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Ballast water deoxygenation can prevent aquatic introductions while reducing ship corrosion

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Abstract

One of the most important mechanisms for the introduction of aquatic nuisance species is transport in ship ballast waters. Although several ballast tank treatments to prevent transport of aquatic organisms appear promising, all existing approaches will result in significant costs to the shipping industry. This study describes a treatment that can dramatically reduce the survivorship of most organisms found in ballast waters while providing economic benefits to ship owners. Purging of oxygen from ballast tanks with nitrogen was recently found to be a cost-effective technique for reducing corrosion and therefore extending ship life. We tested the tolerance of larvae of known invasive invertebrate species to low levels of oxygen, comparable with those resulting from the anticorrosion treatment, and detected significant levels of mortality. Two separate literature reviews further support the conclusion that few organisms will be able to withstand extended periods of exposure to nitrogen-treated ballast water. This novel deoxygenation technique may therefore have direct benefits to both marine conservation and the shipping industry. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Invasive species; Ballast water; Corrosion; Deoxygenation; Oxygen tolerance

1. Introduction

Invasions by non-native aquatic species are increasingly common worldwide in coastal habitats (Cohen and Carlton, 1998). Estuaries in particular harbor large numbers of introduced species (Ruiz et al., 1997, 1999). For instance, there are 234 known invasive species in the San Francisco Bay and Delta (American Pacific coast; Cohen and Carlton, 1998), 119 in the Hudson River Basin (American Atlantic coast; Mills et al., 1996), and 99 in Port Phillip Bay (Australian Southern coast; Hewitt et al., 1999). Even in these relatively well-studied areas, there are many more invaders to be discovered because surveys for non-native species have focused on conspicuous, macroscopic taxa.

Although the effects of many introduced aquatic species on habitats they colonize remain largely unknown, some have had demonstrably strong negative influences. Impacts include: decrease in abundance and even local extinction of native species (e.g. by the Japanese mudsnail *Batillaria attramentaria* in California; Byers, 1999), alteration of habitat structure (e.g. by the Atlantic cordgrass *Spartina alterniflora* on the Pacific coast; Daehler and Strong, 1996), and massive economic costs due to biofouling (e.g. by the European zebra mussel *Dreissena polymorpha* in the Great Lakes; Johnson and Carlton, 1996).

Global shipping, which moves 80% of the world's commodities and is fundamental to world trade, inadvertently transports many aquatic organisms (see review by National Research Council, 1996). In particular, ballast water (water that is pumped into dedicated ballast tanks or into empty cargo holds to increase the draft, change the trim, regulate the stability, or maintain the stress loads) is considered the most important vector responsible for transporting and introducing non-native aquatic species to new biogeographic regions (Carlton and Geller, 1993). Vessels commonly pump in water in one port, and discharge it at another. Many planktonic

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organisms captured in ballast waters survive even lengthy journeys on board ships. Examination of ballast water upon arrival of vessels has revealed bacteria (McCarthy and Khambaty, 1994), protists (Galil and Huelsmann, 1997; Pierce et al., 1997), dinoflagellates (Hallegraeff and Bolch, 1991), diatoms, zooplankton, benthic invertebrates, and fish (Williams et al., 1988; Carlton and Geller, 1993; Wonham et al., 2000). Although other vectors, such as ship-fouling and aquaculture, are still important mechanisms introducing aquatic species to new places, none match ballast water transport for the sheer magnitude of organisms introduced (National Research Council, 1996).

Theoretical and empirical studies have shown that "propagule pressure" (the number of larvae, spores, seeds, or dispersive adults introduced) is one of the best predictors of invasion success (Williamson, 1996). Since ballast water transport is a key source of propagules, attention has focused recently on means of limiting ballast water introductions. It has proven challenging to find a technique that is effective at reducing introductions, environmentally friendly, and yet also acceptable to the shipping industry in terms of safety, time, and cost. For instance, exchange of ballast water on the high seas is currently recommended to reduce introductions (since coastal organisms are unlikely to invade open ocean areas, and vice versa), but the process is time-consuming and cannot be performed in rough sea conditions.

Analysis of different ballast water treatments by the National Research Council (1996) suggested that intensive filtration, thermal treatment, and biocides were the most promising options. However, discharging warm water or water laden with biocides potentially threatens biological communities around ports, biocides can be dangerous to crewmembers, and fine filtration systems are expensive to install and maintain (National Research Council, 1996). Recently, a more comprehensive and complex treatment system has also been proposed that combines filtration, centrifugation, and ultraviolet radiation of ballast waters (Hyde Marine, Inc.; Cangelosi et al., in prep.). However, unless mandated to do so by law, the shipping industry is unlikely to voluntarily implement any costly, time-consuming, or potentially dangerous procedures. Widespread adoption of such ballast water treatment measures therefore lies well in the future.

