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Relative contributions of domestic and foreign sourced ballast water to propagule pressure in Puget Sound, Washington, USA

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ABSTRACT

The movement and release of non-indigenous species (NIS) in ship ballast water is a global threat to the conservation of native aquatic species and habitats. One key to successful NIS establishment in coastal waters is propagule pressure – the size and frequency of NIS inoculations. We estimated propagule pressure of high-risk coastal zooplankton delivered in ballast water to Puget Sound, Washington, USA, which receives 7.5×10^6 m^3 of ballast water annually. We weighed the relative propagule pressure from domestic and foreign ballast water, in terms of propagule size (number of individuals), frequency of NIS occurrences, and diversity (number of known NIS species). Ship discharge volume was not a good predictor of propagule pressure. Instead route type (domestic or foreign) and ballast water exchange status (exchanged in mid-ocean vs. unexchanged) were much better predictors of propagule supply. Overall, while the diversity of non-indigenous zooplankton was higher in trans-oceanic ballast, the annual discharge of coastal zooplankton propagules to Puget Sound was much greater for ships conducting domestic voyages. These results suggest that intra-coastal ballast water must be further scrutinized as a pathway for NIS introduction, and calls into question regional "common waters" agreements that allow vessels to move ballast without conducting ballast water treatment.

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1. Introduction

Non-indigenous species (NIS) threaten the conservation of coastal habitats through reductions in native diversity (Blackburn et al., 2004), alterations in ecosystem functioning (Mack et al., 2000), and homogenization of faunas (Olden et al., 2004). Propagule pressure is one key factor influencing the likelihood of establishment of a NIS – increasing size and frequency of NIS propagule inoculations increases the likelihood of successful establishment (Lockwood et al., 2005). Coastal managers need, but usually lack, assessments of propagule pressure associated with the various pathways of NIS introduction that would allow them to craft the most effective policy to reduce the likelihood of invasions (Puth and Post, 2005). Preventing NIS introductions by managing these pathways is widely recognized as the most favorable management strategy when compared to the relative costs of controlling or eradicating a NIS once established (Lee and Chown, 2009).

The global movement of aquatic organisms in ship ballast water is one recognized pathway for the introduction of non-indigenous marine species to coastal habitats (Carlton, 1985; Carlton and Geller, 1993; Molnar et al., 2008). Coastal ports receive ballast water from a variety of sources, but the majority of research aimed at estimating propagule pressure to coastal ports has focused on vessels discharging ballast from foreign destinations (Minton et al., 2005; Verling et al., 2005). While a few studies have considered domestic routes as a source of NIS (Lavoie et al., 1999; Simkanin et al., 2009), even fewer have compared both pathways simultaneously (McGee et al., 2006). However, many ports in the world receive both domestic and international shipping traffic, and both route types are pathways for NIS invasions, particularly when ports along domestic routes are highly invaded. Understanding the relative contributions of potentially invasive propagules from each source is required to properly manage coastal systems to reduce invasion risk. This is particularly true in regions that have 'common water' agreements allowing the intra-coastal movement of ballast without requiring ballast water management. The 'stepping stone' model of invasion suggests that invasions can occur from both distant and nearby, previously invaded, sources (Carlton, 1996; MacIsaac et al., 2004).

Currently, international (e.g. International Maritime Organization), national (e.g. US Coast Guard), and state (e.g. state of California) governing bodies have passed or proposed regulations that determine the allowable number of viable propagules that discharged ballast water may contain. However, the technology available to treat ballast to meet these standards is largely still in development, testing, and verification stages and few ballast

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treatment systems (summarized in Mamlook et al., 2008) have become commercially available for routine ballast water management. As an interim risk reduction measure vessels are required to conduct mid-ocean ballast water exchange (BWE), a procedure that replaces water collected from a source port with oceanic water, before discharging the ballast to a destination port.

Requirements to conduct BWE vary widely throughout the world. In Australia, all salt water from ports and coastal waters outside Australia's territorial sea are considered high-risk and must undergo BWE or treatment before discharge (Australian Quarantine and Inspection Service, 2008). Similarly, in the United States (US), all ships arriving from overseas are required to conduct a BWE at least 200 nautical miles (nm) offshore before discharging ballast into US ports (Federal Register Final Rule 69 FR 44952). In the European Union the situation is complicated by the numerous governmental jurisdictions, and with few exceptions, countries there are only beginning to formulate ballast water management practices (David and Gollasch, 2008). For coastal voyages within the US, ballast discharge is regulated differently depending on regional requirements. Each state along the US Pacific coast has unique ballast water management regulations for vessels conducting intra-coastal voyages. In Washington state, ships traveling within "common waters" (including waters of Washington state, the Oregon portions of the Columbia River system, and the internal waters of British Columbia south of latitude 50° N) are not required to conduct BWE, while ships arriving from outside of common waters are required to complete BWE at least 50 nm offshore (Revised Code of Washington 77.120.030). In Oregon state, the common waters zone is larger, encompassing an area between 40 and 50° N latitude (Oregon Revised Statutes 783.630). In contrast, the state of California does not allow unexchanged or untreated ballast water to be discharged at all, unless it is from within the same "port or place" (e.g. water being transported from one San Francisco Bay port to another – California Code of Regulations, Title 2, Division 3, Chapter 1, Article 4.6, Section 2284). On the Atlantic coast of the US vessels transiting within 200 miles of shore, or that do not go out past 200 miles for long enough to conduct exchange without delaying or diverting, do not have to conduct exchange. This includes vessels moving across the United States–Canadian border, within 200 miles of shore (R. Everett, US Coast Guard, personal communication).

While studies comparing the numbers of coastal organisms in before-and-after ballast exchange experiments confirm that BWE can be an effective treatment method (capable of removing 67–95% of coastal organisms – McCollin et al., 2008; Ruiz and Reid, 2007; Taylor et al., 2007), many ships that record having completed BWE still contain large numbers of coastal organisms (Cordell et al., 2009). This discrepancy suggests that BWE is sometimes ineffective, either because the exchange was not conducted properly, the ship design does not allow for an efficacious exchange, or the exchange was reported by the vessel operator, but not actually completed (Harkless, 2003). Thus, many vessels continue to release coastal propagules in discharged ballast water, and resource managers have little or no data on the relative contributions of different ballast water vectors to the overall propagule supply to a given coastal system.

