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Quantifying potential propagule pressure of aquatic invasive species from the commercial shipping industry in Canada

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ABSTRACT

We quantify and compare different measures of potential propagule pressure (PPP) of aquatic invasive species (AIS) from commercial vessels in Canada. We used ship arrivals and ballast water discharge volumes as proxies for PPP from ballast water organisms, and wetted surface area (WSA) as a proxy for hull fouling PPP, to determine their relative contributions to total PPP. For three regions studied, PPP proxies correlated significantly across ports and some vessel categories. Relative contributions of ship arrivals, ballast discharge, and WSAs to PPP, evidenced by non-significant correlations across these measures, varied across regions, ports, vessel types, and seasons. Flow-through (dominant on east and west coasts) and empty-refill (in Great Lakes-St. Lawrence region) were the major ballast water exchange methods employed by the vessels surveyed. These methods have different biological efficacy for AIS removal, influencing PPP. Our study illustrates benefits and limitations of using different PPP proxies to estimate invasion risk.

1. Introduction

Shipping is the primary source of unintentional introductions of aquatic invasive species (AIS) in North America (Ruiz et al., 2000). The impacts of AIS are far-ranging, and include the depletion of fisheries and other resources and secondary economic impacts stemming from human health effects and loss of biodiversity (Chapin et al., 2000; RN Mack et al., 2000; Raaymakers, 2002). The uptake and discharge of ballast water for ship stabilization purposes is one of the principle mechanisms of transporting AIS (Ruiz et al., 2000). Recent studies, however, demonstrate that hull fouling, which occurs when organisms attach to the vessel hull and other surfaces, are also an important source of AIS (Coutts and Taylor, 2004; Davidson et al., 2009) and can even pose a greater risk of species introductions than ballast water (Drake and Lodge, 2007). Other possible commercial shipping vectors of AIS are resting egg stages of various organisms that reside in ballast water sediments (Bailey et al., 2005; Briski et al., 2010).

Factors involved in the establishment success of invasive species include the characteristics of the recipient community or of the species itself, availability of spatial or nutrient resources, and previous invasion success (Colautti et al., 2008). One of the more recently-studied predictors of establishment success is propagule pressure, with various definitions encompassing the number of individuals in an introduction event, and the frequency of these events (Drake and Lodge, 2006; Elton, 1958; Lockwood et al., 2009; Simberloff, 2009), as well as the genetic variation among propagules (Ricciardi et al., 2011). While several studies have demonstrated a positive relationship between propagule pressure and establishment success i.e. (Duggan et al., 2006), the nature of this relationship is as yet undetermined (Colautti et al., 2006; Kolar and Lodge, 2001 and literature therein).

Propagule pressure can be further classified as potential, actual or effective. The potential propagule pressure of AIS (PPP) to a given site is a measure of the introduction effort; it is useful in the absence of AIS abundance data. For ballast water organisms, PPP can be defined as the frequency and volume of ballast discharge, assuming that the number of AIS is proportional to the volume of ballast discharge. Actual propagule pressure is a measure of the number of organisms being introduced, which can be determined by enumerating organisms in ballast water, while effective propagule pressure is a measure of the proportion of introduced organisms that survive the entrainment process and produce viable offspring. The wetted surface area (WSA) of a vessel is an

Abbreviations: AIS, aquatic invasive species; PPP, potential propagule pressure; FT, flow-through exchange; MOE, mid-ocean exchange; SWF, saltwater flushing.

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analogous measure of PPP for hull fouling organisms and includes not only the hull, but other potentially colonizable surfaces such as propellers, rudders, sea chest gratings, bilge keels, bulbous bow, anchors and rope guards (Coutts and Taylor, 2004; Davidson et al., 2009).

Worldwide, ballast is generally managed by mid-ocean exchange (MOE), whereby ballast water taken up at a port, typically assumed to be from a coastal origin, is replaced by presumably more saline ocean water. Ballast water organisms are thus theoretically killed by osmotic stress upon ballast water discharge. While other treatment technologies (McCollin et al., 2007; Quilez-Badia et al., 2008) are currently under development, many are not yet considered economically viable or technically feasible for most vessels (Drake et al., 2005; Ruiz and Reid, 2007). Canada's Ballast Water Control and Management Regulations (effective June 28 2006), requires all vessels entering Canadian waters to conduct MOE beyond 200 nautical miles from shore, in waters at least 2000 m deep, provided it is safe to do so (Transport Canada, 2006). Various exceptions to the regulations include the exemption of transoceanic "no ballast on board" or NOBOB vessels destined for the Great Lakes Basin. These vessels do not carry ballast on board but have residual, often unpumpable ballast and sediment at the tank bottom. In the Great Lakes-St. Lawrence region, the majority (90%) of incoming arrivals are NOBOB (no ballast on board) ships (Grigorovich et al., 2003; Johengen et al., 2005), and subsequently are exempt from MOE. Because the ballast in these types of vessels are typically not exchanged and can be potentially transferred to ports during partial ballasting and de-ballasting, they pose a risk of AIS introductions. NOBOB vessels bound for the Great Lakes basin must therefore undergo saltwater flushing (flushing the unexchanged ballast and sediments in tanks with ocean water so that the salinity of the resulting mixture is greater than 30 parts per thousand) at least 200 nautical miles from shore before entering Canadian waters.