The implementation of ballast water treatment measures may be hastened by providing the shipping industry with economic incentives for doing so. Here, we explore one ballast water treatment that may benefit ship owners by reducing corrosion, while simultaneously limiting the number of aquatic organisms surviving transport in ballast tanks.

The rusting of ballast tanks from exposure to seawater is extremely destructive and costly for individual vessels and the shipping industry as a whole. Currently painting is used almost exclusively as the means to prevent ballast tank corrosion, but it is expensive and time-consuming. Investigators from Sumitomo Heavy Industries, Ltd. of Japan have developed an alternative rust prevention technique that purges oxygen from ballast tanks with nitrogen gas. This new anticorrosion technology was derived from the basic concept that removing oxygen from the ballast tanks will limit the oxidation of metallic structures and thus greatly reduce the problems associated with rusting. Decreased oxygen levels also have the potential to kill a substantial portion of organisms in ballast water; hypoxia is well known to have negative effects on many aquatic species (see reviews by Grieshaber et al., 1994; Diaz and Rosenberg, 1995).

The objectives of this study were to evaluate whether ballast tank deoxygenation is a cost-effective method of reducing corrosion and whether it can successfully curb the introduction of aquatic organisms. We present a synthesis and reanalysis of the relevant parts of a Japanese technical report describing a shipboard field study implementing this anticorrosion approach (Matsuda et al., 1999) and discuss the findings in an international peer-reviewed journal for the first time. As a direct test of whether deoxygenation can limit invasion, we carried out laboratory oxygen tolerance experiments with larvae of three widely introduced aquatic nuisance species. We also conducted two literature reviews to determine more generally the likely effects of ballast water deoxygenation on survival of a wide variety of aquatic organisms. Finally, based on our findings, we evaluate this ballast water treatment mechanism relative to other options.

2. Materials and methods

2.1. Reducing corrosion through deoxygenation

The new anticorrosion system was designed so oxygen is purged from ballast tanks with a continuous supply of nitrogen. For this shipboard study, nitrogen was generated through pressure swing absorption and stored in liquid nitrogen tanks. Nitrogen then passed through an evaporator and was released as a gas, under constant pressure, into the ballast water (Fig. 1).

In order to determine the effectiveness of this system for reducing corrosion, an experiment was conducted using a 150,000-ton coal/ore carrier for approximately 18 months (583 days). Steel test plates and oxygen, temperature, and pressure sensors were placed in two separate 908 m^3 ballast tanks (Fig. 1); one with nitrogen gas added while the ship was underway as a test treatment and the other untreated as a control (standard ballast tank conditions). At the end of the experiment, test plates and all components of the two ballast tanks

were examined for amount of rusting, and corrosion rates were quantified.

A final step was also taken to determine the cost-effectiveness of this corrosion prevention technique. Estimates of cost for equipment, installation and continual use of the deoxygenation technique were made (on a year-by-year basis) for a 25-year period and compared with the cost of standard painting and maintenance techniques over the same amount of time.

2.2. Oxygen tolerances of invasive larvae

In laboratory experiments mimicking the procedures and oxygen levels of the shipboard anticorrosion study, we tested the oxygen tolerance of larvae from three taxonomically diverse invaders known to have substantial economic and ecological impacts.

Ficopomatus enigmaticus (serpulid polychaete) is an Australian reef-building tubeworm that has been introduced to many estuaries in Europe and the Americas (Cohen et al., 1995). Adults were collected from huge aggregations on pilings in Elkhorn Slough, central California. Individuals were induced to spawn and the resulting trochophore larvae were cultured for 3 days until use in the experiment.