Here we estimate propagule pressure of coastal zooplankton delivered to Puget Sound, Washington, USA, which is home to several ports that receive large volumes of ballast discharge from both international and domestic sources, and from vessels that both have and have not conducted BWE. We compared the relative propagule pressure from foreign and domestic ballast waters in terms of coastal species propagule size (number of individuals), frequency of NIS occurrences, and diversity (number of known NIS species). To do this, we calibrated the total volume of ballast discharged to Puget Sound from a variety of sources and BWE histories with known densities of coastal organisms in these various ballast vectors, determined from an extensive ballast tank zooplankton sampling program in Puget Sound (Cordell et al., 2009).

2. Methods

2.1. Ship arrival and discharge patterns

Ship arrival and discharge routines for Puget Sound were derived from the National Ballast Information Clearinghouse (NBIC) online database, maintained by the Smithsonian Environmental Research Center for the United States Coast Guard (USCG) (NBIC Online Database; http://invasions.si.edu/nbic/). As of 2004, all ships calling on Washington state ports were legally required to report their arrival and ballasting operations to the NBIC 24 h prior to arrival (Federal Register Final Rule 69 FR 32864, June 14, 2004). Prior to 2004 reporting to the NBIC was voluntary, and compliance was low, estimated to be approximately 35% by Verling et al. (2005) for the period from 1999 to 2002. In 2005, the most recent year a compliance estimate was calculated for the Puget Sound Captain of the Port zone, compliance was 95% (K. Ryan, NBIC data manager, personal communication). Compliance estimates were derived by comparing the number of arrivals submitted to NBIC to the number of arrivals reported to the USCG National Vessel Movement Center. We used NBIC arrival and discharge data from 2006 and 2007 for this analysis to provide a recent, reliable estimate of the amount of ballast entering Puget Sound.

Fields derived from the NBIC database included: vessel name, vessel IMO number, arrival date, port of arrival, last port, last country, ballast discharge (yes/no), volume of ballast discharged by source (broken down into 'overseas', 'coastwise', and 'unknown' categories), and volume of ballast discharged by ballast management method (empty refill, flow through, alternative management, and unknown), and vessel type. Specific vessel types identified in the database were container, bulk carrier (bulker), general cargo, tanker, passenger, refrigerated ship (reefer), vehicle roll-on roll-off ship (RoRo), and other. The vessel classification 'other' used by the NBIC was further broken down into two categories, articulated and integrated tug barges (ATB/ITBs) and 'other'. ATB/ITBs were specifically identified in this analysis because they are used extensively to carry petroleum products along the west coast of the US and contribute a large amount of ballast to Puget Sound.

Each vessel arrival was assigned a trip type, which included South America (arriving from South America), trans-Pacific (transiting from the west to east Pacific Ocean), west coast (traffic moving up or down the US west coast), and other (e.g. ships arriving from the Atlantic via the Panama Canal). To assign trip type both the last port of call and the source of the ballast were considered, because for some ships the last port of call was not a good indicator of trip type. A small number of the ships arrived to Puget Sound carrying a mixture of both 'overseas' and 'coastwise' water (92 ships out of 6193 total arrivals, or 1.5% of all arrivals). In these cases trip type was assigned based on which source contributed the greatest ballast volume.

2.2. Zooplankton sampling methods

Samples analyzed for this study were taken as part of a ship sampling program that began in 2001, conducted by the Washington Department of Fish and Wildlife (WDFW) in conjunction with the University of Washington (UW). A full description of zooplankton sampling and identification methods is described in Cordell et al. (2009). For this study, we analyzed samples from the ballast tanks of 372 ships arriving to Puget Sound ports from 2001 to 2007. Triplicate vertical plankton tows were taken in ballast tanks

using a 30 cm diameter, 73 μm mesh net. Relevant ship attributes collected for each sample included: ship type, last port, ballast source, and all ballast management activities (including ballast management method, date of exchange, and the position of exchange, if one occurred). Consistent with the NBIC data, all zooplankton samples were categorized by trip type (trans-Pacific or west coast), based on ballast source.

In the laboratory, each sample was sorted and the zooplankton present were identified and counted. Based on the length of the zooplankton net tow, the density of each organism was calculated per m^3. The mesozooplankton present in these samples were characterized as belonging to one of two categories: (1) coastal zooplankton, including non-indigenous species, and (2) oceanic zooplankton, plus those of cosmopolitan or uncertain origins. See Cordell et al. (2009) for a complete list of species and their designations. Coastal mesozooplankton was considered the higher risk of the two categories, as these organisms are more likely to survive when discharged into the coastal waters of Puget Sound.

The WDFW ship sampling effort was designed to sample ship types (e.g. container, bulk carrier, ATB/ITB, etc.) in relation to their relative discharge to Puget Sound. That is, those ship types discharging the most ballast water were sampled more frequently than those contributing less ballast discharge. Given that effort, unexchanged ships on west coast routes were under-represented in the data set, comprising 7.8% (29 of 372) of the ballast tank samples but contributing 19.5% of the total ballast discharged into Puget Sound from 2006 to 2007. Ships on trans-Pacific and west coast routes with exchanged ballast were slightly over-represented in the dataset. Trans-Pacific exchanged tanks made up 61.6% (229 of 372) of the zooplankton samples, but contributed 52.5% of the total ballast discharged. West coast exchanged tanks made up 30.6% (114 of 372) of the zooplankton samples, but contributed 21.8% of the ballast discharged to Puget Sound from 2006 to 2007.

