyhelminthes, Nematoda and Entoprocta) of the groups represented.

Ballast water was one of several possible invasion vectors for 113 (51%), and the sole possible vector for 29 (13%), of the total 222 established ANS (Table 3). Across port systems, the principal mechanism of introduction varied. PS was dominated by ANS associated with shipments of commercial oysters, whereas the majority of ANS from LCR and SFB were potential ballast water introductions; and LA/LB was dominated by potential ship fouling introductions (Table 3). This pattern holds true at PS, LCR and LA/LB regardless of whether the invasion mechanism analyzed was one of many possible vectors or the sole possible vector. At

Table 3
Number of established invertebrate aquatic non-native taxa associated with different invasion vectors. Parentheses indicate the number of taxa for which the vector was listed as the sole potential vector. Also shown is the total number of taxa, the number of unique taxa (*i.e.* taxa found at only that port system), and the total number of taxonomic groups present in each port system.

Vector	Definition	PS	LCR	SFB	LA/LB	All ANS
Ballast water	Carried in ballast water taken aboard by vessels	25 (6)	23 (8)	97 (23)	27 (5)	113 (29)
Ship fouling	Attached or associated with the submerged surfaces of vessels	34 (16)	10 (1)	93 (27)	59 (31)	111 (39)
Commercial oysters	Associated with introductions of Atlantic or Pacific oysters	39 (17)	8 (1)	53 (12)	13 (0)	68 (10)
Other	Solid ballast, intentional or accidental release, or unknown	5 (0)	16 (5)	55 (29)	1 (0)	60 (31)
Total number of taxa		62	30	182	65	222
Number of unique taxa		20	4	95	14	133
Total number of taxonomic groups		9	6	10	8	10

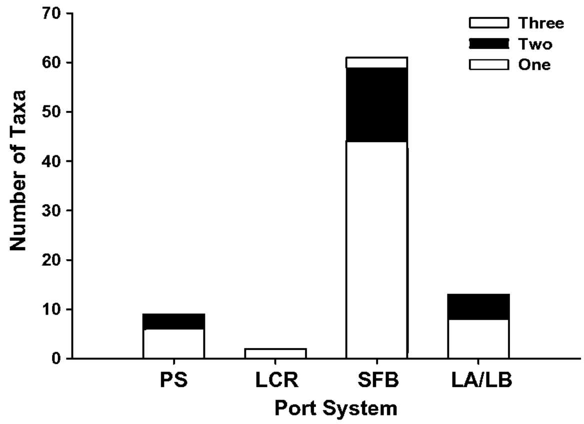

Fig. 5. Shown for the 89 non-native taxa that were recorded at multiple port systems are the locations of initial port system invasion and the number of taxa subsequently found at one, two or three of the other port systems. Four taxa were removed from analysis because the site of first record was unknown.

