Reducing propagule supply and coastal invasions via ships: effects of emerging strategies

Mark S Minton, Emma Verling, A Whitman Miller, and Gregory M Ruiz

Ships' ballast water is a leading mechanism for the transport and introduction of nonindigenous species to ports worldwide. Two management strategies are being advanced to reduce propagule supply and invasions from overseas shipping. Ballast water exchange (BWE) is now required by several nations and is expected to be replaced by discharge standards (maximum organismal concentrations), negotiated as a treaty within the International Maritime Organization (IMO). Here, we provide the first forecast and comparison of changes to propagule supply at a national scale, resulting from these alternate management strategies. For unmanaged ballast water, sampled ships (n = 354) arriving to the US typically contained zooplankton concentrations < 3000 organisms m^{-3}, but some ships (1.1%) contained $> 50\,000$ organisms m^{-3}. Only 3.8% of these arrivals meet the IMO standards. BWE substantially reduces zooplankton concentrations, but we estimate that $\leq 17.2\%$ of BWE ships will meet IMO standards. Although most overseas arrivals discharged < 1500 m^3 of ballast water, discharges are reported as high as $103\,000$ m^3, and total inocula $\geq 10^6$ remain possible, even under the more stringent IMO strategy.

Front Ecol Environ 2005; 3(6): 304–308

Biological invasions are a potent force for ecological and evolutionary change (Vitousek *et al*. 1997; Mack *et al*. 2000). Temporal changes in the magnitude, speed, and diversity of trade have accelerated the worldwide transport and introduction of nonindigenous species (Carlton 1996; Mack *et al*. 2000; Levine and D'Antonio 2003; Ruiz and Carlton 2003). Theoretical models predict a higher likelihood of establishment with higher propagule pressure, which is a function of the size and frequency of inoculation (Williamson 1996; Grevstad 1999). This prediction has been borne out for diverse taxonomic groups in both aquatic and terrestrial systems (Simberloff 1989; Lonsdale 1999; Ruiz *et al*. 2000a).

During the past century, the use of ballast water by commercial ships has created a highly efficient transfer mechanism (vector) for entire plankton communities. Ships take on ballast water from coastal areas, entraining diverse planktonic assemblages that inhabit these areas, which are then discharged en masse at subsequent ports of call (Carlton and Geller 1993; Carlton 1996; Ruiz *et al*. 2000a,b; Figure 1). For overseas ships arriving to Australia and the US alone, ballast water discharges in each country are estimated to be in excess of 70 million metric tons annually (Kerr 1994; Carlton *et al*. 1995), creating a massive transfer of biota across the globe.

Two separate management strategies are being used to limit propagule supply from ships and thereby reduce the likelihood of invasions. Several countries have recently required arrivals from outside their Exclusive Economic Zones (hereafter foreign arrivals) to perform ballast water exchange (BWE) by flushing ballast tanks in the open ocean (Hayden and Whyte 2003; US Coast Guard 2004). This exchange replaces water of coastal origin with oceanic water, removing most of the coastal organisms; although oceanic organisms are entrained during BWE, these are considered less likely to invade coastal ecosystems. A separate strategy, negotiated as a treaty within the framework of the International Maritime Organization (IMO), sets specific upper limits for total organismal concentrations in ballast water discharge according to size or taxonomic group, including oceanic organisms (IMO 2004). The IMO treaty is awaiting ratification by member countries and the discharge standards are to be phased in through 2014, replacing BWE.