To estimate the total propagule pressure to Puget Sound contributed by each vector we first established the average number of coastal organisms present for each ship type, route type, and exchange status combination (e.g. exchanged trans-Pacific bulker). However, our sampling design was skewed towards those ship, route, and exchange status combinations that discharged the greatest volume of ballast (i.e. exchanged trans-Pacific bulker, exchanged and unexchanged domestic ATB/ITB and tankers), leaving other vector combinations with sample sizes that were too small to reliably estimate average propagule supply. Therefore, we established an average number of coastal propagules for each trip type and exchange status combination that was not specific to ship type (i.e. exchanged trans-Pacific vessels, and exchanged and unexchanged west coast vessels). This simplification was appropriate because in a previous analysis by Cordell et al. (2009) there was no significant difference in the abundance of coastal organisms for each ship type within a given route (i.e. no difference between ATB, ITB, product and oil tankers on a west coast route, and no difference between bulk and container ships on trans-Pacific voyages).

To estimate the number of coastal propagules discharged by each major ballast vector we multiplied the average number of coastal propagules for each trip type and exchange status combination (e.g. exchanged trans-Pacific water) by the total 2006–2007 volume discharged for each ship type that carried that kind of ballast (e.g. bulkers that discharged exchanged trans-Pacific water). This calculation was intended to estimate the relative role each ballast vector plays in the overall propagule pressure, not provide an exact number of coastal organisms discharged.

Ships arriving from South America and 'other' destinations comprised <2% of the arrivals to Puget Sound and <3% of the volume discharged there. Since few zooplankton samples were collected from ships on these routes, we were not able to generate reliable zooplankton densities for these trip types, and we thus considered only ships with trans-Pacific and west coast sources.

2.3. Statistical analysis

A one-way ANOVA was used to test for differences in ballast volume discharged by different trip type (trans-Pacific and west coast) and ship type (e.g. bulker, containers, etc.) combinations (Table 1). A one-way ANOVA was also used to determine if the geometric mean abundance of coastal zooplankton was different between the different pathways (i.e. exchanged trans-Pacific, exchanged west coast, and unexchanged west coast vessels). Another one-way ANOVA was used to determine if the geometric mean abundance of known NIS was different between the different pathways. Zooplankton densities were log (x + 1) transformed for these analyses to normalize the data and equalize the variance. If the effect tested in an ANOVA was determined to be significant ($\alpha = 0.05$), a Tukey *post hoc* test was used to distinguish which factor levels were different. All statistics were run in Sigma Plot 11.0 (Systat Software, Inc.).

3. Results

3.1. Vessel arrivals

A total of 6288 ships arrived in Puget Sound from January 1, 2006 to December 31, 2007. The vast majority of these arrivals were ships traveling on either intra-coastal (3839, or 61%) or trans-Pacific (2347, or 37%) routes, making up 98.4% of the total arrivals. The remaining ships arrived from South America (1.2%), Atlantic (arriving to Puget Sound via the Panama Canal, 0.3%), and unknown (0.1%) routes.

Patterns of arrival by trip and ship type were largely asymmetrical (Fig. 1A). Each vessel type generally arrived by either trans-Pacific (i.e. bulkers) or west coast (i.e. ATB/ITBs, passenger, reefer, RoRo, and 'other' ship types) routes, not both. Two exceptions were

Table 1
For ships that discharged ballast water, the average, standard deviation (SD), and maximum discharge for each ship type on trans-Pacific and west coast routes.

Ship type	Trans-Pacific				West coast			
	Average (m^3)	Max (m^3)	SD (m^3)	*n*	Average (m^3)	Max (m^3)	SD (m^3)	*n*
ATB/ITB	–	–	–	0	8544	18,581	4527	370
Bulker	19,556	65,879	7294	372	9796	20,450	5584	29
Container	2461	12,915	2171	275	1811	8337	1530	38
General cargo	2150	12,130	2325	32	1186	5106	1251	28
Other	5608	10,980	5208	4	464	1814	382	108
Passenger	–	–	–	0	949	1714	499	34
Reefer	461	979	360	5	242	1672	422	27
RoRo	773	3705	1198	8	1432	5142	2476	4
Tanker	12,134	30,321	9791	36	11,144	57,427	10,554	235

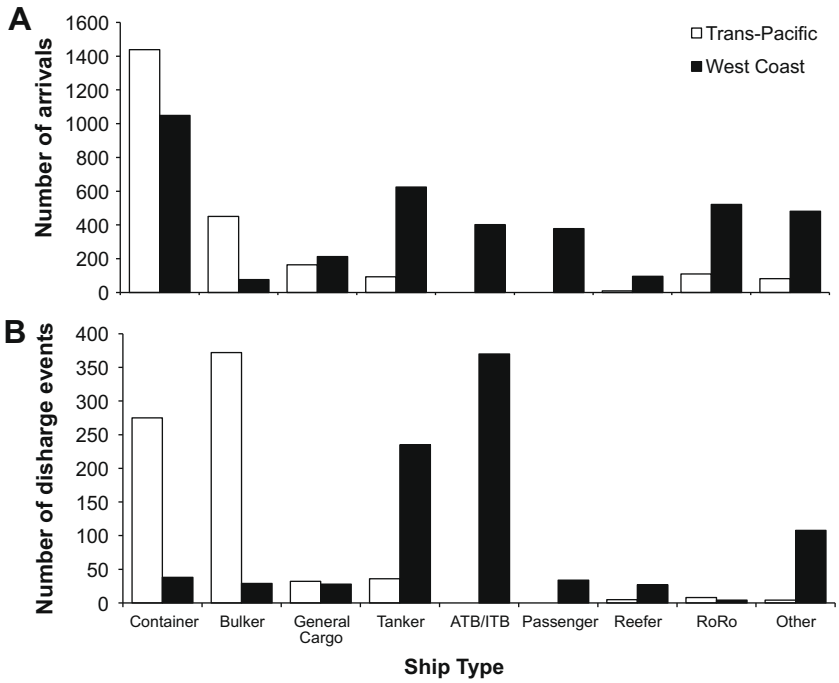

Fig. 1. Number of vessel arrivals (A) and independent ballast water discharge events (B) in Puget Sound from 2006 to 2007, categorized by ship type and route.

