Domestic ballast operations on the Great Lakes: potential importance of Lakers as a vector for introduction and spread of nonindigenous species

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Abstract: Ballast water is recognized globally as a major vector of aquatic nonindigenous species (NIS) introductions; domestic ballast water transfers, however, have generally been considered low risk in North America. We characterize ballast operations of domestic ships in the Great Lakes – St. Lawrence River system (Lakers) during 2005–2007 to examine the risk of primary and secondary introductions associated with ballast water transfers over short distances. Results indicate that Lakers transported at least 68 million tonnes of ballast water annually. Approximately 71% of ballast water transfers were interregional, with net movement being from lower to upper lakes. A small proportion of ballast water discharged in the Great Lakes (<1%) originated from ports in the St. Lawrence River that may serve as sources for new NIS. These results indicate that domestic ballast water transfers may contribute to NIS introductions and are likely the most important ballast-mediated pathway of secondary spread within the Great Lakes. Future efforts to reduce invasion impacts should consider both primary and secondary introduction mechanisms.

Résumé : L'eau de ballastage est reconnue à l'échelle planétaire comme un vecteur primordial d'introduction d'espèces non indigènes (NIS) aquatiques; cependant, on considère généralement que les transferts locaux d'eau de ballastage présentent peu de risques en Amérique du Nord. Nous décrivons les opérations de ballastage des navires domestiques du système Grands-Lacs – Saint-Laurent (cargos hors mer) en 2005–2007 afin d'évaluer le risque d'introductions primaires et secondaires associées aux transferts d'eau de ballastage sur de courtes distances. Nos résultats indiquent que les cargos hors mer transportent au moins 68 millions de tonnes d'eau de ballastage chaque année. Environ 71 % des transferts d'eau de ballastage se font entre des régions, le déplacement net ayant lieu entre les lacs d'aval vers les lacs d'amont. Une petite proportion (<1 %) de l'eau de ballastage déchargée dans les Grands Lacs provient de ports sur le Saint-Laurent et peut servir de source de nouvelles NIS. Ces résultats indiquent que les transferts locaux d'eau de ballastage peuvent contribuer aux introductions de NIS et constituent vraisemblablement la voie prédominante de dispersion secondaire associée à l'eau de ballastage dans les Grands Lacs. Les efforts futurs de réduction des impacts des invasions devraient tenir compte à la fois des mécanismes primaires et secondaires d'introduction.

[Traduit par la Rédaction]

Introduction

Human-mediated invasions by nonindigenous species (NIS) result from a sequence of steps or stages from uptake by a vector in a donor region to eventual live release and establishment in the recipient habitat (see Carlton 1985; Kolar and Lodge 2001; Colautti and MacIsaac 2004). The outcome of each stage, and the overall successful transition among stages, is affected by many factors, including propagule pressure, environmental matching between donor and recipient regions, and biological interactions between introduced species and the recipient community (e.g., Colautti et al. 2006; Hayes and Barry 2008; Miller and Ruiz 2009). Assessment of invasion risk requires an understanding of the probability of introduction, the probability of establishment, and the corresponding impacts in the recipient habitat (see Lodge et al. 2006; Herborg et al. 2007). Management actions aimed at reducing propagule pressure at the introduction stage appear to offer robust protection against biological invasions (Mack et al. 2000; Leung et al. 2002;

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Fig. 1. Map illustrating the 118 port sites on the Great Lakes – St. Lawrence River system. The broken line demarcates the division between the Great Lakes proper and the St. Lawrence River. Major ports of interest to this study are labelled. Lakes are, from left to right, Superior, Michigan, Huron, Erie, and Ontario.

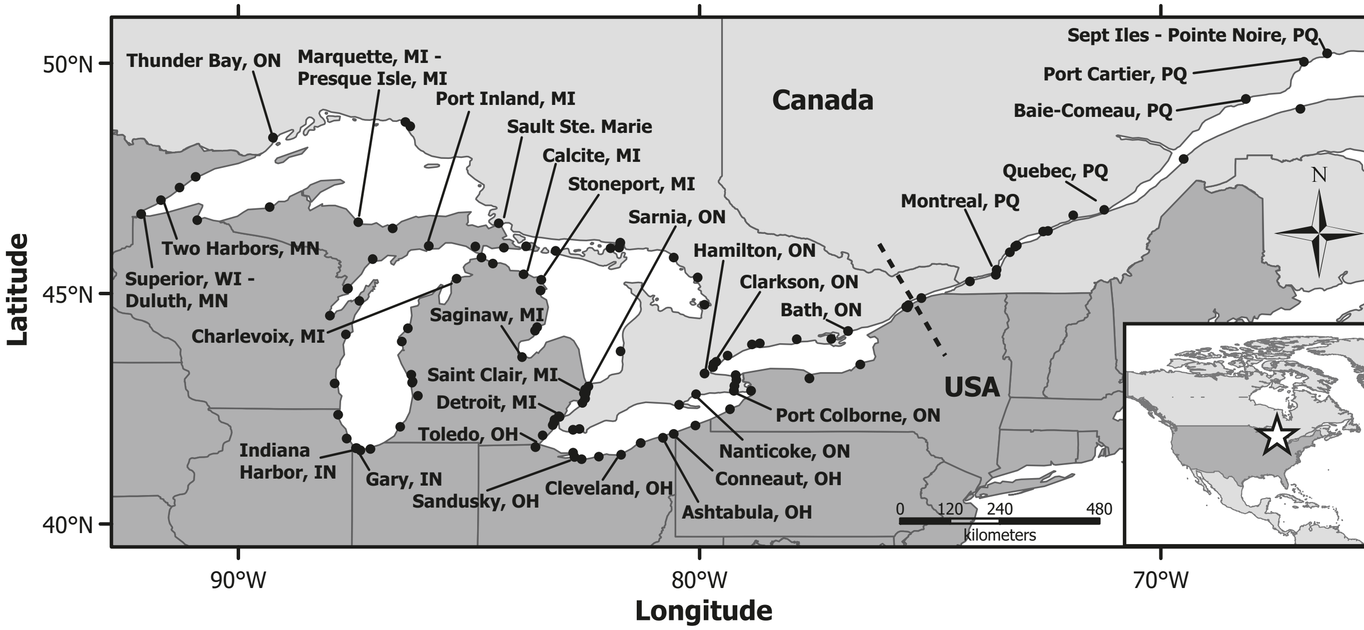


Table 1. Annual statistics on inter- and intraregional ballast water movement by Lakers.