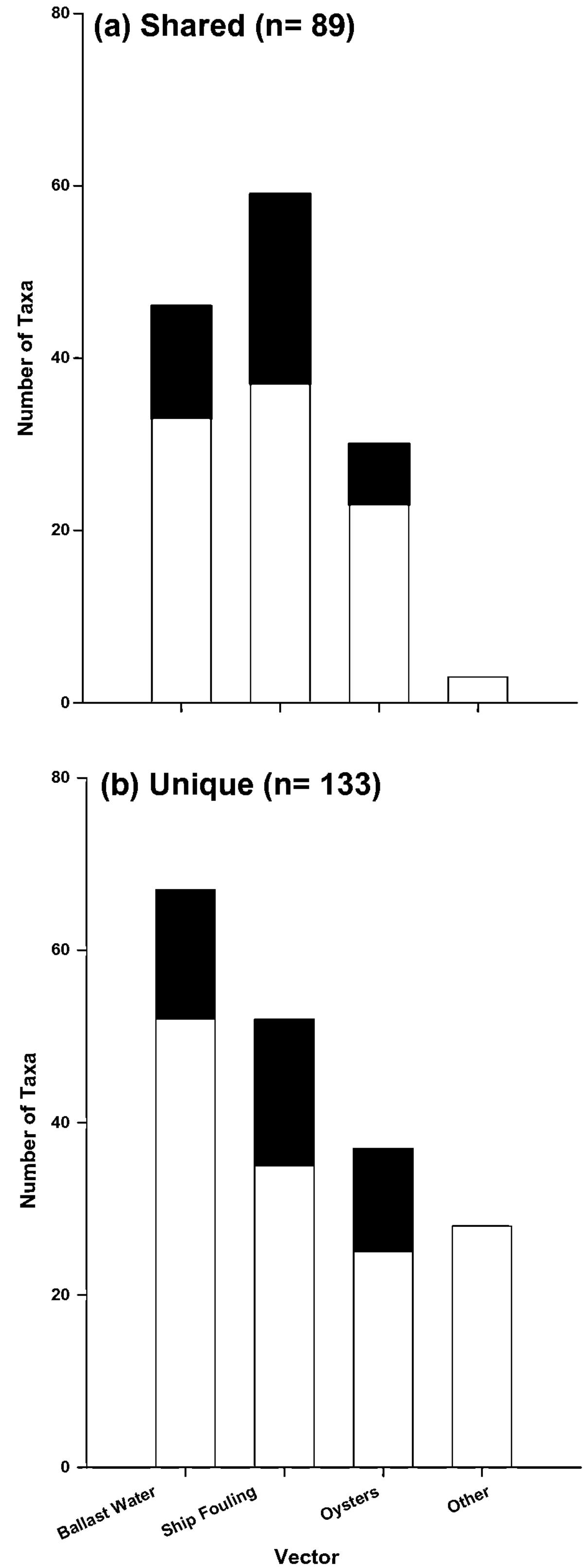

Fig. 6. The number of non-native taxa: (a) shared between more than one port system, and (b) unique to one of the four port systems, associated with each vector type. Shaded portion of bars indicates the number of taxa for which the vector was listed as the sole potential vector.

SFB, the 'other' category (including solid ballast, intentional and accidental releases or an unknown mechanism) was the greatest sole possible vector of ANS.

Over half of the ANS recorded at SFB (95) were unique to SFB waters and not found at any of the other port systems (Table 3). This contrasts with observed patterns at the other three port systems where a majority of recorded ANS were also recorded at one or more of the other port systems (Table 3). In total, 89 ANS were recorded at multiple port systems. A majority (61) of these 89 taxa were first recorded as established in SFB and then subsequently recorded at one or more of the other port systems (Fig. 5). Only two species were reported from all four systems, the amphipod *Grandierella japonica* and the annelid *Streblospio benedicti*, which were first recorded in SFB in 1966 and 1932, respectively. Ship fouling was the dominant invasion vector for ANS that were recorded from multiple port systems (Fig. 6a). Among taxa that were recorded from only one of the port systems, ballast water was the dominant potential invasion vector (Fig. 6b).

As expected, because a majority of the taxa found at multiple ports were first recorded from SFB, the port systems of PS, LCR and LA/LB had a greater proportion of species in-common with SFB than any of the other systems (Table 4). Despite this, there was considerable variation in the overlap of established non-native taxa among port systems (Table 4). The percentage of shared taxa between pairs of port systems varied from 3% to 80% for all ANS and 7% to 85% for ANS with ballast water as a potential vector. Irrespective of whether all taxa or only taxa with ballast water as a vector are considered, SFB and LA/LB had the most non-native taxa in common, whereas, LA/LB and LCR had the fewest (2) taxa in common.

4. Discussion

This study quantifies the volume of ballast water discharged after intra-coastal voyages, which may be a significant pathway for the secondary spread of ANS. One third of the vessels arriving to the US West Coast originated at one of the port systems analyzed, and these vessels discharged 27% of the ballast water discharged throughout the year. In the North Atlantic, including North American and European ports, 60% of the shipping traffic operates within 200 nm of the coast (Endresen et al., 2004). These intra-coastal voyages are typically short in duration (*i.e.* hours to days) and because species entrained in ballast tanks for these durations experience low in-tank mortality and high viability, there is an increased risk of ANS establishment after discharge (Carlton, 1996b; Lavoie et al., 1999;Verling et al., 2005).

Table 4
Overlap of invertebrate aquatic non-native taxa reported among the four port systems, shown as number and percent in parentheses; data shown for (a) all taxa and (b) taxa with ballast water as a possible invasion vector. Values in parentheses represent the number of shared species as a percentage of the total species recorded at the row site.

