Available online at www.sciencedirect.com
ScienceDirect
Harmful Algae 6 (2007) 547–566
HARMFUL ALGAE
www.elsevier.com/locate/hal

The response of zooplankton and phytoplankton from the North American Great Lakes to filtration

Allegra A. Cangelosi [a,*], Nicole L. Mays [a], Mary D. Balcer [b], Euan D. Reavie [c], Donald M. Reid [d], Rochelle Sturtevant [a,1], Xueqing Gao [e,2]

[a] *Northeast-Midwest Institute, 50 F St., N.W., Suite 950, Washington, DC 20001, USA*
[b] *University of Wisconsin-Superior, P.O. Box 2000, Superior, WI 54880, USA*
[c] *Natural Resources Research Institute, University of Minnesota Duluth, 1900 East Camp St., Ely, MN 55731, USA*
[d] *200 Grandview Rd. Nepean, Ontario, Canada K2H 8B1*
[e] *Kent State University, Kent, OH 44242, USA*

Received 27 September 2006; received in revised form 30 October 2006; accepted 21 November 2006

Abstract

Filtration of ballast water was investigated as a means of minimizing the introduction of nonindigenous zooplankton and phytoplankton by ships visiting the North American Great Lakes-St. Lawrence Seaway system (GLSLSS). An automatic backwash screen filtration (ABSF) system with nominal filtration options of 25, 50 or 100 μm was mounted on the deck of an operating Seaway-sized dry bulk carrier, the *MV Algonorth*. Water was pumped through the ABSF with a deck mounted pump at 341 m^3 hr^{-1} during routine ship operations in the GLSLSS, and effectiveness of the various screen pore sizes at removing taxonomic categories of zooplankton and phytoplankton was measured using matched treatment and control ballast tanks. The smallest pore sizes (25 and 50 μm) performed better than the 100 μm pore size at removing biological material. There was no difference in the filtration efficiency of the 25 and 50 μm screens relative to macro- or microzooplankton in these tests, but this result was probably due to low densities of macrozooplankton, and soft-bodied (aloricate) characteristics of the microzooplankton present. The 25 and 50 μm pore sizes were subjected to more controlled tests on board a stationary barge platform equipped with triplicate 700 L catchment bins moored in Duluth Harbor of Lake Superior. In these tests, filter pore size, organism size and rigidity influenced zooplankton removal efficiency by the ABSF. The 25 μm screen reduced both macrozooplankton and microzooplankton significantly more than the 50 μm screen. Zooplankton width was more determinative of filtration performance than length, and both filters removed loricate species of rotifers significantly more efficiently than aloricate species of the same length and width size classes. The 25 and 50 μm ABSF also significantly reduced algal densities, with the exception of colonial and filamentous green algae (50 μm only). Filter efficiency relative to algal particles was influenced by filter pore size, organism morphology and structure, and intake density, while algal particle size was not determinative. This research provides compelling evidence that 25 or 50 μm filtration is a potentially powerful means of reducing densities of organisms discharged by ships operating in the Great Lakes but an additional treatment step would be necessary to effectively minimize risk and meet the International Maritime Organization's discharge standards associated with organisms of all sizes in the water column.

Keywords: Ballast water; Filtration; Great Lakes; Phytoplankton; Treatment; Zooplankton

* Corresponding author. Tel.: +1 202 544 5200; fax: +1 202 544 0043.
E-mail address: acangelo@nemw.org (A.A. Cangelosi).
[1] Present address: Great Lakes Environmental Research Lab, 2205 Commonwealth Blvd, Ann Arbor, MI 48105, USA.
[2] Present address: Florida Department of Environmental Protection, 2600 Blair Stone Rd., Mail Station 3565, Tallahassee, FL 32399, USA.