	Number of discharge events	Ballast water discharged (Mt)
2005 interregional transfers	2828	47.6
2006 interregional transfers	2920	50.6
2007 interregional transfers	2722	47.4
Mean annual interregional transfers	2823 (57)	48.6 (1.0)
2005 intraregional transfers	1797	19.2
2006 intraregional transfers	2024	21.6
2007 intraregional transfers	1744	18.2
Mean annual intraregional transfers	1855 (86)	19.7 (1.0)
Cumulative mean annual transfers	4678 (143)	68.3 (2.0)

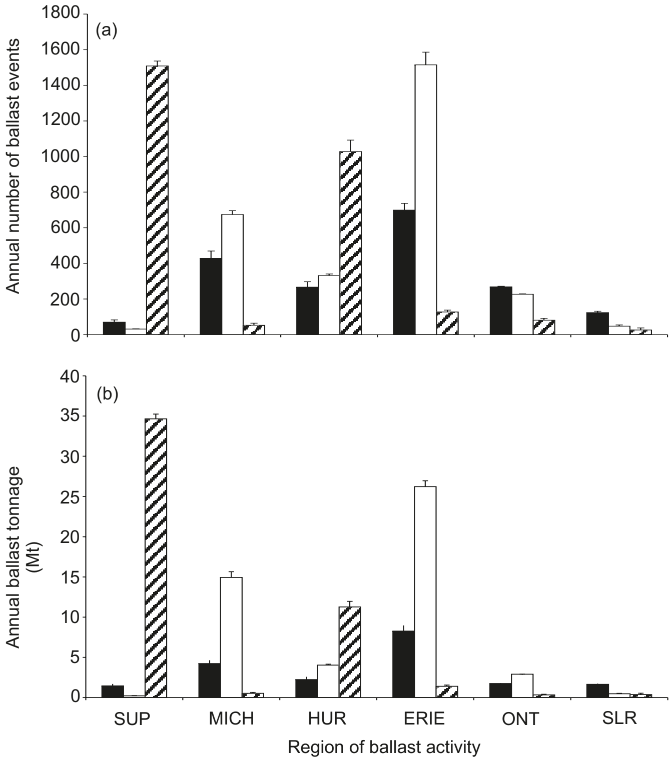
Note: Mean values include SEM in parentheses.

Drake and Lodge 2004). Once introduced and established in a new location, the extent of secondary spread of NIS will greatly affect the magnitude of any ecological and economic impacts (Lodge et al. 1998). Thus, it has also been suggested that NIS management programs should include measures to reduce the rate and extent of secondary spread (Moody and Mack 1988; Floerl et al. 2009).

Ballast water transfers by commercial shipping activities are recognized as a dominant transport vector for marine invasions globally (Carlton 1999; Drake and Lodge 2004). Current ballast water management regulations in North America aim to reduce propagule pressure but address only primary introductions associated with international shipping activities (e.g., US Coast Guard 2004; Government of Canada 2006). Domestic vessels, which typically move ballast water over short geographic distances, have generally been considered low risk for species invasions under the assumption that closely located ports will be within the same biogeographic region and will contain similar biological communities (but see Gaines and Gaylord 2005; Simkanin et al. 2009). In contrast, domestic ballast water could rapidly facilitate secondary spread of NIS introduced by other vectors, since survival is expected to be high for short-distance ship transits (Rigby and Hallegraeff 1994; Smith et al. 1999; Wonham et al. 2001).

Secondary spread by short-distance ballast water transfers from domestic sources might be very important in North America where 50% and 70% of commercial vessel arrivals to coastal ports in the United States and eastern Canada, respectively, are from domestic last ports-of-call (based on reports submitted to NBIC and INNAV; see Materials and methods). Approximately 90% of commercial shipping operations in the Great Lakes – St. Lawrence River system are domestic, creating a dense web of interconnections and making this region potentially more vulnerable to secondary spread. Vessels operating in the Great Lakes – St. Lawrence River can be divided into three categories: (*i*) foreign vessels operating outside the Canadian and American 200 nautical mile exclusive economic zones (EEZ) for at least part of the year (hereafter ‘‘Salties’’), (*ii*) domestic vessels operating exclusively within the Great Lakes – St. Lawrence River west of 63°W (i.e., inland waters, hereafter ‘‘Lakers’’), and

Fig. 2. Mean (+SEM) annual inter- and intraregional ballast water movement in the Great Lakes – St. Lawrence River system by (*a*) number of ballast events and (*b*) tonnage. Solid bars denote ballast loaded for intraregional discharge, open bars denote ballast loaded for interregional discharge, and hatched bars denote ballast received from interregional source. Regions: SUP, Lake Superior; MICH, Lake Michigan; HUR, Lake Huron; ERIE, Lake Erie; ONT, Lake Ontario; SLR, St. Lawrence River.



(*iii*) foreign or domestic vessels operating exclusively between ports in inland waters and coastal ports within the EEZ of Canada and the United States (hereafter "Coastal vessels").

In the absence of effective and widely available treatment technologies, Canada and the United States currently rely on a reduction in propagule pressure by means of midocean ballast water exchange or tank flushing to prevent invasions in the Great Lakes (US Coast Guard 2004; Government of Canada 2006; Saint Lawrence Seaway Development Corporation 2008). All Salties and Coastal vessels arriving to the Great Lakes from ports outside the Canadian EEZ must comply with ballast water management regulations, but Lakers and Coastal vessels travelling between Canadian ports are currently unregulated. At least nine established NIS in the Great Lakes, only four of which were presumably introduced by ship ballast, are considered native to the St. Lawrence River and other rivers of the northeastern North American coast (de Lafontaine and Costan 2002; Ricciardi 2006). These invasions highlight the possibility that domestic ballast water may pose an introduction risk. In addition, at least 13 NIS now established in the Great Lakes were first recorded in the St. Lawrence River (de Lafontaine and Costan 2002), indicating that all vectors moving species between the St. Lawrence River and the Great Lakes should be evaluated for invasion risk. Despite concerns that Lakers might contribute to accelerated spread of NIS within the Great Lakes (Aquatic Sciences, Inc. and Jenkins 1996), there has been no quantitative attempt to characterize the magnitude or direction of ballast water flux by Lakers.

