# Sediments in ships: Biota as biological contaminants

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*Global ports are hubs for industrial activities and trade. In consequence, sediments and water in these areas are often contaminated by an array of chemicals. Sediments also harbour both living, active stages and various diapausing or resting stages of biota. International shipping activities move sediments containing these biotic stages around the world, possibly resulting in biological contamination of port areas. In this study we assess active and resting stages of invertebrates contained in ballast sediment of transoceanic vessels operating on the North American Great Lakes to determine if ballast sediments could serve as a vector of nonindigenous species. A cumulative total of 160 species were identified, including 22 freshwater species not recorded from the Great Lakes' basin. Hatch rates of resting stages are affected by thermal conditions, thereby affecting invasion success. Total abundance and species diversity of freshwater invertebrate animals hatched from resting stages were negatively related to salinity of residual water in ballast tanks from which the sediments were obtained, suggesting that ballasting a shallow lens of saltwater may provide some degree of risk reduction from freshwater species invasions.*

*Keywords:* ballast water, biological invasion, diapausing eggs, invertebrates, resting stages, zooplankton

## Introduction

Harbours, coastal areas and estuaries are primary areas of industrial, agricultural and municipal contaminant discharge (Gross, 1978; McCarthy et al., 1991). Sediments act as both a sink and a source for contaminants by removing PCBs, pesticides, heavy metals and other wastes from the water column, and by increasing exposure of benthic organisms to these contaminants, respectively (Lick, 1982; McCarthy et al., 1991). Sediment may itself be considered a contaminant, in that it increases water turbidity, obstructs navigational waterways, and fouls fish and plant habitats (Lick, 1982; Scheffer, 1998). Furthermore, sediment can affect transport efficiency by accumulating in ballast tanks of transoceanic ships that entrain water in turbid ports.

While many mechanisms contribute to introduction of nonindigenous species to aquatic ecosystems, ship ballast—including ballast sediments—has been considered the principal vector for unintentional species introductions to port areas, and to the North American Great Lakes, since the mid-1900s (e.g., Leppäkoski et al., 2002; Grigorovich et al., 2002, 2003; Hayes and Sliwa, 2003). Ballast sediments may support a diverse biotic community, ranging from bacteria to large crustaceans (Carlton et al., 1995), and could act as a vector for biological invasions to global ports where ballast is discharged (e.g., Leppäkoski and Olenin, 2000; Bailey et al., 2003).



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Uptake of bottom sediments into ballast tanks depends on water and ballast intake depths and river flow or tidal conditions (Pollutech Environmental Ltd., 1992). Generally, as the amount of suspended sediment increases in the water column, the probability of pumping sediment into tanks also increases. Although ballast sediments have been recognized as a potential vector for nonindigenous species for some time (e.g., Locke et al., 1991; Aquatic Sciences Inc., 1995), the relative and absolute importance of this vector remains unresolved. However, studies completed to date indicate that sediments are present on a majority of transoceanic vessels, and contain an array of active and dormant organisms (e.g., Hallegraeff and Bolch, 1992; Hamer et al., 2000; Waters et al., 2001; Bailey et al., 2003). Although these biotic stages occur naturally in bottom sediments, they become a concern when transported by international shipping activities around the world, possibly resulting in biological contamination if discharged into port areas (see Elliott, 2003, for a discussion of biological pollution). Ironically, extensive efforts to reduce pollution in port areas may have improved water/sediment quality to the point that resident species may experience population increases, rendering them more readily available for uptake into ballast tanks (Carlton, 1996).

Over time and repeated ballast loading and discharge cycles, a benthic community—comprised of viruses, bacteria, protists, fungi and moulds, plants and animals, as well as their parasites and pathogens—may develop in ballast tanks (Carlton et al., 1995). The abundance of these taxa will depend on their ability to survive the variable conditions associated with ballast tanks, such as fluctuating water levels, limited or periodic food supplies, complete darkness, and fluctuating temperature, salinity and oxygen regimes (Carlton, 1985; Wonham et al., 2001). As a result, some taxa will be transient members of the sediment community, surviving only a short period after being entrained in a ballast tank. Dormant stages contained in sediments may be a significant factor in the success of ballast-mediated invasions, by allowing organisms to survive the harsh conditions associated with transport inside ballast tanks. In point of fact, 16 of the 19 crustaceans that have successfully invaded the Great Lakes are known or suspected to produce a dormant life history stage (Table 1).