In this paper, we estimate and compare the effects of these two ballast management strategies on zooplankton propagule supply at a national scale. To date, such a comparison has not been made. Past studies have examined ballast biota at an individual location (Carlton and Geller 1993; Smith *et al*. 1999), or used ship arrivals as a proxy for propagule supply (Drake and Lodge 2004). These analyses have not attempted to forecast changes in propagule supply resulting from current management efforts, either within a port system or aggregated across broader spatial scales. In contrast, MacIsaac *et al*. (2002) has begun to explore possible effects of BWE, although this initial approach did not include the inherent variability in zooplankton concentrations or discharge volumes between different ships. Here, we focused on ships

Smithsonian Environmental Research Center, 647 Contees Wharf Road, Edgewater, MD 21037-0028 (mintonm@si.edu)

arriving to the US from overseas, and (a) estimate zooplankton concentrations in unmanaged and managed ballast water, (b) describe ballast water discharge volumes reported to the National Ballast Information Clearinghouse (NBIC), and (c) combine these data to contrast the theoretical distributions of per-ship propagule pressure from ships with unmanaged ballast water, ships that conducted BWE, and ships that meet the IMO discharge standard.

Figure 1. *Oil tanker discharging ballast water while loading crude oil in the Port of Valdez, Alaska.*

Methods

Zooplankton concentration

We initially measured per-ship zooplankton concentrations in unmanaged ballast water by sampling the ballast of foreign arrivals to two Atlantic and two Pacific US ports. For the Atlantic coast, ships were sampled upon arrival to Baltimore, MD, and Norfolk, VA; for the Pacific coast, ships were sampled in Coos Bay, OR, and Valdez, AK. Zooplankton samples were collected from ballast tanks on the ships ($n = 354$) using net tows with 80 μm plankton nets, and the total number of zooplankton per sample was determined using a stereo-microscope.

To estimate the effect of BWE, the distribution of observed zooplankton concentrations from unmanaged ballast water was reduced by 90%. BWE results in approximately 90–99% volumetric exchange (removal) of the initial water mass, and a 90% removal for coastal zooplankton appears to be a conservative estimate (Ruiz unpublished; $n = 30$ experimental voyages).

The frequency distributions of zooplankton concentration for both unexchanged and exchanged ballast water were compared to the IMO discharge standard (< 10 organisms m^{-3} for biota ≥ 50 μm in size; IMO 2004) to estimate the effects of the two management strategies on propagule supply. In addition, we tested the extent to which BWE would increase the proportion of ships meeting the IMO discharge standards, compared to unexchanged ballast water. Since our initial samples were collected with 80 μm nets, our estimates are conservative and overestimate compliance with IMO standards, which involve the use of a 50 μm size threshold for permissible zooplankton concentrations.

Ballast water discharge

We characterized the distribution of ballast water discharge volumes by foreign arrivals to the US based upon ballast water discharge data reported by ships to NBIC. We used data for all arrivals ($n = 21\,654$) that reported discharging ballast water in the continental US from foreign ports, for the period of July 1, 1999, through June 30, 2004. This represents approximately 35% of all qualifying arrivals to the US from overseas, based on comparisons with the US Maritime Administration.

Size of individual inocula per ship

We estimated the effect of the two management strategies on total zooplankton discharged per ship. The per-ship propagule pressure, inocula size, is defined as the organismal concentration multiplied by the volume of discharge:

$$I = C * V$$

where I is the size of inocula, C is the concentration of organisms, and V is the discharge volume. The theoretical frequency distributions of total zooplankton discharged per ship, (inocula size, I) under each strategy (unmanaged, BWE, and IMO) were estimated by multiplying the respective zooplankton concentrations by all recorded ballast discharge volumes. The zooplankton concentrations for BWE were those previously calculated, and the effect of the IMO was modelled by reducing all concentrations that were ≥ 10 organisms m^{-3} to 9.999 organisms m^{-3}.

Results and Discussion

Zooplankton concentration

Zooplankton concentrations in unmanaged foreign ballast water exhibited a highly skewed distribution, with most samples containing < 3000 organisms m^{-3} and 1.1% of ships with concentrations $> 50\,000$ organisms m^{-3} (Figure 2a). Although BWE reduced coastal zooplankton concentrations by one order of magnitude and significantly increased the proportion of ships meeting the IMO