The objective of this study is to quantify the magnitude of ballast water transferred by Laker vessels and to parameterize the corresponding risk of primary and secondary invasions to ports on the Great Lakes. We use the number of discharge events and ballast water volume as a proxy measure for the potential propagule pressure associated with ballast water transported by Lakers. We explore geographical ballast water loading and discharge patterns of Lakers to discern the scale and directionality of movement of ballast water within and between lakes. Finally, we compare ballast water movement within the Great Lakes – St. Lawrence River system by Lakers with that by Salties and Coastal vessels to determine the extent of spatial overlap and relative capacities for secondary spread of established NIS. Quantifying total ballast water movements within the Great Lakes should allow us to identify ports vulnerable to NIS establishment or spread and to inform future management and prevention efforts.

Materials and methods

For this study, we define Great Lakes ports as the freshwater ports located within Lakes Superior, Michigan, Huron, Erie, and Ontario and all connecting waterways west of the St. Lawrence Seaway's Iroquois Lock (i.e., ports of Duluth, Minnesota, to Prescott, Ontario, inclusive; Fig. 1). The term "St. Lawrence River" includes the freshwater and marine ports bounded by the Iroquois Lock and Canadian inland waters as defined by the Canada Shipping Act, 2001 (i.e., ports from Valleyfield to Sept-Îles, Québec, inclusive). Together, these two regions contain all ports within the Great Lakes – St. Lawrence River system.

Data on domestic commercial ship activities at ports in the Great Lakes – St. Lawrence River system were obtained from the Canadian Coast Guard Information System on Marine Navigation (INNAV) and the US National Ballast Information Clearinghouse (NBIC) (http://invasions.si.edu/nbic/ accessed April 2008) for the period 2005–2007. Our analysis was restricted to the 90 vessels with an American or Canadian flag that operated exclusively within the Great Lakes – St. Lawrence River system for the entire period of study (Lakers) and included eight barges previously converted from traditional commercial bulk carriers. All other barges operating within the system were excluded from analysis due to inconsistencies in reporting activities.

Canada requires all commercial vessels to report to the INNAV when entering each Canadian Maritime Communications and Traffic Services Zone, when transiting the St. Lawrence Seaway between the St. Lambert Lock and Long Point, Ontario, and when transiting the St. Clair – Detroit River system, while voluntary reporting typically occurs for all other Great Lakes – St. Lawrence River waters exclusive of Lake Michigan and southern Lake Superior. Information reported to the INNAV includes arrival and departure events and cargo and ballast operations at port. Cargo and ballast information is typically reported in binary format (load or unload, volumes are not reported), and all reports are date

Table 2. Top ballast water source ports for inter- and intraregional movement of ballast water by Lakers.

	Annual tonnage of ballast loaded (Mt)		Annual number of ballast load events	
	Mean (SEM)	%	Mean (SEM)	%
Top interregional source ports				
Detroit, Michigan	5.2 (0.4)	10.8	343 (35)	12.1
Gary, Indiana	4.6 (0.3)	9.5	130 (7)	4.6
St. Clair, Michigan	4.0 (0.1)	8.2	101 (3)	3.6
Nanticoke, Ontario	3.3 (0.1)	6.8	109 (5)	3.9
Indiana Harbor, Indiana	3.2 (0.4)	6.6	123 (14)	4.4
Cleveland, Ohio*	2.1 (0.1)	4.5	202 (12)	7.1
Sault Ste. Marie, Ontario*	2.0 (0.1)	4.2	200 (9)	7.1
Hamilton, Ontario*	2.3 (<0.1)	4.7	174 (2)	6.2
Top intraregional source ports				
Nanticoke, Ontario	2.4 (0.2)	12.0	133 (14)	7.2
Detroit, Michigan	1.7 (0.1)	8.5	140 (1)	7.5
Indiana Harbor, Indiana	1.4 (0.2)	7.1	95 (8)	5.1
Cleveland, Ohio	1.1 (0.2)	5.5	115 (22)	6.2
Saginaw – Bay City – Essexville – Zilwaukee, Michigan	1.0 (0.2)	4.8	98 (16)	5.3
Clarkson, Ontario*	0.9 (0.1)	4.8	104 (1)	5.6

Note: The top five ports by tonnage are listed followed by any additional top five ports by number of load events (indicated by an asterisk). Values are given as annual mean with SEM in parentheses and as a percentage of the inter- or intraregional total, respectively. Note that all top port locations are labelled on Fig. 1.

and time coded. The United States requires all commercial vessels equipped with ballast tanks to submit a ballast water report to the NBIC at each arrival to an American port. Reports to the NBIC include last, current, and next ports-of-call and arrival date as well as the volume, origin, and management history of ballast to be discharged.

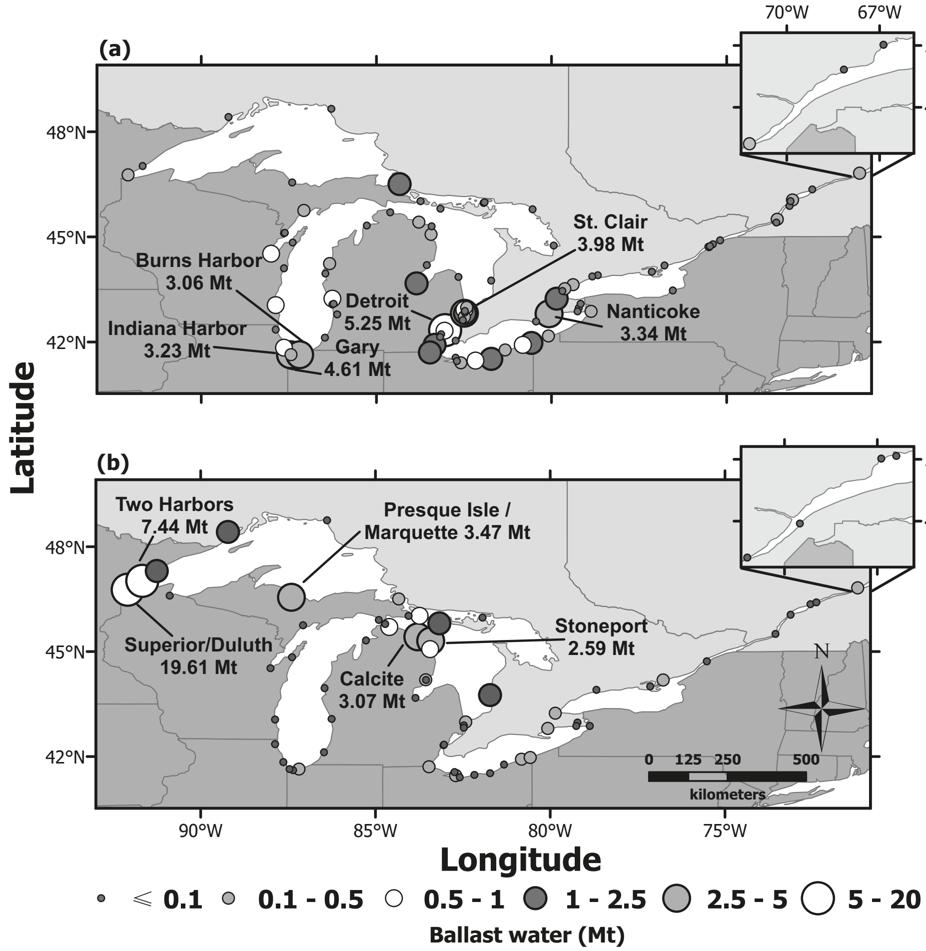
A comprehensive database of ship activity, including date of arrival/departure and cargo and ballast activities, was assembled for 136 port locations in Canada and the United States using the INNAV as the primary data source. The NBIC was used to fill in missing transit data (typically transits to/from Lakes Michigan and Superior) and as the primary source for volumetric ballast water data. Owing to differences in reporting requirements of the INNAV and NBIC as well as variance between individual vessels' reporting practices, some ballast transfers could not be reliably assigned to a specific port but were assigned to port "pairs" (e.g., Duluth, Minnesota –Superior, Wisconsin; see Appendix A), resulting in 118 separate port areas of shipping activity.