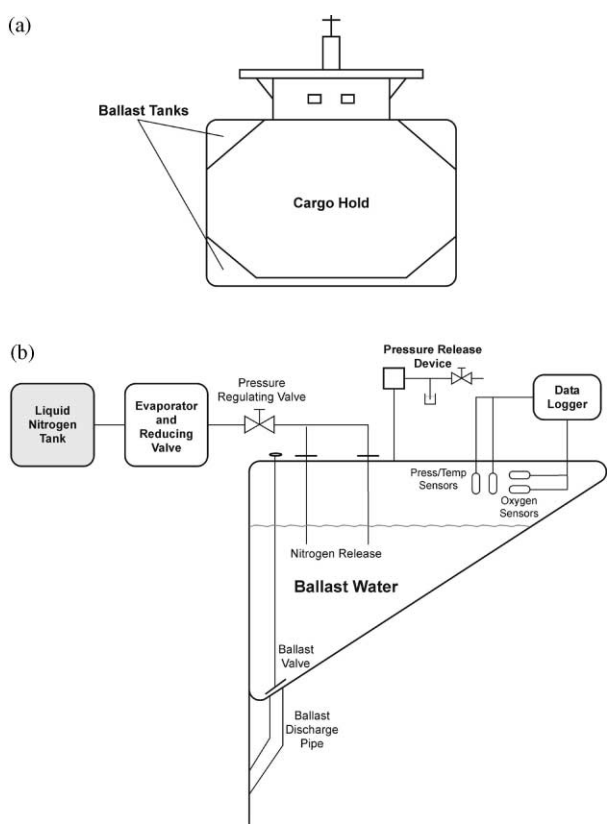

Fig. 1. Anticorrosion technique described in detail by Matsuda et al. (1999): (a) cross sectional diagram of a typical cargo ship, (b) basic design of equipment used to deoxygenate ballast waters and to study corrosion levels on a coal/ore vessel at sea for 18 months.

Carcinus maenas, the common European green shore crab, has been introduced to both North American coasts, Australia, and South Africa (Cohen et al., 1995). We collected an ovigerous (egg carrying) female green crab from Tomales Bay, northern California. The brooding female was maintained in an aquarium until she released first-stage zoea larvae that were subsequently used in the oxygen tolerance experiment.

The zebra mussel, *Dreissena polymorpha*, was introduced from Europe into the Great Lakes region of North America in the 1980s and has since spread extensively. Zebra mussel larvae were spawned from brood stock collected from the Illinois River and the response of 3-day-old veligers to low oxygen levels was tested.

Six identical 200 ml acrylic chambers, with a single top opening, were constructed to determine oxygen tolerance of the different larval forms. In separate trials, 25 larvae of a single species were added to three replicate deoxygenation and three replicate control chambers containing approximately 180 ml of filtered water. In all test and control chambers, food (algae or young brine shrimp, depending on species) was also added at concentrations sufficient to sustain the larvae for several days.

The three replicate deoxygenation chambers were bubbled with nitrogen gas for 10–15 min. Individual sensors (Pinpoint II; American Marine, Inc.), sealed within a hole in the center of a silicon stopper, were used to monitor oxygen levels. When concentrations dropped below 0.8 mg O_2/l, the openings were quickly sealed. With airtight stoppers in place, the sensors remained submerged in the water containing larvae and thus allowed continuous evaluation of dissolved oxygen levels throughout the experiments.

The identical procedure was followed for the three replicate controls; however, rather than nitrogen, air was bubbled for 10 min and the chambers were not sealed with stoppers but left open to air. Oxygen levels in all three control containers were also monitored periodically throughout the experiments with a fourth sensor.

To determine the maximum time of survival under hypoxia, percent mortality of *F. enigmaticus* and *C. maenas* larvae was calculated for the deoxygenation and control chambers after 48 h. The percent mortality of *D. polymorpha* larvae was examined after 72 h since veliger larvae appear to be more tolerant of low oxygen conditions (see Section 3.3).

2.3. Literature review of oxygen tolerances

Two focused literature reviews were conducted to determine whether other aquatic organisms would also perish under the low-oxygen conditions produced in the nitrogen-treated ballast tanks. Because of the numerous publications on the effects of hypoxia and anoxia (e.g.

Diaz and Rosenberg, 1995; Breitburg et al., 1997; Wannamaker and Rice, 2000), literature surveys were conducted to produce only representative samples for oxygen tolerances of diverse species.

The first was a comprehensive search of all published work on the oxygen tolerance levels of marine invertebrate larvae. Both the Aquatic Sciences and Fisheries Abstracts (ASFA; CSA Database Service) and Basic BIOSIS (Online Computer Library Center, Inc.) searchable databases were used to locate publications containing information on the mortality of marine invertebrate larvae when the sole treatment was exposure to hypoxic or anoxic conditions. All publications found through the electronic searches were then also reviewed for references to additional relevant work.