In our study we quantified the PPP of AIS from shipping activities to all major Canadian shipping ports in the Atlantic, Great Lakes-St. Lawrence, and Pacific shipping regions. To our knowledge, this is the first such comprehensive analysis of propagule pressure on a national scale (but see DiBacco et al. (2011) for an analysis of ballast water zooplankton densities for vessels transiting Port Metro Vancouver and several East coast ports). Since the introduction of Canada's ballast regulations, reporting of ballasting activities has been mandatory for all vessels entering Canadian waters (Transport Canada, 2006). Using this shipping data, we estimated PPP by using ballast discharge volumes as a surrogate for the direct sampling of propagules, and estimated PPP of hull fouling organisms by determining the total wetted surface area of the vessels in the ballast water database.

We compared vessel arrivals, total wetted surface area and ballast discharge across shipping ports and vessel categories in the Atlantic, Great Lakes-St. Lawrence and Pacific shipping regions. We determined the shipping ports where the combined PPP of hull fouling and ballast organisms is greatest. We also investigated vessel arrivals and ballast discharge patterns across time. WSA was not included in this seasonal analysis as we lacked the data to determine the distribution of WSA across time.

With respect to ballast water, we compared ballast management methods across shipping regions. The two widely used methods of MOE are empty-refill (ER) and flow-through (FT), also called dilution. In the former method, ballast is pumped out of a tank and subsequently refilled with ocean water. In the latter (FT), ballast is pumped out while ocean water is simultaneously pumped in. An alternative management method is saltwater flushing (SWF), as described above. Each method has a different efficacy, so knowledge of which methods are dominant has implications for our understanding of PPP across the three shipping regions. We also determined the origin of ballast water for the three shipping regions, to gain an understanding of the source of PPP from ballast organisms.

2. Methods

2.1. Ballast water and vessel arrival data source

Shipping data were obtained in confidence from the Canadian Ballast Water Information System (BWIS), developed by the Department of Fisheries and Oceans Canada (DFO) and Transport Canada (TC). Prior to the implementation of the ballast regulations in June 2006, reporting of ballasting activities was only mandatory for some regions (e.g. Vancouver Port Authority (now Port Metro Vancouver) and Great Lakes ports) and voluntary for most. We use data from forms submitted between November 2006 and October 2007, as this twelve month period represented the most comprehensive annual record of shipping data available for our analysis after the Canadian ballast water regulations were implemented. In 2007, there was a 95% rate of compliance with the new regulations in the Great Lakes-St. Lawrence region, based on an inspection program examining all ships entering the region (Great Lakes St. Lawrence Seaway, 2008). We thus assume that the data in the BWIS are representative of actual ballasting activities in Canada, and that there has been time for the shipping industry to adapt to and comply with the new regulations.

The data on the forms included ballast (volume taken up, exchanged and discharged), port names (arrival, ballast source, and discharge), date of arrival, vessel category, exchange method, and gross tonnage. Data in the BWIS were further analyzed using BallastScope, a query tool developed by DFO. The database includes both BOB and NOBOB vessels transiting the Great Lakes-St. Lawrence Region.

Data were grouped according to three major shipping regions in Canada: the Atlantic coast, GLSL and Pacific coast. Ports east of Quebec City were classified as Atlantic ports, as the limit of saltwater intrusion is usually at Quebec City or at Île D'Orléans, just west of Quebec City (Gobeil, 2006). In the Pacific region, Port Metro Vancouver sub-ports and regions (Fraser Port, Vancouver Port-Burrard Inlet, Roberts Bank, Port Moody) were treated separately in our analysis as they are geographically distinct and ballast water data were available for each sub-port.

2.2. Estimating wetted surface area

Since neither wetted surface area (WSA in m^2) values nor vessel dimensions were available for vessels in our databases, we obtained average WSAs for each vessel category, then calculated WSAs for individual vessels based on its size relative to other vessels in the same category. Many vessels that pose a risk of hull fouling, such as small fishing vessels or recreational boats, were not recorded in the database; as they typically do not discharge much ballast water, no reporting forms were submitted for these vessels.

We obtained average WSAs for several ship categories from published results in Davidson et al. (2006), using the program Data Thief to extract relevant data. The formula used by the authors includes measures of vessel length, draft, and breadth, and various coefficients (presented in more detail in the supplementary data). Davidson et al. calculated WSAs for 5801 vessels arriving to ports on the Lower Columbia River, USA, for vessel categories including bulk carriers, tankers, containers, car carriers ("roro" vessels in our analysis), barges, and "Other", which included passenger, research, naval, and fishing vessels, in addition to cable ships and other private craft. As we lacked data to repeat these calculations for our vessel data set, we used these published average WSA values for the ships in our arrival database, obtained from the BWIS.