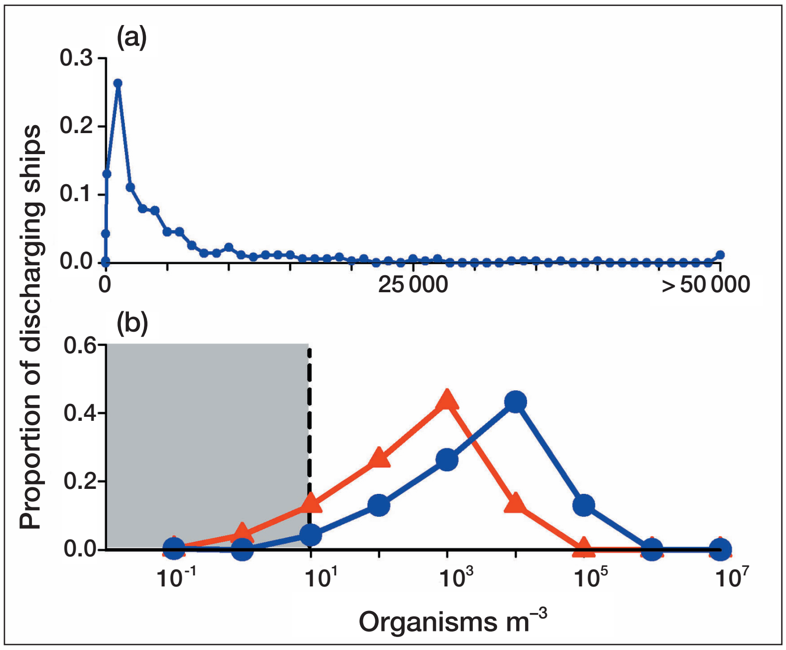

Figure 2. *Zooplankton concentrations in ballast water. (a) Smoothed histogram of zooplankton concentration (organisms* m^{-3}*) in ballast tanks (n = 354) upon arrival at four US ports. (b) Smoothed histograms of zooplankton densities on the log-scale in unexchanged ballast water (blue circles) and ballast water after theoretical BWE (red triangles). Those ships meeting the IMO discharge standard are in the shaded area to the left of the hatched line.*

discharge guidelines ($Z = 5.960$, $P < 0.001$), we estimated that the percentage of ships meeting the IMO guidelines would only increase from 3.8% to 17.2% with BWE (Figure 2b). The estimated reduction of total zooplankton by BWE is conservative for two reasons. First, our approach estimated residual concentrations for coastal species and does not account for oceanic organisms, which are entrained during the process of exchange. Second, our estimates of zooplankton concentrations do not account for some zooplankton below 80 μm in size (see Methods).

Although our analyses indicate that the IMO standards would result in a greater reduction in zooplankton concentrations than BWE for the majority of ships, this should not serve to undermine the value of BWE in reducing transfers of coastal organisms, which are generally viewed as a greater concern than oceanic organisms. At the present time, BWE is the only management strategy available to ships throughout the world, requiring no new technologies. Development and testing of technologies to meet the IMO standards are still underway, and it is likely to be many years before these are available for implementation on all vessels.

Ballast water discharge

Most foreign arrivals to the US that reported to NBIC discharged small volumes of ballast water (< 1500 m^3), and only 5% discharged > 20 000 m^3 (Figure 3a), with a maximum reported discharge of approximately 103 000 m^3. Although our primary interest in discharge volumes is to estimate total zooplankton per discharge (see below), the frequency distribution of discharge volumes is also especially relevant to the development of technologies for the treatment of ballast water. Specifically, concerns over the feasibility of ballast water treatment have focused primarily on the large volumes of ballast water used on some vessels, and the rapid rate at which this water is moved on or off ships. Our data, however, indicate that only a small proportion of vessels discharge large volumes, so the constraints on treatment options for many ships may not be as great as previously thought.