The second search was designed to generate only a representative sample of all published literature for the oxygen tolerances of various aquatic organisms (regardless of life history stage). The ASFA searchable database was used to identify peer-reviewed publications containing original data on the mortality of aquatic organisms due exclusively to low oxygen, from the year 1980 to the present. Using these parameters, two separate searches were conducted with the terms "oxygen tolerance" and "hypoxia tolerance" as key words.

3. Results

3.1. Reducing corrosion through deoxygenation

Oxygen levels in the control ballast tank remained near saturation levels (approximately 20.9%) throughout the field study onboard the coal/ore carrier. Similarly, oxygen was also found to be at air saturation after each uptake of new seawater into the nitrogen-treated ballast tanks. However, once the nitrogen purging treatment was initiated, levels dropped quickly to below 0.5% air saturation ($\leqslant$0.2 mg/l). These rapid and dramatic changes in oxygen concentrations as the ship moved from port to port over the 583-day experiment are illustrated in Fig. 2. It is important to note that once the nitrogen treatment began, oxygen levels typically remained extremely low for extended periods, in most cases for weeks to months. Furthermore, there was no obvious microbial production of hydrogen sulfide in the treated ballast tank as a result of reduced oxygen levels.

The extended periods of hypoxia produced in the treated ballast tank significantly reduced levels of rust (Matsuda et al., 1999). Overall, it was found that the corrosion rates on test plates and various components of the ballast tank itself were lowered to about 10% the levels found in the oxygenated (control) ballast tank (Fig. 3). For example, the rate of rusting on shot blasted steel test plates placed at the bottom of the nitrogen treated ballast tank was 0.06 mm/year, compared with 0.47 mm/year for the same type of plates at the bottom of the control tank. It was also found that under low oxygen conditions metallic structures do not necessarily require initial painting with standard tar epoxy. Corrosion rate of unrefined, bare steel plates placed at the midwater line of the low oxygen tank was again only 0.06 mm/year. While it was found that painting prior to deoxygenation could reduce this rate further to 0.001 mm/year, it is not cost effective. In either case initial coating with shop primer to prevent rusting during vessel construction is recommended.

This deoxygenation technique also proved to be very cost-effective (Matsuda et al., 1999). During a 25-year period (commonly the lifetime of a vessel), the cost of painting and maintenance of ballast tanks on a typical cargo ship was calculated to be approximately $10.9 million (US). During the same time span the deoxygenation technique would cost at least $ 1 million (US)

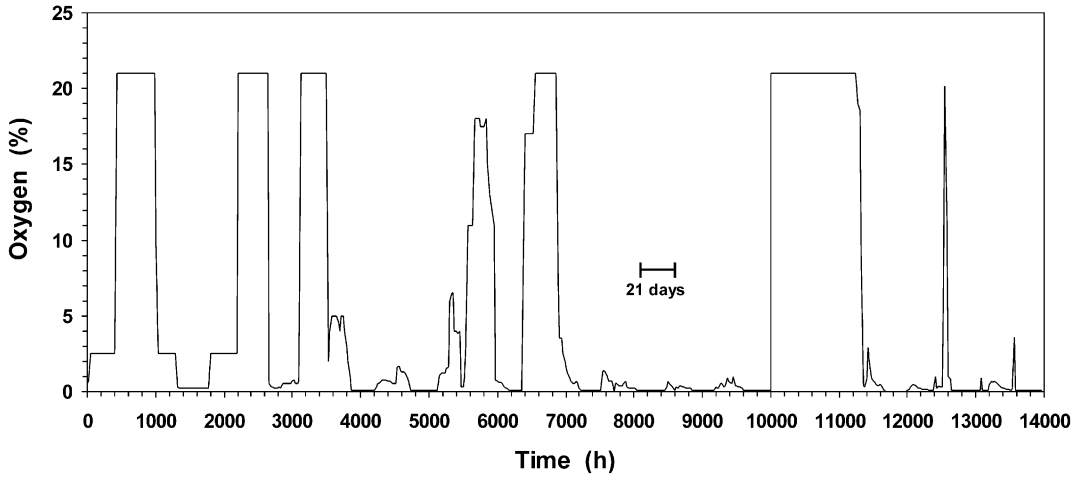

Fig. 2. Percent oxygen in the nitrogen treated ballast tanks during 18 months of operations of the coal/ore vessel. Peaks in oxygen concentration (20.9%) correspond to periods after the ship released ballast water, remained in port, and took on new water; whereas low oxygen levels (down to values below 0.5%) correspond to when the ship was at sea and nitrogen treatment employed (Matsuda et al., 1999).

less, depending on the method used to generate the nitrogen released into ballast tanks. The method used in this study was pressure swing absorption (PSA), which generates nitrogen from air by changing the pressure through zeolite, and would bring the 25-year total cost down to $9.9 million. An alternative to PSA is a liquefied nitrogen generator (LNG) that produces nitrogen by liquefying air and would lower the total cost even further to $9.2 million. Although the typical yearly costs are similar for all three treatments (between $100,000/year and $200,000/year), larger differences are found in the price of initial implementation and major overhauls (Fig. 4). Therefore, when averaged over the total 25 years, LNG deoxygenation can a save a ship owner approximately $70,000/vessel/year when compared with the painting technology currently available.