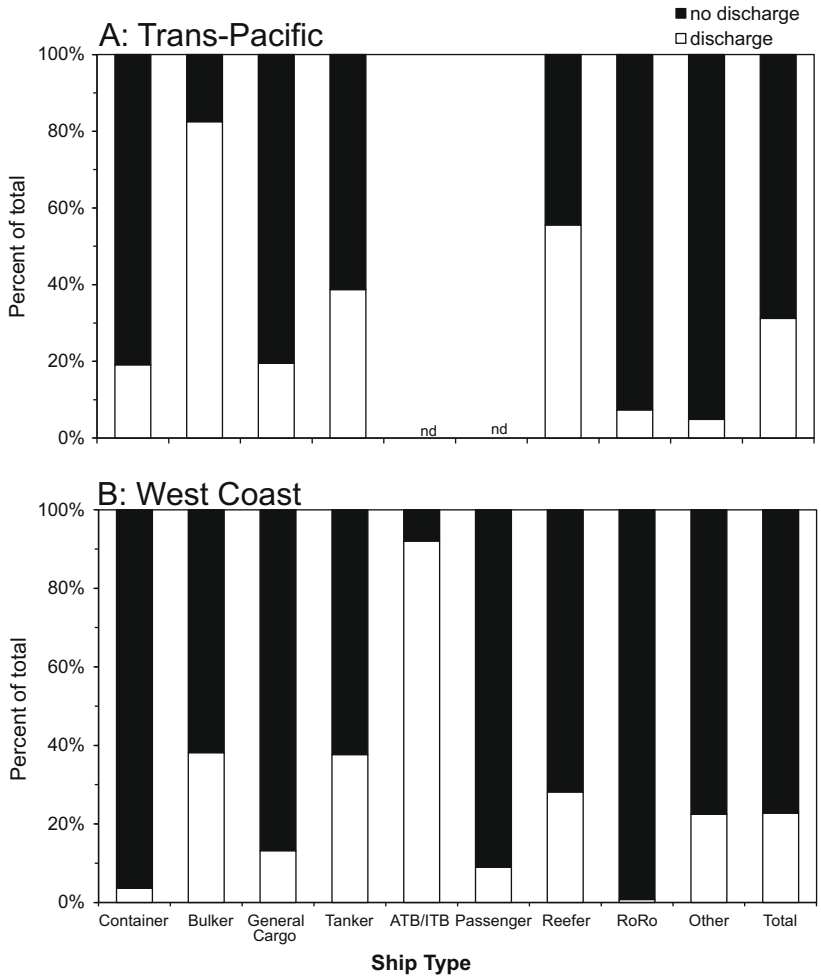

Fig. 2. Percentage of ships on trans-Pacific (A) and west coast (B) trips that discharged ballast water when arriving to Puget Sound.

container and general cargo vessels, which arrived in more similar proportions from trans-Pacific and intra-coastal routes.

Trans-Pacific (23%) and west coast (17%) container ships arrived more frequently to Puget Sound than any other ship type, together accounting for 40% of the total 2006–2007 arrivals (Fig. 1A). Tankers, traveling mainly along the west coast, accounted for 11% of the total arrivals. RoRo, 'other', and bulker vessel types arrived in similar numbers to Puget Sound, each constituting 8–10% of the total. ATB/ITB, passenger, and general cargo vessels each contributed approximately 6% of the total arrivals. Reefer ships arrived infrequently, making up 2% of the total arrivals.

3.2. Discharge frequency

Of the 6288 ships that arrived to Puget Sound in 2006–2007, only 1641 discharged ballast (26%). The remainder (74%) either held their ballast, or arrived with no ballast on board. Of the ships that discharged, 45% arrived from trans-Pacific routes, 53% from west coast routes, and 2% were from other routes.

The ballast water discharge frequency for a given route (i.e. inter- or intra-coastal) was ship type dependent (Fig. 1B). For ships on trans-Pacific routes, containers and bulkers discharged ballast more frequently than other vessel types, making up 31% and 51% of the trans-Pacific discharge events, respectively. For vessels traveling on west coast routes, tankers and ATB/ITBs made up the majority of ballast discharge events (27% and 52%, respectively). For a given ship type, discharge frequency also varied depending on the vessel's route (Fig. 2). For example, 82% of the bulkers on trans-Pacific trips discharged ballast to Puget Sound, while only 38% of bulkers on west coast routes discharged ballast. For ships on west coast routes, ATB/ITBs had particularly high occurrences of discharge to Puget Sound (92%), while container ships had the lowest discharge frequency (4%).

3.3. Per-arrival vessel discharge volumes

Vessels varied significantly in the average volume of ballast discharged to Puget Sound per arrival (Table 1, ANOVA, $p < 0.001$). A Tukey *post hoc* test indicated that bulk carriers arriving from trans-Pacific routes discharged the highest average ballast volumes compared to all other ship types on both west coast and trans-Pacific trips (avg = 19 556 m^3, SD = 7294 m^3, max = 65 879 m^3). When discharging, tankers on both west coast and trans-Pacific routes, and bulkers on intra-coastal routes discharged similar ballast volumes (avg = 11 144, 12 134, and 9796 m^3, respectively, no statistical difference). ATB/ITBs traveling on west coast routes discharged less ballast volume per arrival than foreign bulkers and tankers on both trans-Pacific and domestic routes, but still discharged large average ballast volumes to Puget Sound (avg = 8544 m^3, SD = 4527 m^3, max = 18 581 m^3). By contrast, container, general cargo, passenger, reefer, and RoRo ship types discharged less than 2500 m^3 on average per discharge event.

3.4. Total 2006–2007 ballast discharge

A total of 15.2×10^6 m^3 of ballast was discharged to Puget Sound from 2006 to 2007, for an annual average of 7.5×10^6 m^3. Exchanged trans-Pacific water made up 53% of the 2006–2007 total ballast discharged, or 8.0×10^6 m^3. Vessels carrying exchanged and unexchanged west coast ballast discharged 3.3×10^6 m^3 (22% of the total) and 3.0×10^6 m^3 (20%), respectively, over the same period. The remaining 6.3% of the total ballast volume delivered to Puget Sound was from unexchanged trans-Pacific vessels (3.5%), and exchanged and unexchanged South America (2.4%), Atlantic (0.3%), and unknown (0.1%) routes.