Size of individual inocula per ship

Despite the fact that most ships had relatively low zooplankton concentrations and small ballast water discharge volumes, when these are combined to estimate total zooplankton per discharge event, 95% of unmanaged inocula contained > 10^5 organisms, and over 25% of inocula contained > 10^8 organisms (Figure 3b; Table 1). BWE is estimated to reduce the size of coastal zooplankton inocula by one order of magnitude, shifting the mean dosage from 10^7 to 10^6 propagules (Table 1). Implementation of the IMO standards should result in a further reduction, lowering the median dosage one order of magnitude and the mean dosage two orders of magnitude below BWE (Table 1). With successive reductions in propagule pressure from BWE and the IMO standards (if fully implemented), we expect a decreased risk of new invasions. Even with the more stringent IMO standards, however, per-ship discharges in excess of 10^6 total zooplankton remain possible (Table 1), as a result of the large ballast discharge volumes of some ships. Moreover, the size and frequency of ship discharges to individual port systems are additive in terms of propagule delivery, and may operate in concert to affect the risk of invasions.

It is not surprising that ballast water has emerged as an important vector of marine invasions and also as a focal point for international efforts to minimize future invasions. Not only are ballast-mediated inoculations large, resulting in some high-impact invasions, but unlike many nonindigenous species vectors, ballast water operates to simultaneously transfer entire ecological communities, including viruses, bacteria, phytoplankton, zooplankton, fish, and macrophytes (Carlton and Geller 1993; Smith *et al.* 1999; Ruiz *et al.* 2000a,b). Moreover, these transfers occur on a global scale, driven by international commerce and involving ships that operate throughout the world. This has set the stage for a global, coordinated approach to ballast water management for commercial shipping.

The overall strategy being used to reduce propagule concentrations and per-ship inocula size should reduce the number of new invasions, since the likelihood of establishment increases as a positive function of inocula size (Simberloff 1989; Williamson 1996; Grevstad 1999; Lonsdale 1999; Ruiz *et al.* 2000a). Although it is generally known that lower propagule supply reduces the risk of invasions, a more precise (quantitative) ability to predict the invasion risk associated with specific levels of propagule supply is currently lacking for zooplankton, phytoplankton, protists, and other marine taxonomic groups. Not only are such dose–response relationships unavailable for marine or freshwater species in a specific ecosystem (port), but developing robust predictions is especially complicated for ballast water inocula, which involve thousands of species. Because of the complex nature of shipping and the associated planktonic assemblages, there is considerable uncertainty about the species composition and abundance of any ballast water discharge (Verling *et al.* in press). For many (perhaps most) of these species, very little is known about environmental tolerances and ecological requirements, which will influence their ability to colonize (Lonsdale 1999; Ruiz and Carlton 2003). The existing gap in our understanding of quantitative dose–response relationships for ballast inocula presents a serious challenge in identifying specific standards (either concentrations or per-ship discharge) for ballast water management.