Active organisms enter ballast tanks either as planktonic individuals present in water used as ballast, or as benthic individuals stirred up from bottom sediments by water turbulence and/or river or tidal influence (i.e., factors responsible for turbid conditions are also likely to stir up benthic animals into the water column). Similarly, dormant stages of either planktonic or benthic taxa may enter ballast tanks directly from

**Table 1.** List of nonindigenous crustacean taxa recorded in the Great Lakes (from Riccardi, 2006), with life history resting stage indicated. Resting stage references available from S.A. Bailey.

| Taxon | Species | Date reported | Resting stage |
|---|---|---|---|
| Cladocera | *Bosmina coregoni* | 1966 | egg |
| | *Bosmina maritima* | 1988 | egg |
| | *Bythotrephes longimanus* | 1982 | egg |
| | *Cercopagis pengoi* | 1998 | egg |
| | *Daphnia galeata* | 1980 | egg |
| | *Daphnia lumholtzi* | 1999 | egg |
| Copepoda | *Argulus japonicus* | 1988 | egg |
| | *Cyclops strenuus* | 1972 | copepodid |
| | *Eurytemora affinis* | 1958 | egg |
| | *Heteropsyllus* cf. *nunni* | 1990s | adult |
| | *Megacyclops viridis* | 1994 | copepodid |
| | *Neoergasilus japonicus* | 1994 | none reported |
| | *Nitocra hibernica* | 1973 | adult (suspected) |
| | *Nitocra incerta* | 1999 | adult |
| | *Salmincola lotae* | 1985 | none reported |
| | *Schizopera borutzkyi* | 1998 | copepodid |
| | *Skistodiaptomus pallidus* | 1967 | egg |
| Amphipoda | *Gammarus tigrinus* | 2001 | none reported |
| | *Echinogammarus ischnus* | 1994 | none reported |

the sediment 'egg bank' after bottom sediments are disturbed or via reproduction inside ballast tanks by planktonic adults that were entrained with ballast water. Preliminary evidence suggests that the latter possibility may be particularly important (Hallegraeff and Bolch, 1992; S.A. Bailey, unpublished).

# Methods

In 2001 and 2002, we conducted a comprehensive survey of active and diapausing invertebrate taxa contained in ballast sediments of 39 transoceanic ships entering the Great Lakes. Approximately 1kg sediment was collected from each of 69 ballast tanks sampled for enumeration of active taxa; sediment-associated fauna were separated from sediments using the colloidal silica Ludox®HS40, after preservation in 95% ETOH (Burgess, 2001).

Approximately 4 kg sediment per tank was collected from the same 39 ships for analysis of invertebrate resting stages via laboratory hatching experiments. Sediments were stored at 4°C, without preservation, for at least 2 weeks to allow a refractory period before hatching experiments commenced. Resting stages were isolated from sediments using a sugar flotation protocol (Bailey et al., 2003) for enumeration and identification. To determine if resting stages were viable, we incubated the isolated resting stages under favourable hatching conditions in the laboratory; typically using freshwater media incubated at 20°C in order to simulate the Great Lakes' environment (see Bailey et al., 2003, for detailed methodology). Individuals hatched from resting stages were identified to the species level, when possible, using standard taxonomic keys.

To determine if resting stage viability may be affected by exposure to saline water, we conducted a regression of the total number of individuals hatched and the number of species hatched against salinity of residual water in ballast tanks from which the resting stages were collected. The effect of salinity was also examined experimentally, by exploring hatching success under different environmental conditions. Resting stages, again isolated from sediments, were exposed to three thermal conditions at 0‰ (10, 20 and 30°C) and three salinity conditions at 20°C (0, 8 and 35‰). Experimental growth media consisted of sterile synthetic pond water or filtered, diluted seawater (see Bailey et al., 2004). Experiments were conducted in controlled environmental chambers with at least 3 replicates per treatment, and were examined daily.