Bulkers carrying exchanged trans-Pacific water were the dominant source of ballast water discharged into Puget Sound, making up >45% of the total (Fig. 3). Tankers and ATB/ITBs on west coast routes also contributed large volumes of ballast (both exchanged and unexchanged), each contributing approximately 20% of the total ballast discharged for 2006–2007. The remaining ship types (container, general cargo, passenger, reefer, RoRo, and 'other') discharged far smaller volumes of ballast to Puget Sound over the same period.

3.5. Estimated number of coastal propagules discharged to Puget Sound

Exchanged trans-Pacific vessels carried far fewer coastal propagules (geometric mean = 27 individuals per m^3, lower 95% CL = 20, upper 95% CL = 37, $n = 229$), compared to exchanged (geometric mean = 269 organisms per m^3, lower 95% CL = 176, upper 95% CL = 410, $n = 114$) and unexchanged (geometric mean = 1222 organisms per m^3, lower 95% CL = 482, upper 95% CL = 3092, $n = 29$) ships on west coast routes (Fig. 4). An ANOVA indicated that these groups were statistically different ($p < 0.001$) and a Tukey *post hoc* analysis showed that each group was distinct from the other ($p \leqslant 0.005$).

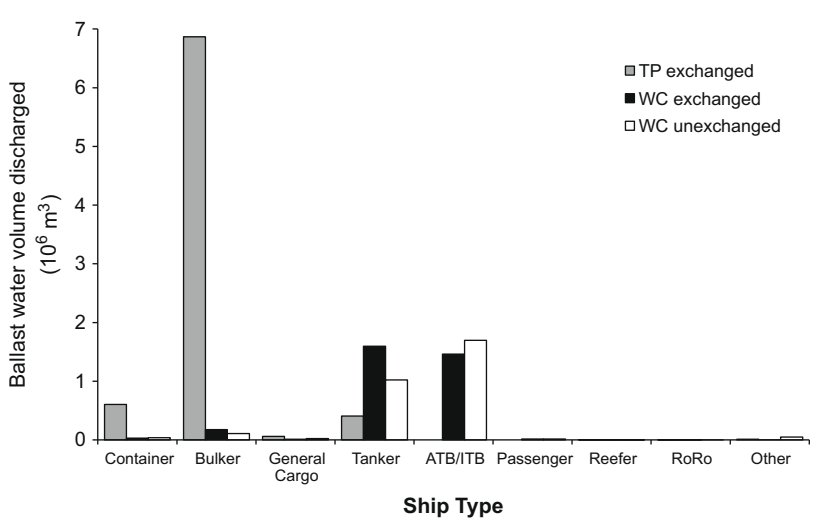

Fig. 3. Total volume of ballast water discharged (m^3) to Puget Sound, 2006–2007, classified by ship type (container, bulker, general cargo, tanker, ATB/ITB, passenger, reefer, RoRo and other), source (TP – trans-Pacific and WC – west coast), and ballast water exchange status (exchanged and unexchanged).

ATB/ITBs and tankers carrying unexchanged ballast on west coast trips delivered the vast majority of coastal propagules to Puget Sound, 2.1×10^9 and 1.3×10^9 coastal propagules, respectively, over the 2006–2007 period (Fig. 5). Thus, while these vectors discharged only 18% the total ballast volume to Puget Sound, they contributed 70% of the coastal propagules released. The next largest contributors of coastal propagules to Puget Sound were tankers and ATB/ITBs discharging exchanged west coast ballast (17% of the total). By contrast, while exchanged trans-Pacific bulkers made up a much greater component of the total ballast volume discharged to Puget Sound (45%), they contributed only 4% of the total number of coastal propagules released there.

3.6. Known NIS propagules discharged to Puget Sound

Twenty-two zooplankton species known to be non-indigenous to Puget Sound (NIS) were identified from the 372 ballast tank samples (Tables 2–4). These species were classified into three categories: (1) not indigenous to the west coast of North America, and native to the Northwest Pacific or Indian Ocean (e.g. only found in Asia, 8 species total), (2) not indigenous to the west coast of North America, but already established elsewhere on the west coast (e.g. native to Asia, but established in San Francisco Bay or the Columbia River, 8 species total), and (3) not indigenous to Puget Sound, but indigenous elsewhere on the west coast of North America (e.g. the Gulf of California, 6 species total).