For WSAs for individual ships, we modified these average values based on the ship's size (measured by gross tonnage) in relation to the variation in gross tonnage within vessel categories, using the following formula:

$$WSA = \mu_{wsa} + m\sigma_{wsa}$$

where μ_{wsa} is the mean WSA for the vessel category, σ_{wsa} is the standard deviation of WSAs for the vessel category, and m is a measure of the ship's size relative to the vessel category given by the following:

$$M = \frac{GT - \mu_{GT}}{\sigma_{GT}}$$

where GT is the ship's gross tonnage value, μ_{gt} is the mean gross tonnage within the vessel class, and σ_{gt} is the standard deviation. Thus m can be negative and is effectively an individual vessel's gross tonnage relative size in its category, measured in number of standard deviations from the mean.

Average WSAs were not available for several vessel categories (chemical carriers, general cargo, reefer and passenger vessels). For these categories, we inferred WSA values from the categories represented in Davidson et al.'s (2006) study using our best estimates of the similarity of vessel categories in terms of mean gross tonnage and vessel shape. As only five vessels in the database were categorized as barges and were likely under-reported, we did not use the mean WSA for barges.

In applying these calculations, we assume that the mean WSA values in Davidson et al.'s (2006) data set are applicable to vessels in our data set—that the vessels arriving to the lower Columbia River are of similar size and shape to those arriving to Canadian shipping ports in our study regions. In applying our gross tonnage modifier to the mean WSA values, we also assume a linear, 1:1 relationship between WSA and gross tonnage.

Arrival and WSA data were categorized as: Class A – values reported in the shipping region with a specific port reported, and Class B – reported arrivals to a shipping region, without a specific arrival port reported. Another class of vessels were those that arrived to ports outside Canada – these were not included in the analysis.

2.3. Data verification and analysis

Possible sources of error in the shipping data include non-compliance (i.e. forms were not submitted), and entry errors, which occurred when data was transferred incorrectly from the reporting forms to the BWIS (such as typographical errors, duplicate entries, and incomplete or inaccurate transfer of data due to illegibility of the forms).

Another source of error was incorrect reporting of data on forms, such as incomplete entries. Many records indicated vessels had arrived at a Canadian port with ballast in tanks, but did not report any ballast discharge on the reporting form. Possible reasons for this include: (1) ballast was discharged at sea; (2) the vessel was transiting several ports (and thus discharged a small amount of ballast, loaded some cargo, and repeated this at another port); or (3) the destination port was unknown at the time the forms were required to be submitted (particularly in the case of the GLSL region).

While we could not remove these types of errors completely from the data before our analysis, several measures were taken to reduce their numbers. First, ship arrival dates were verified by a second person, and duplicate entries were removed. We conducted another verification of reported ballast water volumes by identifying outliers and determining whether it was likely that they were typographical errors. If so, we corrected the total ballast discharge from a particular vessel by using the average amount of ballast discharged per tank. Approximately 12 vessel discharges were corrected by this method.

We analyzed our data using a number of assumptions: (1) if no ballast discharge port or discharge date were given we assumed it was the same as the arrival port or arrival date; (2) if no ballast source port/date was given, it was assumed to be the same as the last port/date; and (3) on some forms, discharge was reported for particular tank(s) but no volume was given (13,822 entries, or 65% of the 39,010 total entries, 99.9% of which exchange had been indicated). A source volume was listed for 88% of the tank entries. In these cases, the discharge volume was assumed to be equivalent to the uptake volume for the particular tank – approximately 9400 tank entries were adjusted this way.

We used S-Plus version 8.0 software for statistical analyses (Insightful Corp, 2007).

3. Results

3.1. Potential propagule pressure across shipping ports

The total number of vessels, wetted surface area and associated ballast discharges arriving to the Atlantic (40 ports), Great-Lakes St. Lawrence (21 ports), and Pacific (23 ports) region are summarized in Fig. 1. The three regions were similar in terms of number of vessel arrivals, but the Pacific region received the highest number (4129 arrivals). By WSA, the three regions were also quite similar but the Atlantic region received the highest percentage of WSA (43%). By ballast, there was a much greater difference between the regions- the Atlantic region received considerably higher ballast volumes (2.3×107 t) than the Pacific region (1.6×107 t), and with the GLSL region receiving a much lower volume than both (1.7×106 t) (see supplementary data for maps of ballast discharge volumes in each region).

The numbers of vessel arrivals, WSA, and ballast water discharges for each port considered in our analysis are summarized in the supplementary data. Ports with the highest percent total of WSA for the region did not always receive the most ballast, e.g. Halifax and Come by Chance in the Atlantic, and Montreal and Quebec in the GLSL. Ports that had a higher proportion of WSA relative to arrivals included Argentia, Canaport, Port Alfred and Sidney in the Atlantic region. Ports with the highest proportion of ballast discharge relative to arrivals included Meldrum Bay and Sault Ste. Marie in the GLSL.

Overall, ports that received the highest quantities of ballast water and hull fouling included Point Tupper, Come By Chance, Halifax, Saint John and Sept Îles for the Atlantic region; Quebec, Montreal, Thunder Bay and Sorel for the Great Lakes St.-Lawrence region; and Vancouver, Roberts Bank, Prince Rupert and Fraser ports for the Pacific region.