When ballast activity was not reported for a particular ship transit, it was assumed that vessels loaded ballast (*i*) if cargo was offloaded, (*ii*) if the port involved does not export cargo, or (*iii*) if the vessel was heading for a port that did not receive a cargo type that was shipped out of the current port. Conversely, ballast discharge was assumed (*i*) if cargo was loaded or (*ii*) if the port involved does not import cargo. Information regarding cargo handled at specific port locations was obtained from the Lake Carriers' Association (2006). We included only transits between ports and did not include stops for fuel or at anchorage. Data for 2360 transits, or <8% of total transits, could not be included in the study because of missing source/destination port information and (or) arrival at ports for which it was not possible to determine whether cargo or ballast was discharged.

Consultation with the ship industry and analysis of NBIC data indicated that Lakers typically carry the same volume of ballast water on each transit through the system. Although variable volumes were reported to the NBIC by 36 ships, these ships reported a standard volume for 90% of transits. As a result, we applied the median value reported by each vessel to all transits by that vessel. Ballast quantities for vessels that did not report to the NBIC (five ships) were assigned by grouping vessels according to class under the assumption that "sister ships" within a size class carried identical quantities of ballast. If vessels were of a unique build, or the size class did not report to the NBIC, estimates of standard ballast volume were obtained directly from the ship's superintendent. We acknowledge that vessels may increase ballast tonnage during foul weather, but consistency of reporting for ballast "top ups" could not be readily evaluated. For cases where the vessel loaded or discharged cargo at multiple ports, the volume of ballast discharged or loaded was assumed to be directly proportional to the number of cargo events. For example, if a ship loaded cargo at two ports, it was assumed that half of the ballast was discharged at each port; this assumption was applied to a very small proportion of the data (<1%).

In the absence of direct biological measures from ballast tanks, we use ballast water volume and the number of discharge events (ballast water flux) as a proxy measure of the number of propagules potentially discharged at each port site by Lakers (i.e., potential propagule pressure). We acknowledge that additional ship-mediated invasion vectors, such as hull fouling and ballast sediments, may increase the potential propagule pressure associated with Lakers, but evaluation of these other vectors is beyond the scope of work for this paper. Analysis of compiled data included assessment of inter- and intraregional movement of ballast water. Each port was assigned to one of six regions within

Fig. 3. Maps depicting (*a*) source and (*b*) recipient ports of domestic ballast water moved from 2005 to 2007 by Lakers between regions of the Great Lakes – St. Lawrence River. Dominant ports, based on volume and number of ballast events, are labelled. The size and shading of the symbol indicate the annual mean volume of ballast water loaded or discharged at each port site as indicated in the figure legend.



the system: Lakes Superior, Michigan, Huron, Erie, and Ontario and the St. Lawrence River. Ports located on connecting waterways were assigned to the downstream region. For example, ballast activities in Detroit, Michigan, or Windsor, Ontario, were attributed to Lake Erie. To determine if Lakers posed a risk for introduction of NIS into the Great Lakes, we evaluated ballast activities undertaken at ports in the St. Lawrence River; these ports could serve as donor ports for NIS to the Great Lakes if the taxa native to those ports are NIS to the Great Lakes or if these ports serve as sites for the primary introduction of taxa that are NIS to both regions (see de Lafontaine and Costan 2002). To further evaluate the capacity of Lakers as a vector of secondary spread of NIS, we examined the extent of Laker ballast loading activities at Great Lakes ports most likely serving as sites of primary introduction (i.e., recipients of foreign or coastal ballast water) and the relative magnitude of ballast flux by each category of vessel.

Results

Over 28 000 Laker transits, corresponding to more than 200 million tonnes (Mt) of ballast water discharged, were compiled for the 3-year period of study (2005–2007). Regional patterns of ballast water discharge were consistent across years, whether measured as the number of discharge events (4682 ± 142 standard error of the mean (SEM)) or as millions of tonnes discharged (68.35 ± 2.04 SEM) annually. Approximately 71% of all ballast water transfers were interregional, with net movement of ballast water being from lower to upper lakes (Table 1; Fig. 2). Thirty-four ports were sites for ballast loading operations exclusively, while nine ports were exclusively recipients of ballast water; the remaining 75 ports both donated and received ballast water (Appendix A).

Most ballast water discharged in Lakes Michigan, Erie, and Ontario and the St. Lawrence River originated from within the same region as discharge, while the majority of ballast discharged in Lakes Superior and Huron originated from Lakes Erie and Michigan (Fig. 2; Table 1). Detroit, Michigan, Nanticoke, Ontario, Indiana Harbour, Indiana, and Cleveland, Ohio, were the most important ballast water source ports for both intra- and interregional ballast water transfers (Table 2; Figs. 3*a* and 4*a*). In contrast, the major recipient ports for intraregional ballast water movement were completely distinct from those receiving interregional discharges (Table 3; Figs. 3*b* and 4*b*).

We identified 10 ports on the St. Lawrence River at which 15 different Lakers loaded ballast that is subsequently

Fig. 4. Maps depicting (*a*) source and (*b*) recipient ports of domestic ballast water moved from 2005 to 2007 by Lakers within regions of the Great Lakes – St. Lawrence River. Dominant ports, based on volume and number of ballast events, are labelled. The size and shading of the symbol indicate the annual mean volume of ballast water loaded or discharged at each port site as indicated in the figure legend.