# Results and discussion

Active stages of invertebrates were recovered from ballast sediment at an average density of 1.32 individuals $g^{-1}$. Approximately 100 taxa were identified from a broad array of taxonomic groups, including hydrozoans, rotifers, nematodes, gastropods, bivalves, oligochaetes, bryozoans, tardigrades, water mites, chironomids, ostracods, barnacle cyprid larvae, cladocerans, copepods, amphipods, and juvenile decapods; nematodes and copepods, however, accounted for almost 99% of total abundance (Figure 1a). Although the recorded species were predominantly marine species, six freshwater species that are currently not established in the Great Lakes (all copepods) were identified.

Resting stages occurred at densities of up to 91 individuals $g^{-1}$ sediment, although the median density was much lower (0.62 individuals $g^{-1}$; Figure 2). Seventy-one species of invertebrates, including gastrotrichs, rotifers, bryozoans, cladocerans and copepods, were identified, including 16 freshwater cladoceran and rotifer species not recorded from the Great Lakes' basin. In contrast to the biological composition of active animals in sediments, animals hatched from resting stages were dominated by freshwater taxa, particularly planktonic rotifers (Figure 1b).

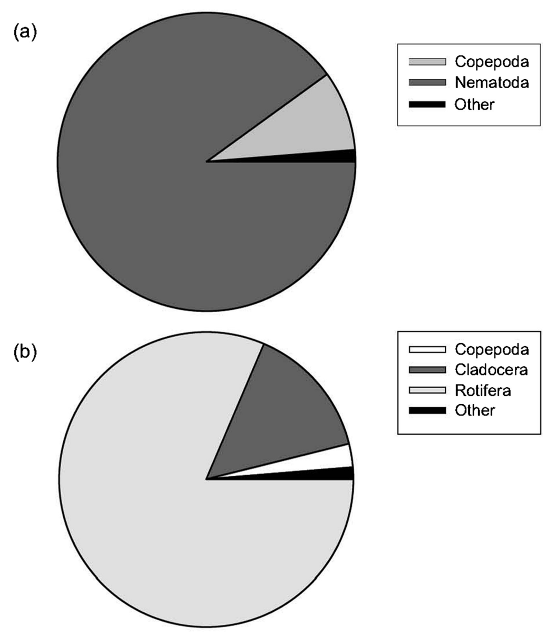


**Figure 1.** Relative total abundance of (a) active stages and (b) resting stages of invertebrates collected from residual ballast sediments of 39 transoceanic ships.

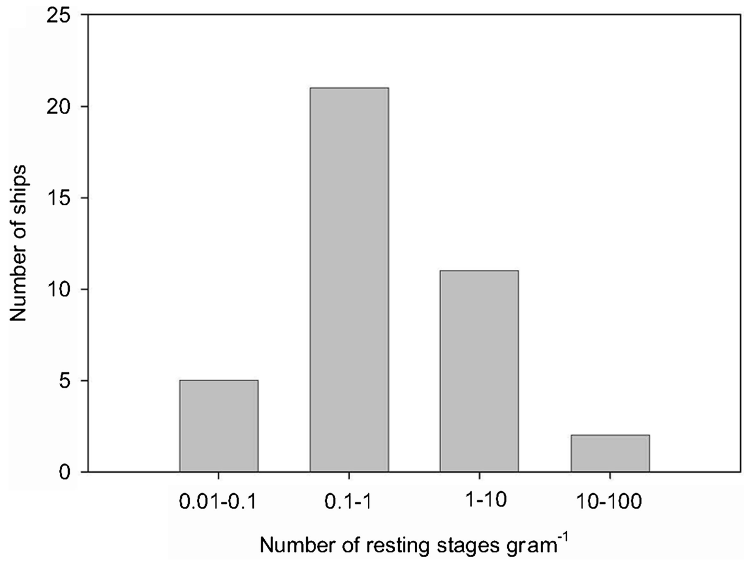


**Figure 2.** Frequency distribution of invertebrate resting stage density for residual ballast sediments of 39 transoceanic ships.