The number of arrivals and volume of ballast discharge were significantly correlated across ports in each of the shipping regions (Table 1) Spearman's $\rho = 0.81$, 0.75 and 0.68, $p < 0.01$ for the Atlantic, GLSL and Pacific shipping regions, respectively). Arrivals and WSA were highly correlated for the Pacific region (Spearman's $\rho = 0.87$, $p < 0.0001$), but the correlations were lower for the Atlantic and GLSL region (Spearman's $\rho = 0.73$ and 0.76, respectively, $p < 0.0001$). Correlations between WSA and ballast discharge were lower across all three regions (Spearman's $\rho = 0.73$, 0.57 and 0.67, $p < 0.01$).

We tested differences between propagule pressure type across ports, using the percent totals for arrivals, WSA and ballast water discharge. No significant relationship was found between arrivals, WSA and ballast discharge across ports (Atlantic: χ^2 (76, $N = 117$) = 81.7, $p > 0.05$; GLSL: χ^2 (40, $N = 63$) = 55.2, $p > 0.05$; Pacific: χ^2 (44, $N = 69$) = 56.6, $p > 0.05$).

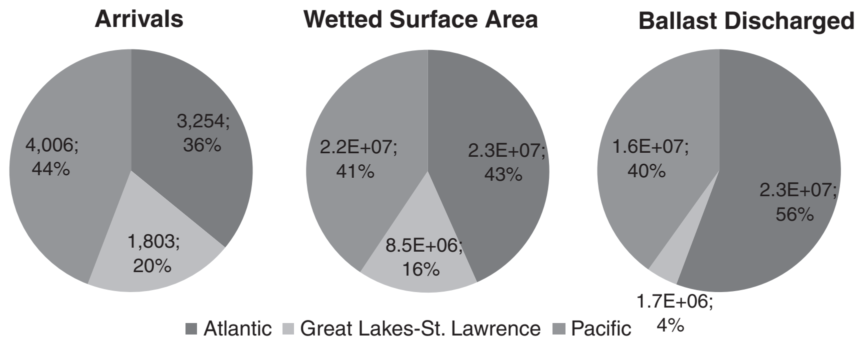

Fig. 1. Total number of vessel arrivals, wetted surface area (mean value, m^2) and volume of ballast water discharged (t) to three Canadian shipping regions from November 1, 2006 to October 31, 2007.

Table 1
Spearman's correlation values for arrivals, WSA; arrivals, ballast; and WSA, ballast across shipping ports and across vessel categories in three major shipping regions. All correlations were significant ($p < 0.05$), with some exceptions which are marked with 'ns'.

Shipping region	Arrivals, WSA	Arrivals, ballast	WSA, ballast
Correlations across ports			
Atlantic	0.73	0.81	0.73
Great Lakes-St. Lawrence	0.76	0.75	0.57
Pacific	0.87	0.67	0.67
Correlations across vessel categories			
Atlantic	0.93	0.64	0.52^{ns}
Great Lakes-St. Lawrence	0.83	0.98	0.79
Pacific	0.98	0.52^{ns}	0.43^{ns}

3.2. Potential propagule pressure across vessel categories

Arrivals, wetted surface area, and ballast discharge were significantly correlated across vessel categories within each of the three regions (see Spearman's ρ values in Table 1, $p < 0.05$).

For each region, bulkers and tankers accounted for the majority of ballast water discharge (Table 2). In the Atlantic region, bulkers and tankers together made up roughly half of arrivals (54%) and WSA (57%). However, they accounted for the majority (95%) of ballast discharge. In contrast, in the GLSL region, the combined number of arrivals and WSA from bulkers and tankers (47.2% and 52.8%) were more similar to the share of ballast discharged from these vessel categories (67.2%). In the Pacific region, bulkers made up roughly a third of arrivals and WSA (37 and 33%, respectively), while they accounted for the majority (82%) of total ballast discharge. Fewer tankers arrived in the Pacific (6% of total) compared to the other regions (27% in the Atlantic region and 21% in the GLSL region).

Another important vessel category was container ships, which contributed 29% of total arrivals, 35.4% of total WSA, and 12% of the total ballast discharged in the GLSL. Container ships were the second and third highest sources of WSA for the Pacific and Atlantic regions, respectively. In contrast, only 0.3 and 1.7 % of total annual ballast discharged was associated with container arrivals in the Atlantic and Pacific.

3.3. Potential propagule pressure across time assessed with ballast water data

The correlation between the number of arrivals and the total volume of ballast water across months were significantly higher for the Atlantic and Pacific regions (Spearman's $\rho = 0.9$, $p < 0.001$; and $\rho = 0.82$, $p = 0.01$, respectively) than for the GLSL shipping region (Spearman's $\rho = 0.64$, $p = 0.049$) (Fig. 2). Total volumes of discharge and number of arrivals varied between regions, as did seasonal patterns of discharge and arrivals. Shipping activity decreased from May to July for the Atlantic region, but increased in the following months of August and September. In the GLSL region, shipping activity was highest from August to October, approximately corresponding to the ice-free shipping season. In the Pacific region, shipping activity was relatively evenly distributed through the months, although it decreased slightly during winter.