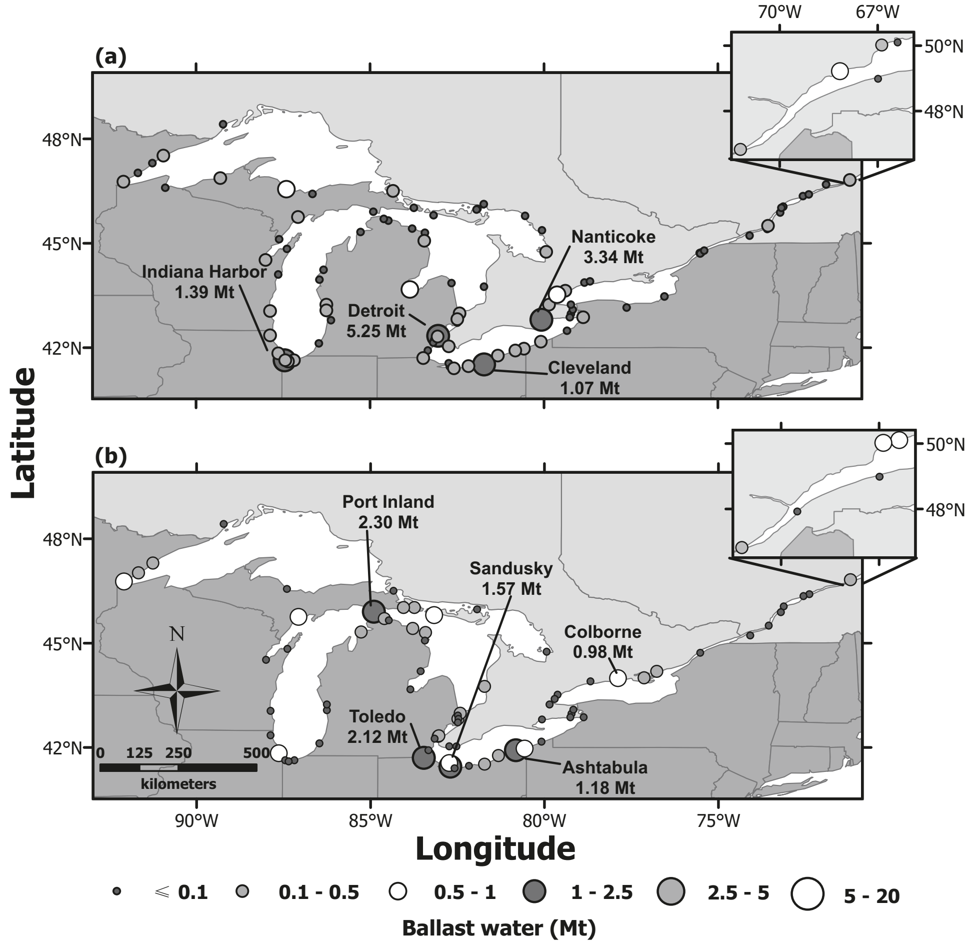


Table 3. Top ballast water recipient ports for inter- and intraregional movement of ballast water by Lakers.

	Annual tonnage of ballast discharged (Mt)		Annual number of ballast discharge events	
	Mean (SEM)	%	Mean (SEM)	%
Top interregional recipient ports				
Superior, Wiconsin – Duluth, Minnesota	19.6 (0.2)	40.4	677 (13)	24.0
Two Harbours, Minnesota	7.4 (0.4)	15.3	208 (10)	7.4
Presque Isle-Marquette, Michigan	3.5 (0.2)	7.2	299 (23)	10.6
Calcite, Michigan	3.1 (0.2)	6.3	250 (17)	8.9
Stoneport, Michigan	2.6 (0.2)	5.3	207 (9)	7.3
Top intraregional recipient ports				
Port Inland, Michigan	2.3 (0.2)	11.7	194 (17)	10.4
Toledo, Ohio	2.1 (0.1)	10.8	163 (11)	8.8
Sandusky, Ohio	1.6 (0.1)	8.0	127 (6)	6.8
Ashtabula, Ohio	1.2 (0.2)	6.0	78 (10)	4.2
Port Colborne, Ontario	1.0 (<0.1)	5.0	109 (1)	5.9
Charlevoix, Michigan*	0.4 (<0.1)	2.1	109 (10)	5.9

Note: The top five ports by tonnage are listed followed by any additional top five ports by number of discharge events (indicated by an asterisk). Values are given as annual mean with SEM in parentheses and as a percentage of the inter- or intraregional total, respectively. Note that all top port locations are labelled on Fig. 1.

Table 4. Annual statistics on interregional ballast water loading activities at ports in the St. Lawrence River by Lakers.

Port	Port salinity (%)[a]	Mean (SEM) annual ballast tonnage loaded for Great Lakes discharge (tonnes × 1000)	Tonnage of exchanged ballast received in 2007 (tonnes × 1000)[b]	Number of ballast discharge events by coastal domestic vessels in 2007[c]
Johnstown Harbour, Ontario	0	5.4 (5.4)	0	0
Côte Ste-Catherine, Québec	0	10.7 (8.1)	0	4
Montréal, Québec	0	102.5 (22.6)	538.8	0
Contrecoeur, Québec	0	5.0 (5.0)	4.3	0
Sorel, Québec	0	116.7 (33.8)	135.8	15
Tracy, Québec	0	1.3 (1.3)	78.1	10
Trois-Rivières, Québec	0	3.8 (3.8)	83.2	6
Québec, Québec	0	142.0 (16.6)	542.5	104
Baie-Comeau, Québec	24–32	52.7 (24.3)	542.3	33
Port-Cartier, Québec	11–32	38.5 (25.6)	2945.8	67

[a]Québec and all ports upstream considered exclusively freshwater (N. Simard, Fisheries and Oceans Canada, Institut Maurice-Lamontagne, Mont-Joli, QC G5H 3Z4, personal communication); salinity data for Baie-Comeau and Port-Cartier from Blasco et al. (1998).

[b]Data from Transport Canada National Ballast Water Database [online]. Available from http://ballast.qc.dfo-mpo.gc.ca/application [accessed February 2009].

[c]Estimated by subtracting number of discharges reported in Transport Canada National Ballast Water Database from number of arrivals to load cargo reported to the Canadian Coast Guard Information System on Marine Navigation.