	PS	LCR	SFB	LA/LB
(a) All taxa				
PS	62	9 (14.5)	40 (64.5)	21 (33.9)
LCR	9 (30.0)	30	24 (80.0)	2 (6.7)
SFB	40 (22.0)	24 (13.2)	182	51 (28.0)
LA/LB	21 (32.2)	2 (3.1)	51 (78.5)	65
(b) Ballast water taxa				
PS	LCR	SFB	LA/LB	
PS	24	7 (29.2)	13 (54.2)	9 (37.5)
LCR	7 (30.4)	23	19 (82.6)	2 (8.7)
SFB	13 (13.4)	19 (19.6)	97	23 (23.7)
LA/LB	9 (33.3)	2 (7.4)	23 (85.2)	27

The four port systems examined during this study span 15 degrees of latitude from 34°N to 49°N. Although these systems share the same continental coastline, variation in temperature and current regimes, among other macro-scale abiotic factors, contribute to biogeographical differences among coastal invertebrate communities. Biogeographical boundaries at Cape Mendecino (40°10′N) and Point Conception (34°27′N) act as barriers for the natural dispersal of marine organisms (Wares et al., 2001; Wonham and Carlton, 2005). The transport of species across these boundaries in ships' ballast water can lead to human-mediated range expansions of native species and secondary spread of non-native species previously introduced to the West Coast. Many studies acknowledge the potential risk of secondary spread, but the dearth of quantitative intra-coastal ballast water data has resulted in limited attention relative to overseas shipping (*e.g.* Carlton et al., 1995; Grigorovich et al., 2003; Herborg et al., 2007).

Ship types vary in ballast water capacity and the volumes routinely carried on voyages (Hines et al., 2004; Verling et al., 2005), and this can also differ among trade routes within vessel type. Although container vessels are the most abundant vessel type engaged in sea-borne commerce on the US West Coast, bulk carriers and tankers carry and discharge the largest ballast water volumes (Fig. 3, Hines et al., 2004; Verling et al., 2005), and as such, have a greater potential for transporting and spreading ANS on a per ship basis. LA/LB receives far more vessel arrivals than LCR, but it receives significantly less ballast water, because of the high number of bulk carriers calling at LCR ports. De-ballasting bulkers typically discharge four- times more ballast water in port than de-ballasting containerships (Fig. 3; Verling et al., 2005).

Despite receiving large volumes of ballast water in 2005 and probably throughout the preceding decades, LCR had the fewest number of recorded ANS. The failure of ANS establishment in the LCR in spite of substantial propagule delivery may be largely attributed to environmental characteristics, including especially low salinities, which provides abiotic resistance against many marine non-native propagules (species). Similar environmental mismatch is thought to play a role in Chesapeake Bay, Maryland/Virginia and Prince William Sound, Alaska (Smith et al., 1999; Hines and Ruiz, 2000). However, large gaps in propagule supply and species delivery data, as well as a broader understanding of factors that influence ANS establishment, currently limit further explanations for differences in ANS establishment rates among port systems.

LA/LB is a pivotal West Coast port, with the highest number of vessel arrivals in the eastern Pacific, and because of its connectedness to Asian ports, may be an important pathway for transoceanic ANS transport (Drake and Lodge, 2004; Falkner et al., 2007). Our data show that a majority of the ballast water being transferred intra-coastally originates from LA/LB. Thus, LA/LB may act as a 'stepping-stone' for the spread of ANS on the West Coast, creating a hub for secondary invasions between Asian and West Coast ports. This potential invasion hub, with numerous regional spokes to other coastal port systems, likely has two major vector sources, ballast water and vessel fouling. Hull fouling appears to be the dominant invasion vector responsible for recorded ANS in LA/LB (Table 3) but ballast water may also be significant. A large number of vessels departing LA/LB traveled to SFB and these vessels carried and discharged the largest volumes of intra-coastal ballast water. LA/LB and SFB also share the greatest proportion of ANS, which suggests that strong connectivity between these two port systems has existed for some time despite the geographic distance. Genetic analyses of ANS populations in each system and from native ranges will help to elucidate whether separate primary introductions or secondary spread of ANS has been occurring (see Voisin et al., 2005; Kelly et al., 2006).