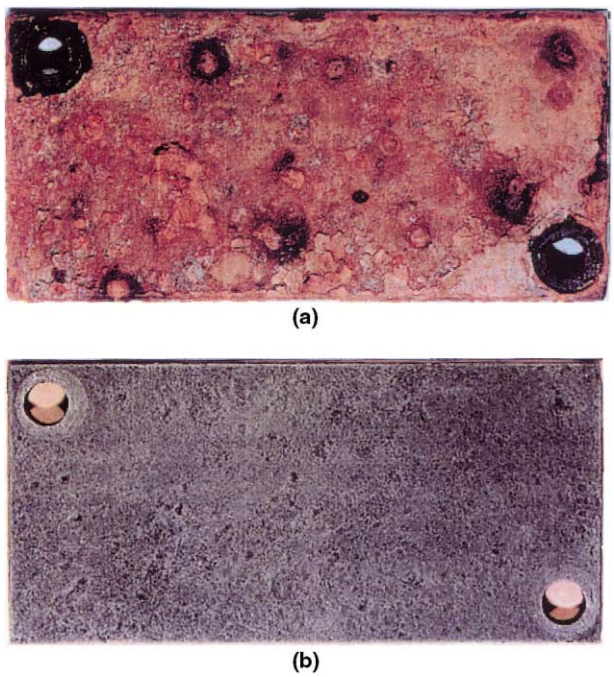

Fig. 3. Corrosion levels (including scale) on steel plates placed in ballast tanks during the 18 months shipboard study: (a) plate from the control ballast tank under constant air saturation levels with a corrosion rate of 0.383 mm/year, (b) plate from the nitrogen treated ballast tanks under periodic hypoxia with a corrosion rate of 0.039 mm/year (Matsuda et al., 1999).

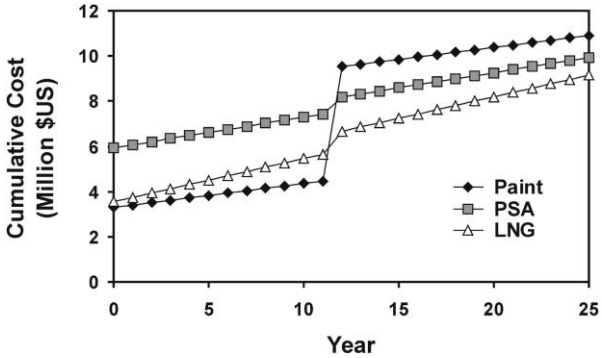

Fig. 4. Cumulative year-to-year cost in US dollars for ballast tank painting, deoxygenation using pressure swing absorption (PSA), and deoxygenation using a liquefied nitrogen generator (LNG); with the final values corresponding to the total 25-year cost. There are significant initial implementation costs in year 1, and major overhaul costs in approximately year 12, for all three anticorrosion treatments considered (Matsuda et al., 1999).

Initial setup and year-to-year costs of each of the three methods investigated (Painting, PSA and LNG) for the typical life span of a vessel are shown in Fig. 4. Although ballast tank corrosion plays a large role in limiting the longevity of ships to approximately 25 years, other factors are involved including the deterioration of hull shell structures, cargo tanks, and engine plants.

3.2. Oxygen tolerances of invasive larvae

Percent mortality of recovered individuals clearly demonstrated that the survivorship of larvae of the three species tested was reduced significantly after exposure to hypoxic conditions when compared with survivorship in normoxic controls (Fig. 5; Student's *t*-test, $P<0.001$ for all comparisons). Although all larvae were typically recovered after completion of the experiments, in a few cases it was not possible to relocate each of the 25 individuals originally placed into the chambers. However, a minimum of 18 larvae from each of the test and control trials were identified and scored as live or dead. While in all cases <26% of l-arvae died in containers open to air, after only 2 days of exposure to oxygen levels continuously below 0.8 mg/l, 79% of *F. enigmaticus* and 97% of *C. maenas* larvae were killed. Similarly, 82% of *D. polymorpha* larvae did not survive the low oxygen environment after 3 days.