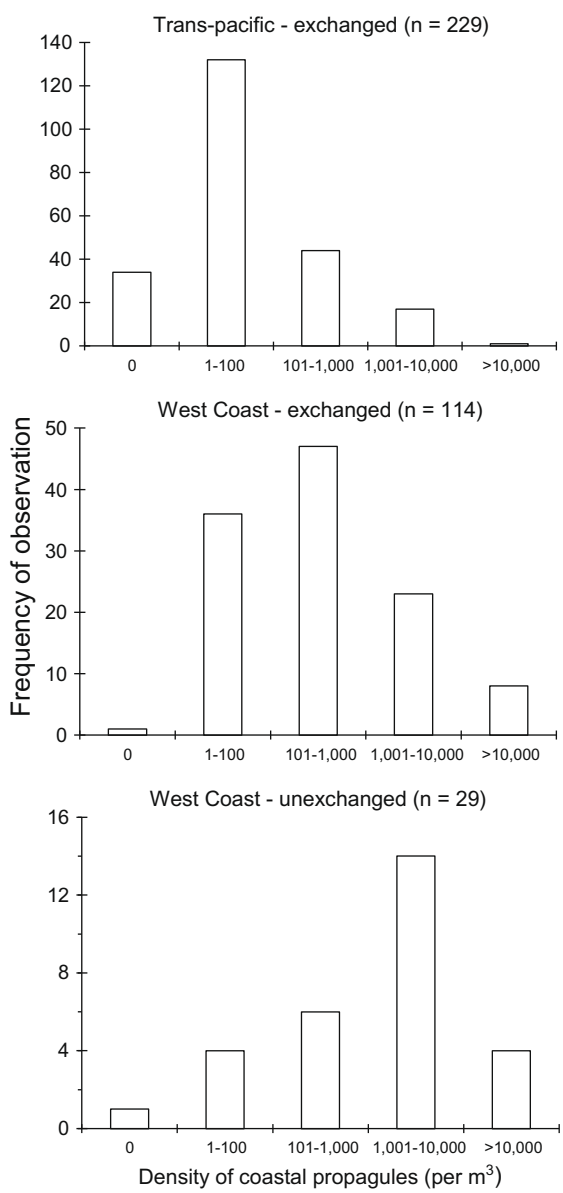

Fig. 4. Frequency histograms of densities of coastal propagules (individuals per m^3) in ballast samples of trans-Pacific exchanged vessels, and west coast exchanged and unexchanged vessels.

In total, the 229 ballast samples from exchanged trans-Pacific ships contained almost twice as many NIS species (19 species) than did those from ships on west coast routes (both unexchanged and exchanged samples, 143 samples, 10 species). There was some overlap in NIS carried by each route. Seven of the 22 NIS species identified were found in both trans-Pacific and west coast routes. Trans-Pacific and west coast ships also had unique occurrences of some NIS. Trans-Pacific ballast tanks contained 12 NIS not found in west coast samples, while west coast ships contained 3 NIS not found in trans-Pacific ships.

The eight NIS species native to Northwest Pacific or Indian Ocean, but not established on the west coast of the North America, were found exclusively in trans-Pacific ballast (Table 2). The three most common species, in order of frequency, included *Calanus sinicus* (overall frequency = 13.1%), *Calanus jashnovi* (3.1%), and *Labidocera rotunda* (1.3%). Five of the eight NIS species in this category were rare *(Acartia hongi*, *Acartia pacifica*, *Labidocera kroyeri*, *Oithona brevicornis*, and *Sinocalanus sinensis*), occurring in only 0.4% of exchanged trans-Pacific samples.

For the eight species non-indigenous to the west coast of the US, but established elsewhere on the west coast, four occurred in both trans-Pacific and west coast samples, three occurred in west coast samples only, and one occurred only in trans-Pacific samples (Table 3). Only two species (*Oithona davisae* and *Pseudodiaptomus marinus*) occurred frequently enough to determine if the mean abundance differed statistically among the different vectors of ballast transport (i.e. exchanged trans-Pacific, exchanged west coast, unexchanged west coast). The geometric mean abundance of *O. davisae* varied significantly among the different ballast vectors (ANOVA, $p < 0.001$), and a Tukey *post hoc* test revealed their abundance declined in the following order: unexchanged west coast ballast > exchanged west coast ballast > exchanged trans-Pacific ballast. In contrast the geometric mean abundance of *P. marinus* did not vary significantly among the ballast water vectors (ANOVA, $p > 0.05$).

Six species considered non-indigenous to Puget Sound but native to other areas of the west coast of North America were found in the ballast samples (Table 4). Three of these species, *Labidocera euchaeta*, *Paracalanus aculeatus*, and *Paracalanus denudatus*, were only found in ballast from ships arriving from trans-Pacific routes (Japan, China, Korea). For those species found in ships on west coast and trans-Pacific voyages, the frequency of occurrence was typically higher in ships on west coast routes (e.g. *Dioithona oculata*, *Parvocalanus crassirostris*), although the difference was small for some species (e.g. *Oithona nana*).

4. Discussion

A major goal in ballast water management is identifying the propagule pressure associated with the variety of vectors discharging water into a given coastal system. This allows managers to focus on management practices that can achieve the greatest risk reduction. To our knowledge this is the first study to estimate the total annual propagule pressure delivered to a coastal system, and simultaneously compare the relative contribution of intra- and inter-coastal pathways to the total propagule supply.

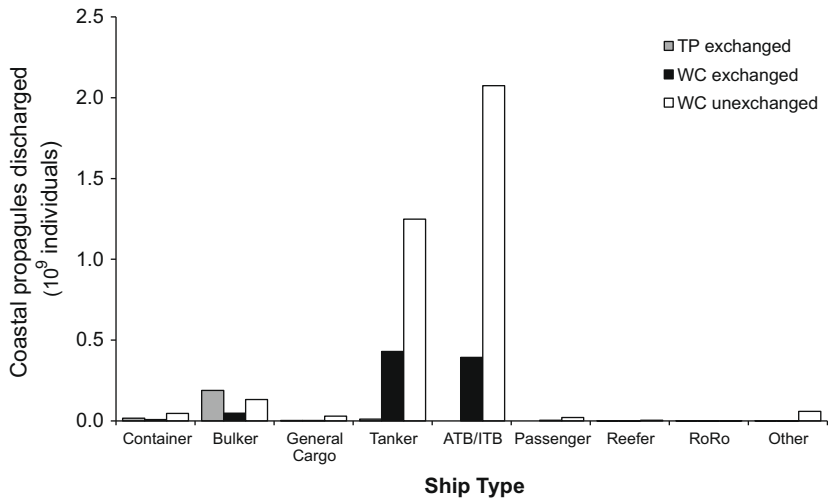

Fig. 5. Estimated number of individual coastal propagules discharged to Puget Sound, 2006–2007, classified by ship type (container, bulker, general cargo, tanker, ATB/ITB, passenger, reefer, RoRo and other), source (TP – trans-Pacific and WC – west coast), and ballast water exchange status (exchanged and unexchanged).

Table 2
Frequency of occurrence, geometric mean density, maximum density, and sample size of zooplankton species not indigenous to Puget Sound, and native to the NW Pacific or Indian Ocean. Samples were collected from the ballast water of ships arriving to Puget Sound, and were classified according to the ship's route and exchange status.