The number of arrivals in the Pacific region was similar in winter, spring and summer. The Pacific region experienced a summer peak in arrivals, whereas the Atlantic had a marked downturn. The Great Lakes region generally received fewer arrivals than the other two regions, with the lowest number of arrivals occurring in December, January and February, corresponding to the St. Lawrence Seaway's non-navigable season (Great Lakes St. Lawrence

Table 2
Arrivals, wetted surface area, and ballast discharged (% total) by vessel category.

	Bulker	Tanker	Other	General Cargo	Container	Chemical	Roro	Combo	Passenger	Reefer
Atlantic										
Arrivals	26.9	27.2	4.1	8.9	18.6	1.5	6.5	0.6	4.6	1.3
WSA	28.9	28.1	2.3	2.6	25.0	1.4	4.7	0.6	6.2	0.2
Ballast	39.6	54.9	1.9	1.6	0.3	1.1	0.6	0.1	0.0	0.0
Great Lakes-St. Lawrence										
Arrivals	26.6	20.6	1.7	17.0	27.8	3.0	0.5	0.5	2.3	0.0
WSA	30.3	22.5	1.0	4.2	35.4	2.8	0.3	0.2	3.2	0.0
Ballast	47.9	19.3	8.8	7.2	12.2	3.6	0.7	0.2	0.1	0.0
Pacific										
Arrivals	37.1	6.0	5.0	14.1	16.9	2.9	7.8	2.4	7.8	0.0
WSA	33.4	4.7	2.6	6.5	28.7	2.1	5.5	0.6	15.9	0.0
Ballast	81.9	3.7	5.5	5.0	1.7	0.4	0.8	1.0	0.0	0.0

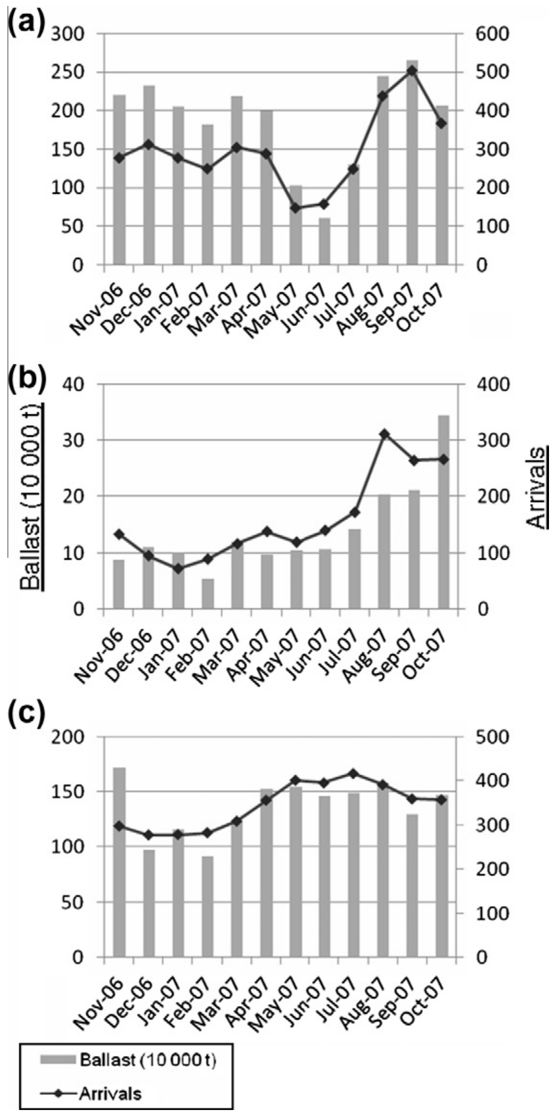

Fig. 2. Vessel arrivals and ballast discharged in Canada between November 2006 to October 2007 for the (a) Atlantic, (b) Great Lakes-St. Lawrence and (c) Pacific shipping region. Solid bars indicate ballast discharge (10,000 t), and the solid line indicates the number of monthly arrivals.

Seaway, 2008). The amount of ballast discharged in this region followed a more variable pattern, and was lowest between November to February, and April.

In terms of ballast discharged, the Atlantic region received the greatest volumes overall, but was exceeded by the Pacific region throughout April to July.

3.4. Management of ballast water across shipping regions

Results of our analysis showed that ballast water management methods were similar for ships discharging ballast in the Atlantic and Pacific shipping regions (Fig. 3). 65% and 67% of the ballast discharged had been exchanged by the FT method, while 35% and 32% had been exchanged by the ER method for the Atlantic and Pacific, respectively. For the Great Lakes, 37% and 58% of ballast had been exchanged via the ER and FT methods, respectively. Another 5.5% was classified as "alternative", while no vessels selected SWF as a method. It is possible that exchange methods may have been misclassified as "alternative" when SWF was actually conducted.