Table 5. Annual statistics on ballast loading activities by Lakers at top ports of ballast water discharge by Salties and Coastal vessels in the Great Lakes (as indicated by M. Minton, National Ballast Information Clearinghouse, Smithsonian Environmental Research Center, 647 Contees Wharf, Edgewater, MD 21037, USA, unpublished data).

	Mean (SEM) annual ballast loaded (tonnes × 1000)	Mean (SEM) annual number of ballast loading events	Interregional movement (%)
Top five ports receiving ballast water from Salties and Coastal vessels			
Duluth, Minnesota – Superior, Wisconsin	542.8 (165.2)	44 (10)	30.0
Sarnia, Ontario	520.4 (16.8)	72 (3)	24.4
Toledo, Ohio	1631.1 (46.9)	136 (5)	83.5
Thunder Bay, Ontario	77.9 (5.1)	12 (1)	48.2
Hamilton, Ontario	2684.6 (61.9)	204 (5)	84.8
Top five ports receiving Great Lakes water mixed with residual ballast of Salties and coastal vessels			
Duluth, Minnesota – Superior, Wisconsin	542.8 (165.2)	44 (10)	30.0
Toledo, Ohio	1631.1 (46.9)	136 (5)	83.5
Thunder Bay, Ontario	77.9 (5.1)	12 (1)	48.2
Sandusky, Ohio	44.9 (8.3)	5 (1)	61.9
Ashtabula, Ohio	1161.5 (241.5)	79 (15)	73.8

Note: The top ports receiving ballast discharged directly (i.e., from ships entering the Great Lakes with ballast on board) are listed separately from the top ports receiving residual ballast mixed into local Great Lakes water (i.e., ships entering the Great Lakes with only residual ballast), as the two types of ballast may pose different levels of invasion risk. Note that all top port locations are labelled on Fig. 1.

discharged at a Great Lakes port (Table 4). The number of ballast events (47 ± 7 SEM) and the tonnage of ballast water moved (0.48 ± 0.07 Mt) from these ports annually into the Lakes is relatively small, representing less than 1% of all ballast transported by Lakers. Two of these ports (Baie-Comeau and Port-Cartier, Québec) are saltwater ports in the lower St. Lawrence River Estuary. Eight of the 10 ports receive exchanged ballast water discharged by Salties and (or) Coastal vessels, while seven of the ports receive unexchanged ballast from Canadian coastal ports (Table 4).

We identified 58 ports within the Great Lakes where ballast loading operations of Lakers overlap with discharge of ballast by Salties and Coastal vessels (see Appendix A). The cumulative volume (51.62 Mt ± 1.72 SEM) and number of loading events (3539 ± 110 SEM) at these ports are 10 times greater than the interregional transfer of ballast from the St. Lawrence River (Table 5), underscoring that the potential for secondary spread of NIS by Lakers is far greater than the potential for primary introductions. Furthermore, comparative analysis of discharge activities by Lakers and all other commercial vessels operating within the Great Lakes – St. Lawrence River system reveals that Lakers transfer a disproportionate volume (95%) of the Great Lakes ballast water moved between and within the lakes (M. Minton, National Ballast Information Clearinghouse, Smithsonian Environmental Research Center, 647 Contees Wharf Road, Edgewater, MD 21037, USA, unpublished data).

Discussion

The volume of ballast water moved by Lakers is 20 times greater than the volume of local ballast transferred by

Salties and Coastal vessels combined, likely rendering Lakers the most important ballast-mediated pathway of secondary spread within the Great Lakes. With ballast transfers being overwhelmingly in the upstream direction, the potential distance and speed of secondary spread of NIS are much greater than would be achieved by natural, passive dispersal. The extent of secondary spread of NIS will greatly affect the magnitude of any ecological and economic impacts (Lodge et al. 1998); thus, large-scale transfers of ballast water within the Great Lakes by Lakers contribute to the impacts of NIS.

Lakers load 30% of their ballast water at the ports of Detroit, Michigan, Nanticoke, Ontario, Indiana Harbour, Indiana, and Cleveland, Ohio. New introductions of NIS into these ports, by any vector, have a high potential for rapid secondary spread throughout the Great Lakes by Lakers. Conversely, 56% of all Laker ballast water is discharged at Superior, Wisconsin – Duluth, Minnesota, Two Harbours, Minnesota, Presque Isle-Marquette, Michigan, Calcite, Michigan, and Stoneport, Michigan, suggesting that these ports have the greatest potential to receive propagules of NIS following introduction into other sites within the Great Lakes. Monitoring programs aimed at early detection and reducing secondary spread of new NIS in the Great Lakes by ballast water should include a focus on these nine locations.

This assessment of ballast loading and discharge patterns by Lakers indicates that Lakers could serve as a vector for primary introduction of NIS into ports on the Great Lakes by moving ballast water sourced from ports on the St. Lawrence River, if taxa native to ports on the St. Lawrence River are NIS to the Great Lakes, or if ports on the St. Lawrence River serve as sites for the primary introduction and establishment of taxa that are NIS to both regions. While less than 1% of all Laker ballast transfers introduce water from the St. Lawrence River into the Great Lakes, the absolute volume (0.48 Mt ± 0.07 SEM) is roughly equivalent to that added to the system each year by transoceanic and coastal vessels combined, so the corresponding potential propagule pressure is not inconsequential. Potential propagule pressure, however, is only a coarse proxy for invasion potential. A better determinant of invasion potential is effective propagule pressure (i.e., actual propagule pressure × the survival rate of released propagules in the recipient area). Our estimate of potential propagule pressure should be a robust indicator of actual propagule pressure (i.e., total number of individuals discharged), since the volume of ballast water left in tanks after discharge is typically less than 0.5% of tank capacity (M.G. Deneau and S.A. Bailey, Fisheries and Oceans Canada, Great Lakes Laboratory for Fisheries and Aquatic Sciences, Burlington, ON L7R 4A6, Canada, unpublished data).

With many intraregional transits taking less than 24 h, and typical interregional sailing times of 3–4 days, plankton survival in ballast tanks of Lakers is expected to be very high. As a result, our estimate of potential propagule pressure should also be a robust indicator of effective propagule pressure for the eight freshwater donor ports on the St. Lawrence River, since the range of environmental conditions at these ports overlaps with those on the Great Lakes and post-introduction survival is expected to be high. We caution, however, that the corresponding impact might be low, since taxa native to freshwater ports in the St. Lawrence River are expected to be very similar to Great Lakes' communities due to passive downstream dispersal (A. Ricciardi, McGill University, Redpath Museum, Montréal, QC H3A 2K6, Canada, personal communication). Nevertheless, considering that at least nine established NIS in the Great Lakes were potentially sourced from the St. Lawrence River, this assumption requires further testing.