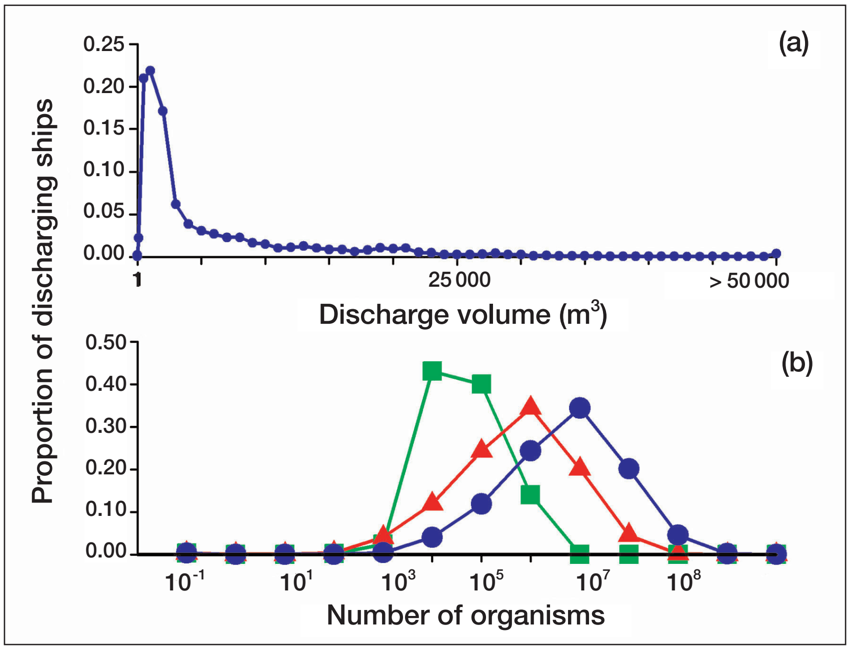

Figure 3. *Characterization of discharge volumes and inocula. (a) Smoothed histogram of ballast water discharge volumes (m^3) reported to NBIC (July 1999–June 2004, n = 21 654). (b) Smoothed histograms of the theoretical propagule dosages (number of organisms) on the log-scale of all combinations of zooplankton densities and discharge volumes (7 665 516 combinations) for unexchanged (blue circles) ballast water, ballast water after theoretical BWE (red triangles), and ballast water meeting the IMO discharge standard (green squares).*

It is noteworthy that current ballast management strategies target the vector rather than individual species. This approach has emerged because of the vast number of species available for transport in ballast, combined with the high level of uncertainty about which species are present in any particular ballast tank and their potential to colonize (as described above). Although species richness and evenness of ballasted communities are important in defining invasion risk, both among ships and recipient ports, the effort required to adequately characterize species assemblages in each ballast tank and to interpret associated risk is widely viewed as impractical. Instead, vector management has been adopted as a precautionary approach and a more efficient means of reducing invasion risk for ships' ballast, since this is aimed at limiting abundance of all species (Ruiz and Carlton 2003).

Table 1. Summary of the theoretical propagule dosages (total organisms) from ships (7 665 516 combinations) discharging unmanaged ballast water, ballast water following BWE, and ballast water meeting the IMO discharge standards

	Unmanaged	*BWE*	*IMO*
Maximum	8.92×10^9	8.92×10^8	1.03×10^6
Third quartile	9.83×10^6	9.83×10^5	4.72×10^4
Median	1.85×10^6	1.85×10^5	1.15×10^4
First quartile	2.63×10^5	2.63×10^4	5.16×10^3
Minimum	0.00	0.00	0.00
Mean	2.12×10^7	2.12×10^6	4.35×10^4
Standard deviation	8.83×10^7	8.83×10^6	7.42×10^4

Using vector management, the IMO has advanced discharge standards for several different taxonomic groups that seek to limit permissible concentrations in ballast water released in coastal waters. For zooplankton, our results indicate that this standard will result in a substantial reduction in concentrations, beyond that provided by the current management strategy, BWE. It is important to note that our analysis is confined solely to waterborne zooplankton. We have not yet compared the effect of the IMO standards to current practices for (1) smaller organisms across several taxonomic groups (ie phytoplankton, protists, bacteria, and viruses), including some that are found in biofilms, or (2) benthic organisms and resting stages at the bottom of ballast tanks. While BWE may be less effective at removing organisms associated with biofilms and bottom habitats, compared to planktonic organisms, the relative magnitude of discharge from these sources may also be low and remains largely unquantified at present.

Conclusions

This analysis provides a first quantitative estimate of the zooplankton propagule supply in ballast water at a national scale, highlighting changes to per-ship inoculations that result from emerging management strategies. For zooplankton, we find the IMO strategy yields a substantial reduction in propagule supply compared to the present BWE strategy. With successive reductions in propagule pressure from BWE and the IMO strategy, if implemented, we expect a decreased risk of new invasions, because a positive relationship exists between propagule supply and the likelihood of establishing non-native populations (Simberloff 1989; Williamson 1996; Grevstad 1999; Lonsdale 1999; Ruiz *et al*. 2000a). Nevertheless, predicting the magnitude of risk reduction and the risk associated with particular organismal concentrations depends upon as yet undefined dose–response functions in marine ecosystems (Ruiz and Carlton 2003). Understanding the quantitative effects of density, magnitude, and frequency of inoculation on invasion outcome is a major challenge for invasion ecology and a high priority for advancing effective management strategies.