1568-9883/$ – see front matter
doi:10.1016/j.hal.2006.11.005

1. Introduction

Over 160 nonindigenous aquatic species have become established in the North American Great Lakes due to a variety of transport vectors (Ricciardi, 2001; Colautti et al., 2003). Since the opening of the St. Lawrence Seaway waterborne transportation system in 1959 linking this mammoth fresh water system to the Atlantic Ocean for shipping, commercial vessels have become the primary vector of transport of these organisms (e.g., Mills et al., 1993; Ricciardi and MacIsaac, 2000). Ballast water is likely responsible for a majority (70%) of these established species, and for a full 40% of the total of introduced aquatic organisms (Grigorovich et al., 2003). Negative ecological effects of aquatic invaders in the lakes range from the highly visible, such as habitat destruction, to the insidious, such as the degradation of nutritional value of forage base for fish.

Impacts of nonindigenous species, almost always regional in scope initially, can also rapidly expand to become national or continental problems. The poster child of ballast-mediated invasions in the Great Lakes, the Zebra mussel (*Dreissena polymorpha*), is now established in all five Great Lakes, many inland lakes of the Great Lakes region, and most of the large navigable rivers in the eastern United States and Canada. The species is associated with a wide range of changes to inland lake and river ecosystems, specifically impacting native populations of mussels and zooplankton. Research has also shown that lakes colonized by zebra mussels can have, on average, three times higher levels of the cyanobacterium, *Microcystis* (Sarnelle et al., 2005). Those same lakes may also have approximately two times greater levels of microcystins, toxins produced by the cyanobacteria that that can poison aquatic organisms as well as wildlife, domestic animals, and humans (Vanderploeg et al., 2001). Economically, the biofouling capabilities of zebra mussels have also caused widespread impact to hydroelectric and nuclear power plants, public water supply plants, and industrial facilities. Park and Hushak (1999) report that the species cost Great Lakes raw water users alone over $20 million dollars per year in added maintenance during the 1990s.

Despite the ecological and economic impact of past introductions like the zebra mussel, nonindigenous species continue to be introduced to the Great Lakes. Because the Great Lakes supply drinking water to more than 25 million North Americans, of grave concern are transfers of organisms which present public health threats, such as red tide and pathogens. Johengen et al. (2005) recently identified microbial pathogens, including *Vibrio cholerae*, *Cryptosporidium parvum*, *Giardia lamblia*, *Encephalitozoon intestinalis*, and *Pfiesteria piscicida*, among others, in ballast residuals of overseas vessels that entered the Great Lakes. The same authors also identified the brown-tide organism, *Aureococcus anophagefferens*, in two vessels entering the Great Lakes that had exchanged their ballast in the open ocean.

Requirements for vessels entering the Great Lakes from outside the 200-mile exclusive economic zone to manage their ballast water were first established by Congress in the National Aquatic Nuisance Prevention and Control Act of 1990 (P.L. 101–646). In 1996, through the National Invasive Species Act (P.L. 104–332), Congress expanded the scope of this prevention program to a national level. Other nations with ballast management requirements include Australia, Brazil, Chile, Israel, Canada, and New Zealand. The International Maritime Organization (IMO) has called for ballast management through voluntary action since 1997.

In the United States, both the Great Lakes and the national programs require ships to either conduct a purge of ballast water tanks in the open ocean (ballast water exchange) or to treat ballast water prior to discharging in a United States port. Ballast water exchange has proved to be a helpful but limited prevention method which both industry representatives and environmental activists consider an interim stopgap measure. Problems associated with ballast water exchange include: vessels in the unballasted condition cannot conduct complete exchange of their ballast water and thereby purge residuals due to load limits; not all ships are structurally designed to safely carry out the process in the open-ocean, even when empty of cargo; the process may not be possible in rough weather; some coastal organisms can survive in ocean water; ballast water exchange does little or nothing to attenuate risk of transfers by ships plying exclusively near coastal areas; and finally, ballast water exchange effectiveness trials have produced mixed and inconsistent results, and implementation is difficult to monitor for enforcement purposes with any precision (Cangelosi and Mays, 2006). Most important to residents of the North American Great Lakes system, treatment of ballast water could resolve the problems associated with resuspension and subsequent discharge of unexchanged ballast residuals by ships. Approximately 90% of ship visits to the system each year are by ships in the unballasted condition which carry unexchanged ballast residuals (Holeck et al., 2004).