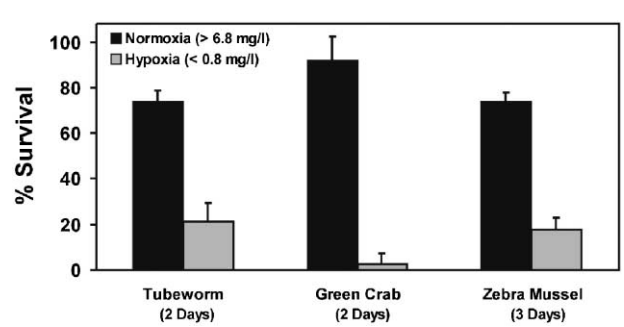

Fig. 5. Mean percent survival (±S.D.) of *Ficopomatus enigmaticus* (tubeworm), *Carcinus maenas* (green crab), and *Dreissena polymorpha* (zebra mussel) larvae after 2 or 3 days of being held in water open to air (normoxia) and in water where oxygen was removed by purging with nitrogen gas (hypoxia).

Table 1
Time until significant mortality (LD_{50}, LT_{50}, or survivorship in treatment significantly less than control) was found for invertebrate larvae held under various low oxygen concentrations

Species	O_2 level (mg/l)	Time to sign. mort. (h)	Source
Crassostrea virginica[a] oyster 82 μm veligers	0.02	11	Widdows et al. (1989)
C. virginica oyster 167 μm veligers	0.02	18	Widdows et al. (1989)
C. virginica oyster 312 μm veliger	0.02	51	Widdows et al. (1989)
Ilyanassa obsoleta[a] mudflat snail veligers	1.7	96	Vernberg and Vernberg (1975)
Cancer irroratus brachyuran crab first stage zoea	1.69	4	Vargo and Sastry (1977)
C. irroratus second stage zoea	1.54	4	Vargo and Sastry (1977)
C. irroratus third stage zoea	0.64	4	Vargo and Sastry (1977)
C. irroratus forth stage zoea	0.87	4	Vargo and Sastry (1977)
C. irroratus fifth stage zoea	0.97	4	Vargo and Sastry (1977)
C. irroratus megalopae	2.26	4	Vargo and Sastry (1977)
Metapenaeus monoceros white shrimp zoea	3.4	48	Kang and Matsuda (1994)
M. monoceros mysis	3.4	48	Kang and Matsuda (1994)
Portunus trituberculatus Japanese blue crab zoea	3.4	48	Kang et al. (1993)
P. trituberculatus megalopae	2.6	48	Kang et al. (1993)
Coscinasterias calamaria[a] seastar pluteus	2.0	0.5	Mountfort et al. (1999)
Mytilus edulis[a] mussel 106 μm veligers	0.02	15	Wang and Widdows (1991)
M. edulis mussel 224 μm veliger	0.02	30	Wang and Widdows (1991)
Theora fragils bivalve veligers	1.7	48	Tamai (1996)
Argopecten irradians bay scallop veligers	0.0[b]	12	Wang and Zhang (1995)
Marenzelleria viridis[a] polychaete trochophores	0.0[b]	4	Fritzsche (1997)

[a] Larvae of known invasive species.
[b] 0.0 mg/l corresponds to publications that only present experimental oxygen concentrations as "anoxic".

Table 2
A representative sample of time until significant mortality (LD_{50}, LT_{50}, or survivorship in treatment significantly less than control) was found for aquatic organisms held under various low oxygen concentrations

Species	O_2 level (mg/l)	Time to sign. mort. (h)	Source
Dreissena polymorpha adult zebra mussel	0.03	72	Matthews and McMahon (1999)
Corbicula fluminea adult Asian clam	0.03	283	Matthews and McMahon (1999)
Gadus morhua adult cod	1.6	96	Plante et al. (1998)
Astronotus ocellatus adult freshwater fish	0.4	24	Muusze et al. (1998)
Amphiura filiformis adult brittle star	0.01	180	Vistisen and Vismann (1997)
Ophiura albida adult brittle star	0.01	60	Vistisen and Vismann (1997)
Gammarus pseudolimnaeus adult male freshwater amphipod	1.5	24	Hoback and Barnhart (1996)
G. pseudolimnaeus adult female	1.9	24	Hoback and Barnhart (1996)
G. pseudolimnaeus juvenile	0.9	24	Hoback and Barnhart (1996)
Platichthys flesus juvenile flounder	1.0	2	Tallqvist et al. (1999)
Cytherissa lacustris adult freshwater ostracod	1.0	20	Newrkla (1985)
Hexagenia limbata mayfly nymph	1.0	24	Winter et al. (1996)
Loimia medusa adult polychaete	0.5	72	Llanso and Diaz (1994)
Meganyctiphanes norvegica adult krill	1.8	2	van den Thillart et al. (1999)