Temperature appears to have a significant impact on the hatch rate of resting stages. While resting stages exposed to 30°C began hatching within the first day, those incubated at 20°C hatched within 2 days, and those at 10°C did not initiate hatching until day four (Figure 3a). While overall differences in abundance were not profound between 20°C and 30°C, earlier hatching times could be important depending on the length of the trip because it provides greater opportunity for exponential population growth in the ballast tanks before water is discharged (see Wonham et al., 2005). The vast majority of resting stages hatched into freshwater media, indicating that few resting stages comprised of either brackish- or salt-water taxa (Figure 3b). This is possibly because production of dormant stages is a common life history strategy for freshwater taxa, but less so for marine taxa (Cáceres, 1997). This indicates that resting stages are a more important mode of survival and range expansion by freshwater organisms than for marine taxa.

## Pathways of introduction

Over one thousand nonindigenous species have been reported from marine, estuarine and freshwater habitats in North America, Europe and Australia (e.g., Grigorovich et al., 2003; Hayes and Sliwa, 2003). Ships arriving at port can be classified as one of two types: those with empty cargo holds, having only 'ballast on board' and those loaded with cargo, having 'no ballast on board' (NOBOB). Although both types of ships may cause species invasions, NOBOB ships comprise more than 90% of ship traffic inbound to the Great Lakes, and enter without any form of formal ballast treatment (MacIsaac et al., 2002; Colautti et al., 2003).[1] Consequently, these vessels are a potentially important vector of nonindigenous species.

Although ballast tanks of NOBOB ships are considered empty, most cannot completely remove all ballast owing to structural and/or operational limitations. These vessels typically carry 60 t of un-pumpable residual water and sediment (Bailey et al., 2003). NOBOB vessels could introduce nonindigenous species contained in residual ballast after loading, and subsequently discharging, ballast water during multi-port operations, as it provides an opportunity for admixture of residual ballast and any active or dormant organisms therein (see Bailey et al., 2003). Virtually any species in the residual water ballast, and perhaps even some at the sediment-water interface, could be stirred into the water column during ballast loading and discharge events. These taxa can then be provided with opportunities for establishment in novel ports if present in the water column when ballast is discharged. Discharge of resting stages contained in residual sediment is more complicated; resting stages are less likely to be stirred

[1] Although NOBOB ships were not regulated at the time of writing this article, Canada became the first country to introduce mandatory ballast water regulations for NOBOB ships in June 2006, including 'flushing' of ballast tanks with saltwater as described below in the Management options section.