3.5. Ballast water origin across shipping regions

Ballast water origins for each shipping region are listed in Table 3. Source ports for each shipping region are illustrated in Fig. 4. In the Atlantic region, 64% of ballast originated from coastal ports along the eastern coast of the US, and 6.2% originated from Canada. The rest originated from various European ports. In the Great Lakes-St. Lawrence, about 40% of discharged ballast originated from the US (22.5%) and Canada (19.3%), with the rest coming from European ports. In the Pacific region, ballast origin was dominated by northeast Asian ports (47.2%, 11.7% and 10.4% from Japan, South Korea and China, respectively). 14.2% originated from ports on the west coast of the US, while the rest originated from various ports in Canada, Mexico, South and Central America, Cuba, and Southeast Asia.

4. Discussion

4.1. Data quality

We made a number of assumptions about our data in order to conduct our analysis, including the assumption that all information was correctly reported and inputted. Input error was reduced via data verification at Transport Canada, but the accuracy of the actual reporting is unknown. Other studies (BMT Fleet Technology, 2006a,b,c)have reported inconsistencies in shipping databases by different agencies, suggesting a "significant gap between the ship movements recorded by administrative bodies and the actual ship movements." Their analysis took place prior to mandatory reporting requirements, however. Thus, the data from the reporting forms used in our analysis were the most accurate records of ballast water volumes after implementation of the ballast water regulations that were available to the authors at the onset of our research.

Because many of the ballast water reporting forms were incomplete, we lacked ballast discharge volumes for many vessels and thus assumed that the volume of ballast taken up at the source port was equivalent to what was discharged. While not all vessels discharge all the ballast in their tanks, a subset of the forms for which we had complete ballast water data showed that the majority of vessels had indeed discharged roughly the same volume that was taken up at the source port. To avoid making these assumptions, accurate reporting of ballast discharge volume and other fields in the ballast water reporting forms are important for future analyses of propagule pressure from the commercial shipping sector.

To determine the representativeness of our data, we compared our results from our study to previous shipping analyses for Canadian coastal regions. Several of these other studies use different

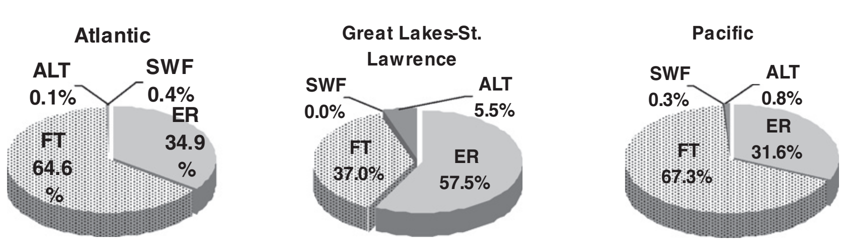

Fig. 3. Ballast management methods in major Canadian shipping regions. ALT = alternative exchange method, ER = empty-refill, FT = flow-through, SWF = saltwater flushing.

Table 3
Origin of ballast water discharged to the Atlantic, Great Lakes-St. Lawrence and Pacific region.

Atlantic			Great Lakes-St. Lawrence			Pacific		
Origin	Volume (1000 t)	% Total	Origin	Volume (1000 t)	% Total	Origin	Volume (1000 t)	% Total
USA	14471	63.9	USA	380	22.5	Japan	7711	47.2
Netherlands	2136	9.4	Canada	325	19.3	USA	2316	14.2
UK	1763	7.8	UK	207	12.2	China	1902	11.7
Canada	1399	6.2	Belgium	82	4.9	South Korea	1693	10.4
Spain	448	2.0	France	72	4.2	Canada	202	1.2
Belgium	280	1.2	Netherlands	68	4.0	Mexico	167	1.0
France	245	1.1	Spain	50	3.0	Taiwan	128	0.8
Denmark	198	0.9	Italy	50	2.9	Philippines	63	0.4
Germany	175	0.8	Denmark	29	1.7	Guatemala	40	0.2
Puerto Rico	91	0.4	Ireland	27	1.6	Chile	31	0.2
Italy	83	0.4	Germany	24	1.4	El Salvador	30	0.2
Ireland	73	0.3	Israel	10	0.6	Costa Rica	20	0.1
Indonesia	68	0.3	Russia	9	0.6	Cuba	18	0.1
Romania	67	0.3	Iceland	9	0.5	Ecuador	16	0.1
Algeria	64	0.3	Venezuela	8	0.5	Thailand	14	0.1
Other	1099	4.9	Other	339	20.1	Other	1972	12.1
Total	22660			1688			16323	