3.3. Literature review of oxygen tolerances

Although the oxygen tolerance of various organisms and larval forms varied, previously published values suggest that almost no aquatic animals would be able to survive long ocean crossings in nitrogen-treated ballast tanks. The comprehensive review for oxygen limits of invertebrate larvae shows that hypoxia or anoxia can only be tolerated at most a few days and commonly just a few hours (Table 1). The representative sample review of all aquatic organisms found similar results but in a few cases adult animals were able to withstand near anoxia for over a week (Table 2). However, the ability to withstand such extended periods of low oxygen appears to be the exception and was commonly the reason oxygen tolerance of the particular species was studied (e.g. Vistisen and Vismann, 1997).

4. Discussion

4.1. Benefits of ballast tank deoxygenation for ship owners

The shipboard field test described here has demonstrated that nitrogen addition is an economically viable means of significantly reducing corrosion in ballast water tanks. Over the life of a typical vessel, the cost of outfitting a ship with the appropriate plumbing for nitrogen addition, and the cost of generating the nitrogen required, is much less than the cost of the alternative, painting of tanks.

The vessel used in the shipboard study never transports seawater in empty cargo holds. However, this practice is common for some international vessels. Based on the study by Matsuda et al. (1999), we believe the same on-board nitrogen purging technique would function effectively for large cargo holds, with the same benefits of corrosion prevention.

4.2. Larval response to deoxygenation for three known aquatic invaders

Our laboratory experiments mimicking the shipboard deoxygenation procedures revealed that the resulting hypoxia caused significant mortality in larvae of three known invaders (*F. enigmaticus*, *C. maenas*, and *D. polymorpha*). Our results represent conservative estimates of the effects of deoxygenation because we used higher oxygen levels (<0.8 mg/l versus $\leqslant 0.2$ mg/l) and shorter durations than were attained during the shipboard study (Fig. 2). Given the high mortality after 2–3 days, we predict all larvae tested would have been killed during the 2–3 week duration of most ocean crossings.

The three species we tested are ones that have become remarkably abundant following introduction to new regions. Vast reefs of the Australian tubeworms clear enormous volumes of water daily, damage pilings, and interfere with lock operations (Davies et al., 1989; Read and Gordon, 1991; Cohen and Carlton, 1995). Zebra mussels have become numerically dominant in the Great Lakes region, replacing other benthic organisms, altering planktonic food webs, and costing several billion dollars annually in control measures (Ruiz et al., 1997). Green crabs are implicated in the collapse of the soft shell clam fishery on the North American Atlantic coast, and only a decade after invading the Pacific coast have already had significant ecological effects on benthic communities there (Grosholz et al., 2000). It is probably too late to reverse the impacts of these species on the communities they have already invaded. However, there are still many regions of the world that have not yet been invaded by them. Our experiments suggest that deoxygenation of ballast water would help to prevent the transport of these species to new biogeographic regions.

4.3. Hypoxia tolerances of other ballast water organisms

Various recent studies (e.g. Carlton and Geller, 1993; Smith et al., 1999) have quantified the diversity and abundance of organisms transported in ballast water. Since water is drawn in through a mesh, typically only small organisms are transported in ballast tanks. Planktonic larvae represent the dispersal stage for many species and are among the most abundant organisms found in ballast water (Carlton and Geller, 1993; Smith et al., 1999). Our comprehensive review of larval response to hypoxia (Table 1), which included a number of invasives, revealed significant mortality for all species, typically within hours or days. Nitrogen treatment of ballast tanks therefore is likely to effectively kill the great majority of invertebrate larvae on voyages of more than 72 h.

From our second literature review, it appears that early developmental stages of vertebrate species (those small enough to be drawn into ballast tanks) are also sensitive to low oxygen environments. Tallqvist et al. (1999) found that juvenile flounder (*Platichthys flesus*) only survived 2 h of exposure to hypoxia, which is similar to the physiological tolerance of other larval and juvenile fish (e.g. Crocker and Cech, 1997).