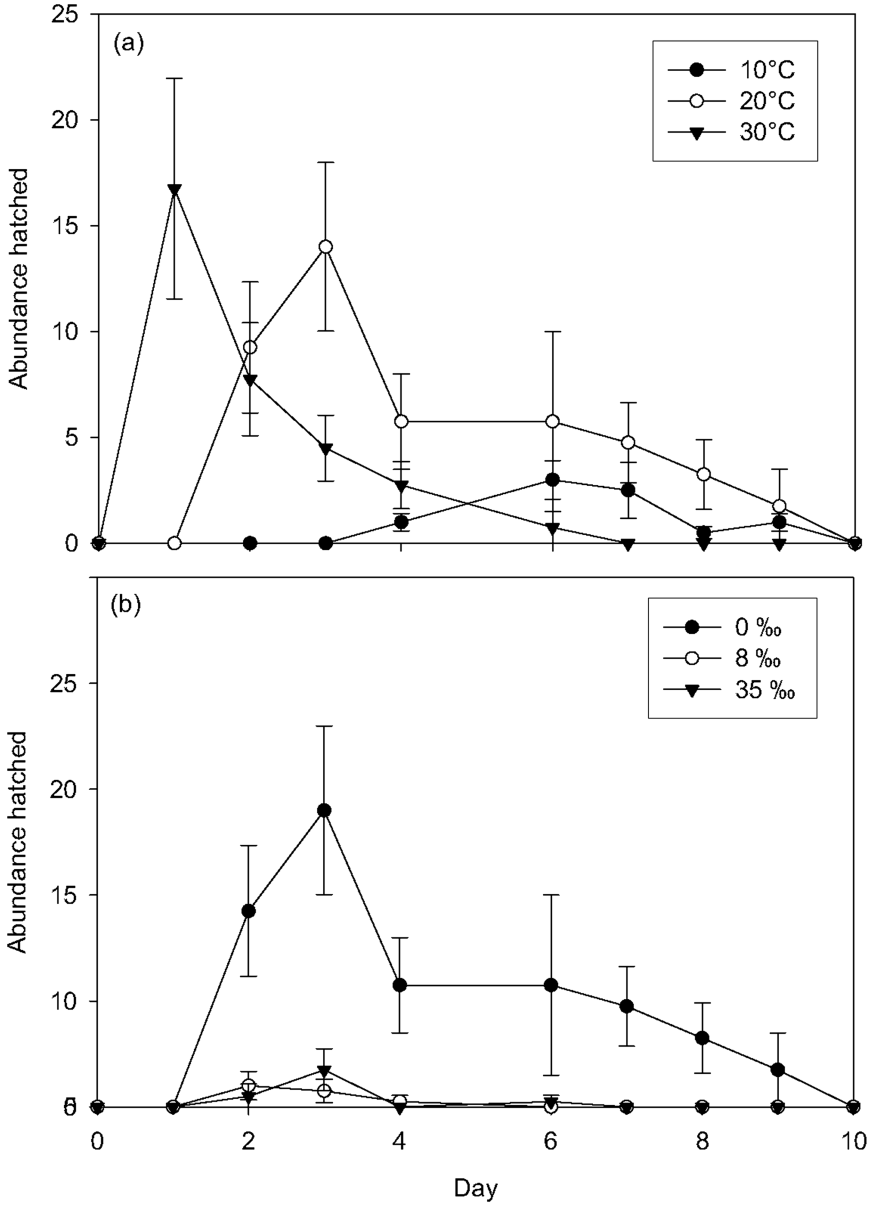


**Figure 3.** Hatch rate of invertebrate resting stages isolated from residual ballast sediment of a transoceanic vessel. Experimental conditions were (a) 0‰ growth medium at 10, 20 and 30°C and (b) 0, 8 and 35‰ growth media at 20°C.

up into the water column as sediments become more compact inside ballast tanks. However, resting stages may be induced to hatch within ballast tanks such that active individuals become part of the discharged inoculum, if environmental conditions inside the tank are hospitable.

Hatching of resting stages inside ballast tanks will depend on numerous biological, chemical and environmental factors. Even under ideal laboratory conditions, only about 40% of resting stages could be induced to hatch after transport in ballast tanks (Bailey et al., 2003). Temperature is an important factor on both the hatch rate and the subsequent reproductive rate of the population. However, hatching experiments conducted inside ballast tanks demonstrated that small populations of reproductive rotifers can arise from diapausing eggs within the timeframe of a Great Lakes voyage (Bailey et al., 2005).

## Management options

Most freshwater species cannot live in marine habitats, and vice versa (e.g., Sumich, 1992). Given this clear pattern of distribution of freshwater and marine species, we sought to explore the consequences of exposing freshwater species' resting stages to water of different salinity. Both the total abundance and species diversity of freshwater taxa that hatched were negatively related to residual water salinity (Figure 4a, b). These patterns, while preliminary, indicate that prolonged exposure of freshwater invertebrate resting stages to open-ocean water could adversely affect subsequent viability when exposed to freshwater stimuli. However, these results are confounded by the fact that significantly more resting stages are present in ships with low salinity residual water (Figure 4c). Results for experimental studies on the effect of salinity on egg viability have been mixed (Bailey et al., 2004; Gray et al., 2005), suggesting that while salinity exposure may be used to reduce the invasion risk associated with resting stages of some species, it likely will not serve as a comprehensive management tool. Flushing tanks mid-ocean with saline water may, however, be an effective management tool in that animals living in residual water or in the sediment-water interface would likely be discharged from tanks (Locke et al., 1993). While ships laden with cargo ordinarily would not seek to carry ballast water, loading and flushing of even modest amounts of highly saline water (30‰) could further reduce risk of introducing fresh- or brackish-water nonindigenous species by exceeding tolerable salinity limits since the current average salinity of residual ballast carried by ships entering the Great Lakes is only 18‰ (Niimi and Reid, 2003).