Acknowledgements

We thank JT Carlton for providing access to ballast water samples from Oregon, K Lion for her assistance with the NBIC data, and L McCann, G Smith, M Frey, and T Huber for their assistance with the plankton analysis. We thank RA Everett for discussion and comments while preparing this manuscript, and MA Evans for statistical discussions. This research was supported by the Maryland Sea Grant Program, National Sea Grant Program, Prince William Sound Regional Citizens' Advisory Council, and US Coast Guard.

References

Carlton JT and Geller JB. 1993. Ecological roulette: the global transport of nonindigenous marine organisms. *Science* **261**: 78–82.

Carlton JT, Reid D, and van Leeuwen H. 1995. The role of shipping in the introduction of nonindigenous aquatic organisms to the coastal waters of the United States (other than the Great Lakes) and an analysis of control options. Washington, DC: US Coast Guard. Technical Report No. CG-D11-95.

Carlton JT. 1996. Pattern, process, and prediction in marine invasion ecology. *Biol Conserv* **78**: 97–106.

Drake JM and Lodge DM. 2004. Global hot spots of biological invasions: evaluating options for ballast water management. *Proc R Soc London Ser B* **271**: 575–80.

Grevstad FS. 1999. Factors influencing the chance of population establishment: implications for release strategies in biocontrol. *Ecol Appl* **9**: 1439–47.

Hayden BJ and Whyte CF. 2003. Invasive species management in New Zealand. In: Ruiz GM and Carlton JT (Eds). Invasive species: vectors and management strategies, Washington, DC: Island Press.

IMO (International Maritime Organization). 2004. International Convention for the Control and Management of Ships Ballast Water & Sediments. BWM/CONF/36, London, UK. 16 February 2004.

Kerr S. 1994. Ballast water ports and shipping study. Australian Quarantine and Inspection Service, Ballast Water Research Series. Report No 5.

Levine JM and D'Antonio CM. 2003. Forecasting biological invasions with increasing international trade. *Conserv Biol* **17**: 322–26.

Lonsdale WM. 1999. Global patterns of plant invasions and the concept of invisibility. *Ecology* **80**: 1522–36.

MacIsaac HJ, Robbins TC, and Lewis MA. 2002. Modeling ships' ballast water as invasion threats to the Great Lakes. *Can J Fish Aquat Sci* **59**: 1245–56.

Mack RN, Simberloff D, Lonsdale WM, *et al*. 2000. Biotic invasions: causes, epidemiology, global consequences, and control. *Ecol Appl* **10**: 689–710.

Ruiz GM, Fofonoff PW, Carlton JT, *et al*. 2000a. Invasion of coastal marine communities in North America: apparent patterns, processes, and biases. *Annu Rev Ecol Syst* **31**: 481–531.

Ruiz GM, Raulings TK, Dobbs FC, *et al*. 2000b. Global spread of microorganisms by ships. *Nature* **408**: 49.

Ruiz GM and Carlton JT. 2003. Invasion vectors: a conceptual framework for management. In: Ruiz GM and Carlton JT (Eds). Invasive species: vectors and management strategies. Washington, DC: Island Press.

Simberloff D. 1989. Which insect introductions succeed and which fail. In: Drake JA, Mooney HA, di Castri F, *et al*. (Eds). Biological invasions: a global perspective. Chichester, UK: John Wiley & Sons Ltd.

Smith DL, Wonham MJ, McCann LD, *et al*. 1999. Invasion pressure to a ballast-flooded estuary and an assessment of inoculant survival. *Biol Invasions* **1**: 67–87.

US Coast Guard. 2004. Final rule: mandatory ballast water management program for US waters. Washington, DC: US Coast Guard. 69 FR 44952; 28 July 2004.

Verling E, Ruiz GM, Smith LD, *et al*. Supply-side invasion ecology: characterizing propagule pressure in coastal ecosystems. *Proc R Soc London Ser B*. In press.

Vitousek PM, Mooney HA, Lubchenco J, and Melillo JM. 1997. Human domination of Earth's ecosystems. *Science* **277**: 494–99.

Williamson M. 1996. Biological invasions. London, UK: Chapman & Hall.