Species	Route	Exchanged ?	Frequency (%)	Geometric mean density (m^{-3})	Max density (m^{-3})	Total *n* for this source	Found in *n* samples
Acartia hongi	Trans-Pacific	Yes	0.4	31	31	229	1
Acartia pacifica	Trans-Pacific	Yes	0.4	1	1	229	1
Calanus jashnovi	Trans-Pacific	Yes	3.1	30	6936	229	7
Calanus sinicus	Trans-Pacific	Yes	13.1	8	285	229	30
Labidocera kroyeri	Trans-Pacific	Yes	0.4	2	2	229	1
Labidocera rotunda	Trans-Pacific	Yes	1.3	6	30	229	3
Oithona brevicornis	Trans-Pacific	Yes	0.4	14	14	229	1
Sinocalanus sinensis	Trans-Pacific	Yes	0.4	0.3	0.3	229	1

Some previous attempts to assess risk associated with ballast discharge relied on either ship arrival rate (Drake and Lodge, 2004) or ship discharge volume (McGee et al., 2006). While these proxies for ballast risk are easier to assess than determining the number of propagules in different ballast vectors, they may not produce an accurate assessment of risk for the variety of ballast

Table 3
Frequency of occurrence, geometric mean density, maximum density, and sample size of zooplankton species not indigenous to Puget Sound, native to the NW Pacific or Indian Ocean, and known to be established elsewhere on the west coast of North America. Samples were collected from the ballast water of ships arriving to Puget Sound, and were classified according to the ship's route and exchange status.

Species	Route	Exchanged ?	Frequency (%)	Geometric mean density (m^{-3})	Max density (m^{-3})	Total *n* for this source	Found in *n* samples
Acartiella sinensis	Trans-Pacific	Yes	0.4	4	4	229	1
	West coast	Yes	3	1	1	114	3
		No	3	14	14	29	1
Limnoithona tetraspina	Trans-Pacific	Yes	0.4	5	5	229	1
	West coast	Yes	12	13	427	114	14
		No	21	92	4716	29	6
Oithona davisae	Trans-Pacific	Yes	34	30	7083	229	77
	West coast	Yes	79	119	39,930	114	90
		No	38	1056	117,113	29	11
Pseudodiaptomus forbesi	West coast	Yes	2	1	1	114	2
		No	21	46	4366	29	6
Pseudodiaptomus inopinus	Trans-Pacific	Yes	1	12	18	229	3
Pseudodiaptomus marinus	Trans-Pacific	Yes	11	11	375	229	26
	West coast	Yes	36	13	4326	114	41
		No	38	35	660	29	11
Sinocalanus doerrii	West coast	No	3	39	39	29	1
Tortanus dextribbatus	West coast	Yes	12	2	15	114	14
		No	17	17	79	29	5

Table 4
Frequency of occurrence, geometric mean density, maximum density, and sample size of zooplankton species not indigenous to Puget Sound but known to be indigenous elsewhere on the west coast of North America. Samples were collected from the ballast water of ships arriving to Puget Sound, and were classified according to the ship's route and exchange status.

Species	Route	Exchanged ?	Frequency (%)	Geometric mean density (m^{-3})	Max density (m^{-3})	Total *n* for this source	Found in *n* samples
Dioithona oculata	Trans-Pacific	Yes	2	28	625	229	4
	West coast	Yes	39	11	573	114	45
		No	14	153	3005	29	4
Labidocera euchaeta	Trans-Pacific	Yes	3	5	165	229	8
Oithona nana	Trans-Pacific	Yes	0.4	10	10	229	1
	West coast	Yes	2	2	3	114	2
Paracalanus aculeatus	Trans-Pacific	Yes	1	3	3	229	2
Paracalanus denudatus	Trans-Pacific	Yes	0.4	3	3	229	1
Parvocalanus crassirostris	Trans-Pacific	Yes	3	5	20	229	8
	West coast	Yes	15	38	3482	114	17

vectors a coastal system receives. Verling et al. (2005) cautioned against using proxies such as ship arrival counts as a predictor of propagule pressure in coastal ports because not all ballast vectors are created equal with respect to propagule supply. Our results confirm this: it is clear that the proportion of ballast delivered to Puget Sound for a given ship type is not simply a function of arrival rate. For example, container vessels were the most frequent ship type arriving to Puget Sound (40% of total arrivals), but contributed only a small fraction of the total ballast discharged (4% of the total).

Our findings also indicate that it is not appropriate to assess risk based solely on the volume of ballast discharged. For example, in Puget Sound such a management strategy would identify trans-Pacific vessels as the dominant risk factor for NIS introduction. However, our results show that ships delivering west coast ballast to Puget Sound discharge by far the largest numbers of coastal propagules. Despite these findings, we suggest that management should not be based solely on the magnitude of coastal propagules released by a given vector. Our study shows that while some vectors (such as exchanged trans-Pacific ballast water) release fewer propagules, the propagule diversity may be higher in that vector, and thus still present the risk of introducing a new species to the region.

The primary ballast water vectors to Puget Sound included ships conducting trans-Pacific trips, and those conducting intra-coastal, domestic voyages (including those traveling from British Columbia ports such as Vancouver). Almost all of the ships arriving from trans-Pacific ports underwent BWE, while only some of the ships moving domestically conducted BWE. The density of coastal propagules was related to these varying ballast water histories: exchanged and unexchanged domestic vessels had average coastal zooplankton densities 1–2 orders of magnitude greater, respectively, compared to exchanged trans-Pacific ballast. Thus, although exchanged bulk carriers conducting trans-Pacific trips contributed by far the largest volume of ballast to Puget Sound in 2006 and 2007 (>45%), they made up only a small fraction of the total coastal organism propagule pressure (4%). Two ship types, ATB/ITBs and tankers, moving unexchanged ballast water on west coast routes discharged less ballast volume to Puget Sound (together accounting for 18% of the total ballast discharged) but delivered far more coastal organisms (>70% of the total). These findings demonstrate that managing ballast from intra-coastal ship traffic should be a high priority in order to reduce the risk of secondary spread of NIS on the west coast of North America.