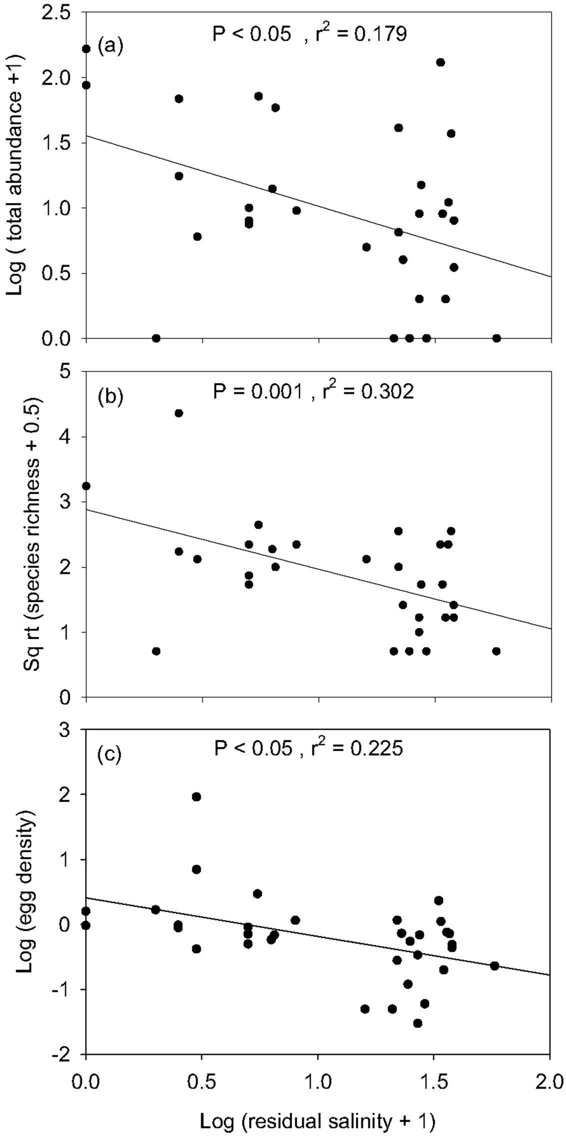


**Figure 4.** Scatterplots depicting the relationship of (a) total abundance hatched, (b) species richness hatched and (c) resting stage density for residual ballast sediments of 34 transoceanic ships with salinity of residual ballast water. All variables have been transformed to improve normality.

An alternative or complementary procedure consisting of not ballasting water in turbid port areas has been suggested as a 'best management practice' by the International Maritime Organization (IMO, 1997). This guideline would help to prevent inoculation of ballast tanks with sediment, thereby minimizing habitat for benthic species. If this procedure were implemented in conjunction with immediate flushing of ballast tanks after ballasting in turbid ports (when trim and/or stability needs permit it), sediment and resting stage accumulation in ships could be minimized, as would the attendant risk of new invasions.

## Conclusions

Although ballast water has long been recognised as a major vector of aquatic species introductions, the magnitude of importance of ballast sediments as a mechanism for introduction has not been thoroughly investigated. Ballast sediments contain a diverse array of active and dormant taxa, but the availability of taxa and resting stages in the water column during deballasting events may be a limiting factor for the sediment vector. A marked discrepancy exists between the composition of taxa living in residual sediment of ballast tanks and those hatched from resting stages contained in the same sediment. Prevailing conditions in ballast tanks probably reduce abundances of active organisms, whereas tolerant resting stages may be an important key for invasion success. As temperature is an important influence on both the hatch rate and the subsequent reproductive rate of the population, invasion success will fluctuate seasonally. The successful invasion by numerous crustacean taxa capable of producing resting stages is consistent with the view that introduction of nonindigenous species via resting stages in ballast sediments is a potentially important mode of introduction. Finally, salinity of residual ballast water is negatively related to resting stage density, and total abundance and species richness of hatched taxa. This suggests that saline water may be used as a management tool to reduce the risk of invasion posed by dormant, freshwater taxa in ballast sediment.

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