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Analysis of invertebrate resting eggs and other biota in ballast tank sediment of domestic Great Lakes cargo ships

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ABSTRACT

Domestic shipping in the Laurentian Great Lakes may be a vector of secondary spread for non-native species, but research has not yet assessed the role of ballast tank sediment. Here, ballast tank sediment was collected from three domestic ships (*M/V American Century*, *M/V Edwin H. Gott*, and *M/V Mesabi Miner*) during 2011 and 2012 at Lake Superior harbors in the USA and analyzed for invertebrates. Samples contained evidence of active life stages of Bivalvia, Cladocera, Copepoda, Gastropoda, Hydracarina, Nematoda, Oligochaeta, and Ostracoda as well as dormant life stages of some species including ones hatched in the laboratory from Cladocera, Copepoda, Ostracoda, and Rotifera. Excluding resting eggs, the groups Bivalvia, Copepoda, and Ostracoda comprised 83% of individuals recovered. The mean density of resting eggs per ballast tank ranged from 16.0 to 24.8 eggs/g wet sediment for samples collected during November and from 0.2 to 2.7 eggs/g wet sediment for samples collected during December to March. The mean viability (percentage hatched) of resting eggs per ballast tank ranged from 31.2% to 75.8% for samples collected during November; December to March samples were not assessed for egg viability. Bosminidae (Cladocera) were the most commonly hatched taxa and comprised 548 of 819 hatchlings (or 67%). Hatched eggs included *Eubosmina coregoni* and *Bythotrephes longimanus* which are non-native to the Great Lakes. Densities of resting eggs and other biota were comparable to, or greater than, published densities of organisms in ballast tank sediment of foreign ships entering the Great Lakes and ballast tank water of domestic ships operating within the Great Lakes.

Introduction

For over a century, species native to other continents have been steadily invading the Laurentian Great Lakes of North America (Mills et al., 1993; Ricciardi and MacIsaac, 2000; Holeck et al., 2004; Bailey et al., 2011). While most non-native species in the Great Lakes appear to have had little measurable impact on the ecosystem (Ricciardi and Kipp, 2008), some have become invasive as a result of excessive population growth and novel interactions with the environment. Noteworthy examples of non-native, invasive species in the Great Lakes include spiny water flea (*Bythotrephes longimanus*), quagga mussel (*Dreissena bugensis*), zebra mussel (*Dreissena polymorpha*), and round goby (*Neogobius melanostomus*) (Vanderpleog et al., 2002; Corkum et al., 2004; Hecky et al., 2004; Bunnell et al., 2011). As a group, invasive species have caused enormous changes to the structure and function of the Great Lakes ecosystem (Ricciardi, 2001), with economic costs associated with United States waters recently estimated at $138 million annually for the sub-set of non-native species originally introduced by ocean-going ships (Rothlisberger et al., 2012).

Once established in a new ecosystem, non-native, invasive species often prove to be resilient to eradication (Simberloff, 2003). In cases where eradication has been successful it is often time sensitive and resource intensive, and requires early detection and swift management response (Myers et al., 2000; Simberloff, 2003). Vander Zanden et al. (2010) recently envisioned a large-scale, proactive detection and eradication program against invasive species in the Great Lakes, but its enactment remains uncertain.

Short of eradication, some degree of control of invasive species in the Great Lakes has been suggested to be attainable by reducing secondary spread (Vander Zanden and Olden, 2008). Secondary spread, defined here as range expansion of a non-native species within its non-native environment, is a legitimate management concern because it broadens the geographic range of a species, potentially increasing damage and control costs and diminishing future opportunities for containment and eradication. Furthermore, habitats reached through secondary spread may support better growth opportunities, or vector networks, than original colonization sites and accelerate range expansion (MacIsaac et al., 2004; Johnson et al., 2008).

While a substantial reduction in secondary spread of non-native, invasive species in the Great Lakes may be an effective management tool, it will be challenging to achieve. The Great Lakes are not only vast in spatial and volumetric scale but support diverse coastal and

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offshore habitats that can provide numerous opportunities for suitable matches between source and recipient environments. Additionally, non-native species often use multiple dispersal vectors during their lifetimes including swimming, drifting, associations with other organisms (epizooic or endozooic), and associations with human traffic vectors (e.g., recreational boating and shipping). Containment policies that are too narrowly focused on eliminating a single dispersal vector may be ineffective in a broader management framework if other vectors remain open. This presents a major impediment to comprehensive management (Mills et al., 1993; Ricciardi, 2006; Williams et al., 2013).

Domestic shipping has gained considerable attention coastally and in the Great Lakes as an important dispersal pathway of secondary spread (Simkanin et al., 2009; Lawrence and Cordell, 2010; Rup et al., 2010; Briski et al., 2012; Adebayo et al., 2014). In the Great Lakes, domestic shipping refers specifically to ships that operate exclusively within the Great Lakes and St. Lawrence River system (Rup et al., 2010). This subset of ships, also called Lakers, are responsible for the transfer of up to 68 million tonnes of ballast water annually, a figure that greatly exceeds the contribution of local ballast carried by coastal and foreign ships in the system (Rup et al., 2010). To date, Laker ballast water has been regarded as an important subvector of secondary spread because of the diversity of organisms found there and the large volumes of water exchanged (Briski et al., 2012; Adebayo et al., 2014). Less attention, however, has been given to the analysis of biota present in sediment that accumulates on ballast tank floors and other internal surfaces of ballast tanks. Although typically smaller by volume than ballast water, ballast sediment may be a more likely subvector for the transport of benthic species and species that produce dormant life stages, known as resting eggs, which often sink following maternal release (Pennak, 1989) and accumulate in benthic environments (Hairston, 1996; Bailey et al., 2003, 2005; Duggan et al., 2005).