The densities of coastal and known NIS organisms in the ballast of ships on west coast routes far exceeded those of trans-Pacific routes for several reasons. First, some ships on west coast routes did not conduct BWE. Most of these ships ballasted in California ports, where densities of coastal propagules are high, and NIS are diverse (Simkanin et al., 2009). Second, ships on domestic routes have much shorter voyages (2–3 days) compared to trans-Pacific vessels (12–14 days), reducing in-transit mortality (Cordell et al., 2009). For example, Verling et al. (2005) found that greater reductions in plankton abundances occurred during trans-oceanic voyages than during either Pacific or Atlantic coastwise voyages. Third, those vessels on coastal routes that performed BWE did so directly on or near the 50 nm line (from shore) as required by state law (Cordell et al., 2009). Ships operators typically do not go further offshore than required, because of the cost in fuel and time. Vessels on trans-Pacific routes, however, performed BWE at least 200 nm from shore, as required by US federal law, and their exchange positions occurred across a broad swath of the North Pacific (Cordell et al., 2009). Domestic ships performing more shoreward BWE may entrain coastal organisms advected offshore by mesoscale oceanographic features such as anticyclonic eddies and large river plumes (Mackas and Galbraith, 2002; Peterson and Peterson, 2008). The extent to which coastal species are advected and persist in offshore waters (50 nm or greater) is not currently well known. Finally, since exchange is not 100% effective, the initial concentrations of zooplankton in the ballast source port plays a role in determining the number of coastal propagules remaining after BWE. We did not conduct sampling of source ports, so we cannot assess the degree to which the differences in coastal propagule abundance between domestic and foreign arrivals is based on ballast source densities.

Like Puget Sound, many ports around the world receive ballast from vessels conducting intra- and inter-coastal voyages. Ballast water management actions undertaken to protect coastal ecosystems have emphasized protecting against ballast water introductions from foreign vessel arrivals. Here we show that ships arriving to Puget Sound from domestic ports comprise a greater risk (in terms of propagule pressure), particularly if those domestic ports are nearby (reducing the transit time, and associated propagule mortality) and heavily invaded.

When considering propagule pressure resulting from ballast discharge, it is also important to examine the diversity of coastal propagules. Propagule pressure is only one, albeit important factor determining whether or not a NIS establishes itself: a range of other biological and physical factors affect an invader's success throughout the stages of an invasion (Catford et al., 2009). Thus, it follows that the higher the species diversity in a ballast water source, the more chance there is that a species in that inoculant pool will be adapted to the conditions particular to the receiving environment. In this study we found that trans-Pacific ballast contained almost twice as many known NIS zooplankton species, as compared to ships containing west coast ballast. The more diverse inoculant pool associated with trans-Pacific ballast reflects that foreign ballast contains more species considered non-indigenous to Puget Sound, while closer domestic ports, which share a biogeo-

graphic province, have species assemblages more similar to those in Puget Sound. It is also possible that the greater number of NIS species found in trans-Pacific compared to west coast routes reflects differences in sampling effort between ships on these routes. A greater fraction of our samples came from ships on trans-Pacific routes (62%) compared to ships on west coast voyages (38%), and the larger sampling effort from trans-Pacific ships may increase the likelihood of finding rare NIS. Eight of the 19 NIS species found in trans-Pacific vessels were rare (frequency of occurrence <1%).

Our results also show that domestic and foreign routes can both be considered vectors of introduction for a subset of the NIS found (7 of the 22 NIS species found). However, for some species (e.g. *O. davisae*) that occurred in both routes, mean and maximum densities were typically much higher in ships arriving from other domestic ports. This is likely related to the short voyage durations of coastal compared to trans-Pacific trips (Cordell et al., 2009). Thus, ballast discharged from ships on intra-coastal routes is more likely to introduce species that are already established elsewhere on the west coast of the United States, while ballast from ships on trans-oceanic routes may result in more primary (i.e. new) introductions.

These results call into question ballast management laws that allow discharge of unexchanged water from vessels conducting coastwise voyages. In some cases ships on domestic voyages do not complete a BWE because sea conditions preclude a safe exchange (Ruiz and Reid, 2007). In other cases, exemptions to ballast exchange requirements assume that designated "common waters" are contiguous and have the same biota, and thus do not pose a risk of introducing NIS. In Washington state a vessel may discharge ballast water without BWE, if that water originated solely within a common waters zone that includes the waters of Washington state, the Oregon portions of the Columbia River system, and the internal waters of British Columbia south of latitude 50° N. However, our data shows that unexchanged coastal water often contains the largest numbers of coastal propagules. While many of these coastal propagules may be native to Puget Sound, they may also be comprised of NIS species from invaded source areas such as the Columbia River. Several NIS zooplankton have successfully invaded the Columbia River and other coastal estuaries within the Washington common waters region and have been shown to be transported from there to Puget Sound in ballast, but they are not currently established in Puget Sound (Cordell et al., 2007, 2008). Allowing ships to take on and discharge ballast within common waters zones may result in further 'hopscotching' of viable NIS propagules from one port to another along a coast, particularly because the voyages between common waters ports are short. Thus, we recommend that any common waters exemptions for ballast water exchange or treatment be re-examined to evaluate these risks.

Finally, it is important to remember that while propagule pressure plays an important role in invasion success, the likelihood that an introduced species becomes established also depends on many species-specific factors (e.g. reproductive habits, seasonality, feeding behavior) and biotic and abiotic characteristics of the recipient environment that affect its invasibility (Catford et al., 2009). This study focused solely on better defining the propagule pressure component of the NIS risk equation for Puget Sound and we did not attempt to assess the invasibility of the recipient waters or of any one species. Propagule supply data should be combined with data on target species and/or the biological and physical characteristics of recipient waters to generate a more complete risk model. While these types of integrative models are relatively rare, and data needed to generate them often lacking, they will be important tools to help resource managers more fully manage the risk associated with ballast water discharge (Leung and Mandrak, 2007; Catford et al., 2009).

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