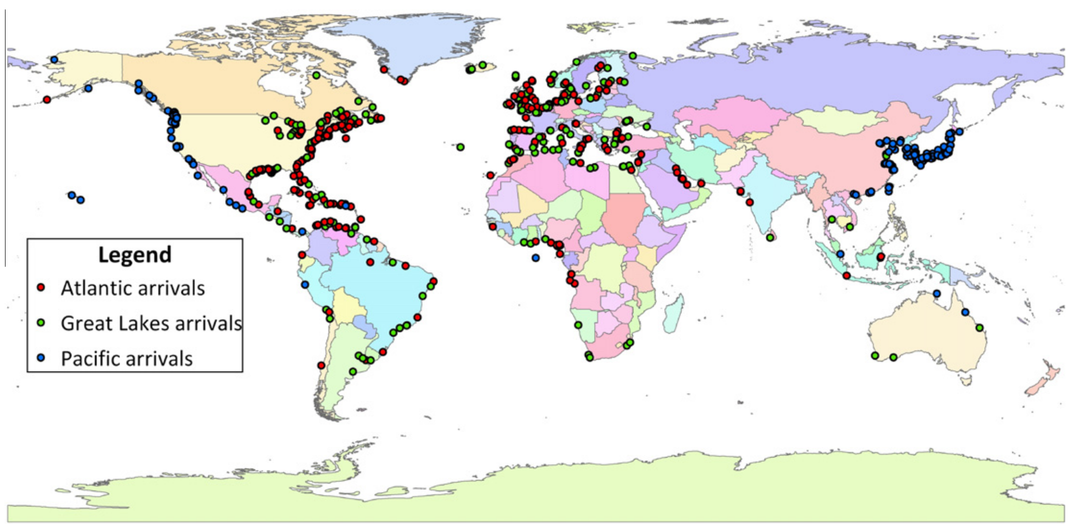

Fig. 4. Locations of ballast water origins for ballast discharged at ports in three Canadian shipping regions (Atlantic, Great Lakes-St. Lawrence, and Pacific), from November 2006 to October 2007.

regional classifications of ports and sources of data, across different time periods, and sometimes across different vessel categories, such that direct comparisons were sometimes difficult. Additionally, several ports included in our analysis are not included in these other studies, and vice versa, particularly for ports in the Great Lakes. These comparisons are treated in detail in Lo (2009).

We note for now, however, that other studies reported a higher number of arrivals for the Pacific region ports of Vancouver, Port Moody and Roberts Bank: 2595–2795 arrivals in Niimi (2000) and 2743 arrivals in Gramling (2000), vs. 1501 arrivals in our study. According to shipping statistics from the Port of Metro Vancouver for the year 2008, the volume of cargo shipped had actually increased from the time of Niimi's and Gramling's studies. Lower arrival numbers could be due to non-compliance of West Coast vessels with Canadian ballast water reporting requirements, but also because not all ballast reporting forms were entered into the BWIS. Additionally, Transport Canada arrivals and ballast water data from 1991 are higher for the ports of Vancouver and Prince Rupert. Thus, it is probable that our study has underestimated ballast water discharge volumes and WSA for particular Pacific ports.

While there is broad agreement between our results and the results of previous shipping studies, some inconsistencies exist, probably due to differences in data sources, port classification systems, annual variation in shipping patterns, and human error in data entry. Despite the differences observed, inter-annual variation in vessel traffic due to market conditions, and thus PPP measures, is common and reported by several port authorities annually. For example, demand for chemical cargo caused a decline of up to 75% in shipping volume in 2009, due in large part to the global economic downturn (InterVISTAS Consulting Inc., 2008).

Despite the comprehensive data set available to us, our estimate of PPP of ballast water AIS is admittedly coarse, as it does not account for other factors that mediate survival. These factors include the method and volume of ballast exchange, voyage duration, and environmental and life history parameters. For example, Cordell et al. (2008) found that salinity and stratification of water column temperatures were important predictors of *P. inopinus*, a non-native copepod in the northeast Pacific. With more comprehensive data and knowledge of species that are likely to become invasive in an area, PPP estimates can be further refined.

4.2. Ballast water management

Ballast exchange methods are significant in determining PPP as each method has an associated biological efficacy, or efficacy of removal of AIS. This efficacy also depends on other factors, such as the volume of water exchanged, tank type, and chemical and biological water properties (Choi et al., 2005; Ruiz and Smith, 2005; Wonham et al., 2001). While our estimates of PPP do not account for whether exchange was conducted, or what method of exchange was used, our findings shed light on the most common methods of exchange.

Our analysis shows that FT and ER are major exchange methods for ballast discharged in Canada, with FT being the dominant exchange method on the east and west coasts, and ER dominant in the Great Lakes-St. Lawrence region. While FT exchange requires more time (due to the requirement of exchanging 300% of the tank's volume), it is a safer method of exchange as the vessel can maintain stability throughout, unlike ER, where all of the source water is pumped out before being refilled with ocean water. This may explain why FT is dominant on both coasts of Canada, as transoceanic voyages typically take longer than coastal voyages. However, FT has also been demonstrated to be less effective than ER (Cordell et al., 2008). ER appears to be the preferred method of exchange for ships discharging ballast to the Great Lakes-St. Lawrence region. It is possible that ships traversing the St. Lawrence River have less time to conduct exchange via the FT method and thus prefer ER.