In contrast, our estimate of potential propagule pressure may overestimate the effective propagule pressure presented by Baie-Comeau and Port-Cartier, Québec, since most taxa in these ports are expected to be polyhaline or euhaline and are expected to have low survival rates if introduced into a freshwater port (see Runge and Simard 1990). However, at least eight species of brackish or marine origin have established nonindigenous populations in the Great Lakes (A. Ricciardi, McGill University, Redpath Museum, Montréal, QC H3A 2K6, Canada, personal communication), indicating that additional research is needed to fully assess the risk posed by ballast water transfers from the lower St. Lawrence River estuary into the Great Lakes.

Concerns about movement of St. Lawrence River water, and any native taxa therein, to the Great Lakes are compounded by the potential for new NIS introductions resulting from ballast discharge by Salties and (or) Coastal vessels into ports on the river. Sept-Îles and Port-Cartier, Québec, each receive nearly 3 Mt of exchanged ballast water annually, at least 40 times more than is received by any port within the Great Lakes (Transport Canada Ballast Water Database: http://ballast.qc.dfo-mpo.gc.ca/application [accessed February 2009]; also see Bourgeois et al. 2001). As a result, these two ports have the highest potential for introduction of new NIS by ballast water. While Lakers did not transport any ballast water from Sept-Îles into the Great Lakes during this study, changes in shipping patterns and economics could make Sept-Îles a viable source port in the future. These two ports, as well as Québec, Sorel, and Montréal, should be considered for future studies investigating the potential for "stepping stone" invasions of NIS from the St. Lawrence River into the Great Lakes (sensu Apte et al. 2000).

We highlight overlap of Laker ballast loading activities with ballast discharge activities of other vessels as a potential source of new NIS because ballast-mediated invasions have been historically important in the Great Lakes (Ricciardi 2006; National Research Council 2008) and ballast discharge activities are well documented. All vessels arriving from foreign and US ports are now required to conduct midocean ballast water exchange and (or) tank flushing prior to ballast water discharge in the Great Lakes, resulting in reduced risk of invasion by ballast water (Gray et al. 2007; Santagata et al. 2008; Ellis and MacIsaac 2009). In consequence, other unregulated human-mediated vectors, such as hull-fouling and unintentional or unauthorized introductions of baitfish, aquarium, or water garden species, could now surpass ballast water in importance for primary introduction of NIS into the Great Lakes. Furthermore, the relative importance of nonshipping vectors, such as activities associated with the 1.7 million recreational boats on the Great Lakes each year, as a means of secondary spread is an important area of future study (Thorp and Stone 2000; US Army Corps of Engineers 2008).

This study is the first comprehensive analysis of domestic vessel transits in the Great Lakes – St. Lawrence River system, and we acknowledge that our estimates of potential or effective propagule pressure are based on proxy measures. Biological sampling of ballast water of all three vessel categories of interest, Salties, Coastal vessels, and Lakers, is needed to further refine comparative estimates of invasion potential, since effective propagule pressure is expected to vary widely according to source port location. At this time, Lakers should be considered a potential vector for primary introduction of NIS and possibly the most important vector of secondary spread in the Great Lakes. This study exemplifies the need to examine domestic shipping patterns in consideration of "stepping stone" invasions to improve management of ballast-mediated invasions across North America.

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Appendix A

Table A1 appears on the following page.

Table A1. Latitude and longitude coordinates for the 118 port sites included in the study.

Latitude	Longitude	Port name	Region	Ballast activity
44.191078	–83.563133	Alabaster, MI	Huron	R
42.62145	–82.531929	Algonac, MI	Erie	D
45.061565	–83.445154	Alpena, MI	Huron	D, R
46.585402	–90.88631	Ashland, WI	Superior	D, R
41.864891	–80.79155	Ashtabula, OH	Erie	D, R*
49.220998	–68.152478	Baie-Comeau, PQ	St. Lawrence River	D*
44.18304	–76.775264	Bath, ON	Ontario	D, R*
46.355047	–72.441796	Bécancour, PQ	St. Lawrence River	D, R*
43.913835	–78.688474	Bowmanville, ON	Ontario	D, R*
46.016708	–84.853859	Brevort, MI	Michigan	R
45.776779	–80.555008	Britt, ON	Huron	D
43.395278	–79.705278	Bronte, ON	Ontario	R
42.886238	–78.878891	Buffalo–Tonawonda, NY	Erie	D, R*
41.638691	–87.427994	Buffington, IN	Michigan	D*
41.618061	–87.134689	Burns Harbor, IN	Michigan	D, R*
45.413921	–83.809471	Calcite, MI	Huron	D, R*
45.31653	–85.260719	Charlevoix, MI	Michigan	D, R
45.6454	–84.476134	Cheboygan, MI	Huron	D, R
41.849838	–87.648193	Chicago–Calumet, IL	Michigan	D, R*
43.51218	–79.634666	Clarkson, ON	Ontario	D, R
41.498779	–81.695297	Cleveland, OH	Erie	D, R*
44.005569	–77.885757	Colborne, ON	Ontario	R
41.947868	–80.555	Conneaut, OH	Erie	D, R*
45.89	–73.27	Contrecoeur, PQ	St. Lawrence River	D, R*
42.885559	–82.453407	Corunna, ON	Erie	D, R*
45.405785	–73.571919	Côte Ste. Catherine, PQ	St. Lawrence River	D
42.818878	–82.474228	Courtright, ON	Erie	D, R
42.331509	–83.046021	Detroit – River Rouge, MI	Erie	D, R*
46.020744	–83.756577	Drummond Island, MI	Huron	D, R
42.48724	–79.335779	Dunkirk, NY	Erie	D
42.255445	–83.139364	Ecorse, MI	Erie	R
42.12944	–80.085243	Erie, PA	Erie	D, R*
45.745215	–87.079759	Escanaba–Gladstone, MI	Michigan	D, R
41.748947	–81.273987	Fairport, OH	Erie	D, R*
43.083015	–86.217339	Ferrysburg, MI	Michigan	D
45.995139	–81.738219	Fisher Harbour, ON	Huron	D
41.593189	–87.345078	Gary, IN	Michigan	D, R*
43.74264	–81.707764	Goderich – Owen Sound, ON	Huron	D, R*
43.06295	–86.225984	Grand Haven, MI	Michigan	D, R
44.512795	–88.010159	Green Bay, WI	Michigan	D, R*
47.916667	–69.5	Gros Cacouna, PQ	St. Lawrence River	R
43.26097	–79.888459	Hamilton, ON	Ontario	D, R*
43.843795	–82.651376	Harbor Beach, MI	Huron	D
48.625599	–86.268112	Heron Bay, ON	Superior	D
42.77309	–86.101754	Holland, MI	Michigan	D
41.396259	–82.5541	Huron, OH	Erie	D, R
41.640671	–87.443649	Indiana Harbor, IN	Michigan	D, R*
44.743828	–75.466553	Johnstown Harbor, NY	St. Lawrence River	D
42.037885	–82.740309	Kingsville, ON	Erie	D, R
42.054155	–82.599714	Leamington, ON	Erie	R
49.002731	–66.96906	Les Méchins, PQ	St. Lawrence River	D, R
45.979389	–81.925377	Little Current, ON	Huron	D, R
41.45224	–82.17897	Lorain, OH	Erie	D, R*
43.954441	–86.452042	Ludington, MI	Michigan	D, R*
45.780683	–84.725557	Mackinaw City, MI	Huron	R
44.24172	–86.318979	Manistee, MI	Michigan	D
44.107595	–87.661724	Manitowoc, WI	Michigan	D