The risk of ANS incursion via intra-coastal ballast water may be highest at SFB among the four systems studied as it was the only port system that received more coastal ballast water than overseas. SFB is considered one of the most invaded port systems in the world (Cohen and Carlton, 1998). Previous work, albeit prior to ballast water management regulations, concluded that most new invasions in SFB are likely the result of the transfer and release of ships' ballast water from overseas ports (Carlton and Geller, 1993; Carlton et al., 1995; Ruiz et al., 1997). Our results (Fig. 5) show that a large majority of the invertebrate ANS recorded at Pacific Coast port systems were first found in SFB (*i.e.* did not arrive from other West Coast port systems). Historically SFB may have been an important donor of ANS to the other coastal port systems. There were 40 non-native taxa present within the other three port systems that were not recorded within this bay. With the high frequency of coastal arrivals and the magnitude of intra-coastal ballast water transferred to SFB, there is a risk that some of these taxa could be introduced to SFB waters.

A large number (133) of the ANS recorded are currently established within only one port system (95 in SFB), and half of these taxa have ballast water as a potential mechanism for invasion. Intra-coastal ballast water is a potentially strong mechanism for increasing the ranges of these species, although coastal ballast water exchange regulations play an important role in reducing this risk. For example, a recent assessment of the mitten crab (*Eriochier sinensis*) on the West Coast found that PS, where the crab has not yet been recorded, has suitable habitat and abiotic conditions to support a mitten crab population (Hanson and Sytsma, 2008). *E. sinensis* is currently only present on the West Coast in SFB, where it was first recorded in 1992 and reached a numerical peak in 1998 (Rudnick et al., 2003). In 2005, 107 vessels traveled directly from SFB to PS and 64 of these vessels discharged 454,520 MT of ballast water. Vessels on this voyage have been required to manage their ballast, through exchange, since 2001 (but only since 2006 in the opposite direction). These regulations are no doubt effective at reducing propagule delivery and likelihood of invasion (Gray et al., 2007; Ruiz and Reid, 2007), although some residual organisms and risk remain.

Our analysis focused on the ballast water vector, but several analyses have shown that vessel fouling is also an active contemporary vector of ANS (Gollasch, 2002; Coutts and Taylor, 2004; Davidson et al., 2008). Globally, commercial shipping is the primary invasion vector for coastal ANS (Ruiz et al., 1997; Minchin and Gollasch, 2002), but estimating the relative importance of ballast water and hull fouling is difficult (Fofonoff et al., 2003; McGee et al., 2006). Many species have life stages that can be carried by both vectors, either as planktonic larvae in ballast water or sessile or sedentary adult stages on ships hulls (McGee et al., 2006). Seachests provide yet another location (niche) on vessels where distinct assemblages of organisms, including mobile species unsuited to attachment on hull surfaces, can be transferred (Coutts et al., 2003). In order to fully reduce the risks of transporting ANS coastally or elsewhere, management strategies must address all sources of ship-mediated transfer mechanisms, with the aim of preventing total organism flux rather than focusing on particular species or sub-vectors.

Short-sea shipping is being promoted by government agencies (*e.g.* by the US Maritime Administration, US Government Accountability Office, 2005) which seek to relieve road and rail congestion at regional scales by increasing seaward intra-coastal transportation of freight. In some parts of Asia and Europe, short-sea shipping has been a significant component of the regional freight transportation industry since the 1970's (US Government Accountability Office, 2005). As short-sea shipping and the number of intra-coastal voyages increases, established ANS will be provided with greater opportunity to hitch-hike on voyages and expand their non-native ranges. Currently some nations and regions, including Canada and the US West Coast, require ballast water management (*i.e.* exchange) on some coastal or intra-regional voyages, but these regulations were only enacted after the focus on international arrivals was widened. Similarly, the secondary spread of ANS via intra-coastal transfer is still largely underestimated as a risk to native aquatic systems. Although coastal ballast water exchange presents impediments to shippers on certain voyage routes, because of the time needed to conduct exchange and the distance and depth requirements (50 nm and 200 m, respectively), it is currently the only method for reducing propagule delivery and preventing coast-wise ANS incursions. As treatment technologies are developed for ballast water management, these obstacles are unlikely to remain an issue, and management efficacy will presumably increase. Our results suggest that a significant pathway for unnatural range expansion of ANS exists on the US West Coast, may have already transferred several ANS among port systems, and is worth the efforts of shippers, ports and agencies to manage.

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