An additional management factor may influence PPP of AIS from ballast water. A study of zooplankton abundances in ballast tanks of ships in various Canadian ports (DiBacco et al., 2011) demonstrated that in terms of actual propagule pressure, intracoastal unexchanged ballast from U.S. ports contained greater species densities than exchanged intracoastal ballast or exchanged foreign ballast. The unexchanged ballast water therefore represented higher actual propagule pressure for zooplankton species relative to exchanged ballast water, even though the latter showed much higher PPP.

4.3. Wetted surface area

The mean WSA values we used to calculate WSA for our data set were derived from 5801 vessels covering a range of different categories (Davidson et al., 2006), so we believe these mean WSA values are representative of the vessels in our data set.

Our other assumption is that gross tonnage is linearly related to WSA. As gross tonnage is a measure of a vessel's volume, which indirectly influences WSA, we have reason to assume that there is a positive relationship between the two, although the shape of this relationship has not been determined and is an area for further research.

While WSA may serve as a rough proxy for hull fouling, a more accurate estimate requires accounting for several other factors, including voyage length, vessel speed, whether the hull is treated with anti-fouling paints, and the history of dry-docking activities, among other factors (Davidson et al., 2006). Voyage length and sampling port were shown to be significant predictors of species richness in a recent modeling study (Sylvester et al., 2011). Empirical studies demonstrate that species richness and invertebrate abundance are negatively correlated with sailing speed, while fouling is strongly associated with time spent in ports (Sylvester and MacIsaac, 2010). Similarly, Davidson et al. (2009) found that taxa accumulation on container ships increased significantly with time since the vessel was dry-docked. Vessel type may also be a factor in the extent of hull fouling propagule pressure – container ships, for example, travel at higher speeds than bulk carriers, and usually spend less than a day at port, so fouling is likely to be less extensive than on other ship types (Davidson et al., 2009). Additionally, our calculations of WSA did not include all colonizable surfaces, such as rudders or rope guards. Sea chest gratings and the leading edge of rudders have been found to be hull fouling 'hotspots' for vessels transiting the Great Lakes, whereas the propeller, hull and other parts of the rudder hosted the fewest species (Sylvester and MacIsaac, 2010).

Actual hull fouling propagule pressure has been measured empirically (e.g. Darbyson et al., 2009; Mineur et al., 2008), and effective hull fouling propagule pressure has been modeled (i.e. Herborg et al., 2009; Sylvester et al., 2011) – but there are few analyses of hull fouling PPP in our shipping regions for which we can compare our results, as we did above with arrivals and ballast water. Additionally, it should be noted that the high traffic volume from recreational boaters and fishing vessels add further to the hull fouling PPP of the other commercial shipping vessel categories represented in this study.

4.4. Relationship between arrivals, ballast discharge and WSA PPP

To our knowledge, this is the first national-scale analysis of PPP for hull fouling and ballast organisms from the commercial shipping sector. Analyses of arrivals and ballast water discharge have previously been conducted only at regional scales or for a handful of shipping ports (Balaban, 2000; Gramling, 2000; DiBacco et al., 2011; McGee et al., 2006). We have also estimated potential hull fouling propagule pressure across Canada in a novel way, by quantifying WSA in relation to a vessel's gross tonnage.

Our estimates of PPP for ballast and hull fouling organisms demonstrate that ballast discharge and WSA estimates are correlated across ports - but more so for Atlantic ports than GLSL or Pacific ports. Arrivals, a coarse proxy for hull fouling and ballast PPs, were highly correlated to both WSA and ballast discharge across ports by roughly the same degree. Arrivals are a better predictor of WSA across vessel categories than across ports, an expected result due to the influence of the shape of different types of vessels on WSA. Ballast discharge, on the other hand, can vary greatly for any vessel. Arrivals were most poorly correlated with ballast discharge for the Pacific region both across ports and vessel categories, and thus are the poorest proxy for ballast discharge and WSA.

Another proxy of PPP that has been used to assess risk of invasive species in ballast water is gross tonnage (GT), a measure of a vessel's volume (e.g. Harvey et al., 1999; Ruiz and Reid, 2007). GT data is widely available worldwide, as it is a common metric of imports and exports. Lo (2009) reported that GT can be a reliable indicator for ballast water discharge for bulkers and tankers, based on analyses of the relationship between GT and ballast discharge for vessels plying Canadian waters. However, GT is a poor proxy for PPP from general cargo vessels, possibly due to more variable discharge volumes for this vessel category relative to bulkers and tankers.

As shipping traffic increases worldwide, the importance of ballast water and hull fouling as vectors for AIS will also increase. The results of our study are significant for policy regarding prevention and detection of AIS. Improved ballast data quality and compliance measures for Canada's ballast water regulations will be important for achieving accurate analyses of PPP. Estimating PPP can be a relatively simple and inexpensive way to determine potentially high-risk ports and regions that may be targeted for AIS prevention and control measures. Where comprehensive data on ballast discharge are limited, arrivals may be an indicator of propagule pressure of ballast organisms, and possibly a better indicator of propagule pressure of hull fouling organisms. Further avenues for research include determining how PPP is related to actual and effective propagule pressure, leading to a better understanding of the factors underlying the establishment success of AIS.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.marpolbul.2011.11.016.

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