Although early developmental stages of various species are commonly found in ballast waters, by far the most abundant animals overall are adult copepod crustaceans (Carlton and Geller, 1993; Smith et al., 1999). The shallow water and estuarine species of copepod likely to be captured in ballast waters are also unable to withstand the extended periods of hypoxia (e.g. Lutz et al., 1994; Stalder and Marcus, 1997). For example, both the survivorship of adult *Acartia tonsa* and *Oithona colcarva* and the hatching of their eggs was found to be reduced significantly by 24 h exposure to oxygen concentrations below <0.2 mg/l (Roman et al., 1993).

Besides animals, small plant and algal parts (fragments, spores, and seeds) as well as single-celled phytoplankton, protoctists, fungi, and bacteria are often transported in ballast water. These microscopic components of ballast water have not been thoroughly characterized and their tolerances for low oxygen environments appear to vary greatly. There are examples of species sensitive to hypoxic conditions (e.g. filamentous fungi, Padgett et al., 1989; zoospores of the seaweed *Undaria pinnatifida*, Mountfort et al., 1999), as well as counter-examples of species that can withstand low oxygen levels (e.g. resistant cysts of toxic dinoflagellates, Hallegraeff, 1998). Marine bacteria, in particular, will have dramatically different responses to the conditions created in nitrogen-treated ballast tanks. While most obligate aerobic strains will be unable to withstand extended periods of hypoxia, some facultative anaerobic strains may actually thrive under the conditions found in deoxygenated ballast waters.

We therefore conclude that ballast water deoxygenation would be highly effective at reducing introductions of aquatic animals (larvae, juveniles, and adults stages), and would have mixed success at eliminating introductions by members of other taxa.

4.4. Evaluation of ballast water deoxygenation as a means of reducing aquatic invasions

Ballast water treatment technologies should be: (1) effective at killing potential invaders; (2) safe for shipboard crew; (3) environmentally benign; and (4) affordable for ship owners (National Research Council, 1996). We will briefly consider how nitrogen addition meets each of these criteria. First, as we have discussed earlier, deoxygenation is highly effective at killing animal invaders but may be less effective for other taxa, particularly those adapted to low oxygen environments or with resistant stages such as cysts. Second, with proper equipment and training, nitrogen (which makes up 78% of the atmosphere we breathe) poses no major threats to crew safety (Matsuda et al., 1999). Third, hypoxic ballast water would appear to be relatively benign when discharged. Hypoxic water will mix rapidly with shallow oxygenated water in harbors, and therefore create little danger for native estuarine organisms. However, if temporary exposure to reduced oxygen levels does prove to harm some native organisms, there are several simple re-oxygenation techniques that can be employed (including utilizing the anticorrosion plumbing system to also bubble air into ballast water prior to release). Finally, ballast water admirably meets the fourth criterion. Rather than an added expense for ship owners, it actually represents a net saving, due to the significant decrease in corrosion. To our knowledge, this is the only example of a ballast water treatment technique with economic incentives for the shipping industry.

The National Research Council (1996) has evaluated 10 candidate technologies for shipboard treatment of ballast water, recognizing that a single treatment method may not be appropriate for all vessels. They concluded that intensive filtration, use of biocides, and thermal treatments held the most promise. Deoxygenation did not receive high priority, because of its failure to kill organisms with stages resistant to hypoxia.

Although other ballast water treatment options may be more comprehensively effective, they come at greater environmental and financial cost. For instance, biocides may be hazardous for the crew as well as for native organisms in the vicinity of the ballast discharge (National Research Council, 1996). Moreover, these techniques come at a significant price for ship owners. Clearly, until mandated to do so, the shipping industry is unlikely to voluntarily install expensive ballast water treatment technologies. Indeed, Mountfort et al. (1999), who did not consider anticorrosion benefits, concluded that deoxygenation of ballast water with nitrogen was reasonably effective at killing aquatic organisms but impractical for shipboard operations due to financial costs. In contrast, we propose that widespread voluntary adoption of nitrogen treatment may result if the economic benefits for controlling corrosion become well known. Ballast water deoxygenation certainly deserves further exploration as a potential high priority treatment option, at least until international legislation mandates total mortality of ballast water organisms. While ballast water treatment has been controversial, raising conflicts between environmentalists and industry, nitrogen treatment represents a working solution that should appeal to both parties.

In summary, nitrogen treatment, by significantly reducing the level of oxygen in ballast tanks, both reduces corrosion and will cause substantial mortality of a large proportion of transported organisms. As such, it represents a rare example of a technology that simultaneously has benefits for marine conservation and industry.

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