Table A1 (*continued*).

Latitude	Longitude	Port name	Region	Ballast activity
48.719935	–86.375696	Marathon, ON	Superior	R
41.540359	–82.735382	Marblehead, OH	Erie	D, R*
45.099998	–87.630638	Marinette, WI	Michigan	D
42.914615	–82.474174	Marysville – Marine City, MI	Erie	D, R
45.921506	–83.115702	Meldrum Bay – Thessalon – Bruce Mines – Serpent Harbor, ON	Huron	D, R*
45.10784	–87.619159	Menominee, MI	Michigan	D*
44.749905	–79.888509	Midland, ON	Huron	D, R
43.04181	–87.906844	Milwaukee, WI	Michigan	D, R*
41.916065	–83.397899	Monroe, MI	Erie	D, R
45.512331	–73.554363	Montréal, PQ	St. Lawrence River	D, R*
42.839851	–82.465759	Mooretown, ON	Erie	D
44.89983	–75.187169	Morrisburg Harbour, ON	Ontario	D
46.40966	–86.650029	Munising, MI	Superior	D
43.23424	–86.245929	Muskegon, MI	Michigan	D, R
42.81074	–80.071979	Nanticoke, ON	Erie	D, R*
43.466175	–79.689584	Oakville, ON	Ontario	D
44.694469	–75.486687	Ogdensburg, NY	Ontario	D
46.872725	–89.317824	Ontonagon, MI	Superior	D
43.88868	–78.859504	Oshawa, ON	Ontario	D*
43.455471	–76.510048	Oswego, NY	Ontario	D*
45.34477	–80.036364	Parry Sound, ON	Huron	D
44.009225	–77.138974	Picton, ON	Ontario	D, R*
42.88509	–79.251984	Port Colborne, ON	Erie	D, R*
45.989429	–84.239464	Port Dolomite – Cedarville, MI	Huron	D, R*
44.266634	–83.519145	Port Gypsum – Tawas City, MI	Huron	D, R
46.028629	–85.86956	Port Inland, MI	Michigan	D, R*
43.223629	–79.21167	Port Weller, ON	Ontario	D*
50.02713	–66.889539	Port-Cartier, PQ	St. Lawrence River	D, R*
46.691831	–71.891309	Portneuf, PQ	St. Lawrence River	D
44.709895	–75.513654	Prescott–Cardinal, ON	Ontario	D, R*
46.543571	–87.395439	Presque Isle[a] – Marquette, MI	Superior	D, R*
46.812749	–71.219359	Québec, PQ	St. Lawrence River	D, R*
43.1555	–77.616033	Rochester, NY	Ontario	D
43.614819	–83.84137	Saginaw – Bay City – Essexville – Zilwaukee, MI	Huron	D, R
41.44876	–82.707374	Sandusky, OH	Erie	D, R*
42.978765	–82.403329	Sarnia, ON	Huron	D, R*
46.51828	–84.347904	Sault Ste. Marie, ON	Huron	D, R*
50.208635	–66.388234	Sept Îles – Pointe Noire, PQ	St. Lawrence River	D, R*
47.293449	–91.269005	Silver Bay, MN	Superior	D, R*
42.714008	–82.478409	Sombra, ON	Erie	D, R
46.04239	–73.112629	Sorel, PQ	St. Lawrence River	D, R*
42.831301	–82.502521	St. Clair, MI	Erie	D, R
42.10339	–86.485259	Saint Joseph, MI	Michigan	D, R
45.293129	–83.428085	Stoneport, MI	Huron	D, R*
44.83519	–87.370659	Sturgeon Bay Harbour, MI	Michigan	D, R
46.72065	–92.103973	Superior, WI – Duluth, MN	Superior	D, R*
47.527119	–90.922043	Taconite Harbor, MN	Superior	D
43.124285	–79.197719	Thorold, ON	Erie	D, R
48.3817	–89.245479	Thunder Bay, ON	Superior	D, R*
41.66391	–83.555122	Toledo, OH	Erie	D, R*
43.648565	–79.385329	Toronto, ON	Ontario	D*
46.015685	–73.147894	Tracy, PQ	St. Lawrence River	D*
42.139469	–83.178101	Trenton, MI	Erie	D
46.34016	–72.545019	Trois-Rivières, PQ	St. Lawrence River	D, R*
47.022911	–91.671089	Two Harbours, MN	Superior	D, R*
45.256409	–74.132462	Valleyfield, PQ	St. Lawrence River	D, R*

Table A1 (*concluded*).

Latitude	Longitude	Port name	Region	Ballast activity
42.36164	–87.833889	Waukegan, IL	Michigan	D,R
42.99345	–79.239239	Welland Canal, ON	Erie	D, R*
46.1	–81.7167	Whitefish, ON	Huron	D
42.3178	–83.033904	Windsor, ON	Erie	D, R*
42.201615	–83.149999	Wyandotte, MI	Erie	D

Note: Ballast activity indicates if the port acts as a donor (D) and (or) recipient (R) of ballast water moved by Lakers. An asterisk denotes sites that act as recipients of ballast water from Salties and Coastal vessels and as donors of Laker ballast.

[a]Note that both ports named Presque Isle in Michigan have been included.