Resting eggs are of particular concern for ballast management because of their lifespans and natural abilities to resist harsh environmental conditions (Gyllström and Hansson, 2004). For example, resting eggs of many zooplankton species have been shown to live for months to years in viable, dormant states before hatching (Hairston, 1996; Gyllström and Hansson, 2004) and to tolerate physical and chemical extremes well outside the ranges of their free-swimming planktonic counterparts (Schwartz and Hebert, 1987; Bailey et al., 2006; Ellis and MacIsaac, 2009; Gray and MacIsaac, 2010; Branstrator et al., 2013). These attributes of resting eggs may enhance species survival during long-term storage in ballast tanks and defeat the efficacy of decontamination protocols that use physical or chemical modes of action.

While numerous studies have demonstrated that ballast tank sediment from ocean-going ships contains a wide diversity of native and non-native taxa ranging from microbes to metazoans (Bailey et al., 2003, 2005; Duggan et al., 2005, 2006; Drake et al., 2007; Briski et al., 2011a; Casas-Monroy et al., 2013), parallel studies on Lakers are lacking. Here we analyze ballast tank sediment from three Lakers for invertebrate taxa, paying particular attention to the diversity, density, and viability of resting eggs.

Methods

Sediment collection

Sediment samples were collected from ballast tanks of the *M/V American Century*, *M/V Edwin H. Gott*, and *M/V Mesabi Miner*. All three ships are approximately 1000-foot long bulk freighters constructed in the United States during the 1970s to 1980s and operate exclusively within the upper Great Lakes (Superior, Michigan, Huron, and Erie).

Sediments were collected from ships during December 2011 to November 2012 at harbors on Lake Superior (Table 1) while ships were at docks either undergoing routine cargo operations (November to January) or during winter layup periods (February to March). Samples were collected from multiple sites within a ballast tank that included the tank floor and elevated surfaces 1–2 m above the floor. The top 1–3 cm of sediment was harvested with a scoop and placed into a plastic, screw-cap bottle resulting in about 100–300 g of wet sediment per sample. During sampling events in November to January, just prior to our entry into a ballast tank, the tank water was emptied to within a few cm of the tank floor. During that period, ballast tank walls were visibly wet and the sediment collected was wet, unfrozen, and ranged from stiff, tightly packed material to loose, soft material. During sampling events in February to March, which coincided with winter layup, ballast tank walls were visibly dry and the sediment collected was either dry and frozen or wet and submerged in shallow water beneath a thin layer of ice (Table 1). Pebbles and rust flakes (presumably metal corrosion) were common in the samples from both periods. Samples were returned immediately to the laboratory at the University of Minnesota Duluth for processing.

The study was conducted in two phases. Phase I objectives were to assess invertebrate diversity and density. Under phase I, sediment samples were collected from multiple ballast tanks and multiple sites within a tank. Samples were amended with ethanol (70% final volume) and stored at room temperature until analysis.

Phase II objectives were to assess invertebrate resting egg density, size, viability (hatching percentage), and taxonomy. Under phase II, one ballast tank on each ship was sampled at five different sites. At each site, three samples were collected from within an area of about 0.5 m^2. One sample per site was amended with ethanol and stored at room temperature. It was used for the determination of resting egg density and size. The other two samples per site, which were used for resting egg viability and taxonomy, were left raw except for the addition of 35 ml of synthetic culture water (hereafter referred to as culture water). They were stored in the dark at 4 °C in an environmental chamber. The culture water was developed from additions of $CaSO_4$, $MgSO_4$, $NaHCO_3$, and KCl to deionized water to produce appropriate pH, conductivity, hardness, and alkalinity levels for rearing crustacean zooplankton based on a protocol used by the Lake Superior Research Institute (University of Wisconsin Superior, Wisconsin, USA: Matt TenEyck, personal communication).

Table 1
Summary of sediment sample collection organized by ship, phase of study, collection date, harbor location (Lake Superior), and ballast tank sampled.

Ship	Phase of study	Collection date	Harbor location	Ballast tank sampled
M/V American Century	I	8 Dec 2011	Duluth-Superior	Port 7
	I	*15 Feb 2012	Duluth-Superior	Port 5
	I	*15 Feb 2012	Duluth-Superior	Port 6
	II	19 Nov 2012	Duluth-Superior	Port 7
M/V Edwin H. Gott	I	4 Jan 2012	Duluth-Superior	Starboard 5
	I	*5 Mar 2012	Duluth-Superior	Starboard 5
	II	18 Nov 2012	Two Harbors	Port 5
M/V Mesabi Miner	I	8 Jan 2012	Silver Bay	Port 4
	I	*5 Mar 2012	Duluth-Superior	Port 4
	II	30 Nov 2012	Duluth-Superior	Starboard 8

* Sediment samples were frozen or in water under ice at the time of collection.

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