The inadequacy of ballast water exchange as a long term prevention practice led Congress to establish a

federal program to hasten development of effective ballast treatment alternatives. Moreover, the IMO recently negotiated a detailed and quantitative discharge standard and a set of deadlines for the treatment of ballast water as part of an international convention (IMO, 2004). Pending United States legislation, the National Aquatic Invasive Species Act of 2005 (S. 770) and the Ballast Water Management Act of 2005 (S. 363), would establish a national standard for ballast water discharged in United States waters.

Ballast water treatment options currently under consideration include filtration, cyclonic separation, heat, biocidal chemicals, ultraviolet irradiation, acoustics, ozonation, nitrogenation, cavitation, and deoxygenation. Though some large-scale evaluations have been undertaken (e.g., Kuzirian et al., 2001; Sutherland et al., 2001; Tamburri et al., 2002; Waite et al., 2003), many options remain largely theoretical or tested only in laboratory-based facilities primarily because large-scale demonstrations of treatment systems are both expensive and difficult to undertake successfully, and no official guidelines are available to steer efforts. But without large-scale analysis of prospective treatments, little can be learned of their ultimate utility or effectiveness on board a ship. Some treatments have been well-tested for other applications, and simply require vetting for the shipboard ballast treatment context.

The National Research Council of the National Academies of Sciences reviewed the potential of a variety of treatment processes to reduce ballast-mediated introductions of aquatic invasive species. The report identified filtration as one of the most promising processes (NRC, 1996). Filtration of ballast water is a straightforward means of reducing transfers of aquatic organisms by ships that would physically separate organisms from ballast uptake for discharge to the source harbor prior to the ship's departure. In this way, filtration could prevent altogether the movement of many near coastal organisms across the open ocean—formerly a natural barrier to transoceanic dispersal—as well as the unwanted accumulation of sediments in ballast systems. Filtration also offers the advantage of producing no residuals such as waste heat or chemical by-products, and is an established water treatment technology which is currently available at the capacities required for shipboard use.

At a given flow rate the filter's footprint increases as mesh size decreases. Accordingly, the lower bound filter mesh size suitable to a shipboard application is governed by available space and ballast throughput requirements of the carrier. It is likely that at a minimum current filter designs can accommodate the range of flow requirements of many classes of ships of concern in global movements of organisms—including container ships, small tankers, cruise ships and St. Lawrence Seaway-sized bulk cargo carriers—at a pore size small enough to exclude a large proportion of organisms within taxa of known concern, including fish, benthic and epibenthic organisms, and many forms of plankton (Cangelosi, 2002). Moreover, filtration has the potential to enhance effectiveness or complement many secondary treatment options, such as ultraviolet irradiation and environmentally-sound chemicals, by removing particulate matter that may consume or interfere with these treatments as well as most zooplankton and phytoplankton taxa from the intake stream. The technology also could afford financial benefits to the carrier by reducing problems associated with sedimentation in ballast tanks. Finally, filtration is versatile—equally effective for ships in the ballasted and unballasted condition, in salt and freshwater conditions, and along trade routes that are coastwise as well as transoceanic.

Filtration comprises several distinct technologies, which vary fundamentally in their approach to removing particles and self cleaning. These differences in turn imply a variety of incumbent impacts in the shipboard context, including footprint size, pressure drop, and the number of moving parts and types of structural materials subject to maintenance. This study focused on the biological effectiveness of perhaps the simplest filtration technology, automatic backwash screen filtration (ABSF), which involves passing raw water through a planar mesh screen. The system evaluated was a self-cleaning system already in use in shore-based facilities for removing zebra mussel veligers from power plant intake flows. Pore sizes tested, 25, 50 and 100 μm, represent a range of operational challenge and biological effectiveness. The biological evaluations reported here were conducted in tandem with operational research on the same filtration technology, which has been reported elsewhere (Parsons and Harkins, 1999). In combination the two types of research provide a vital fact base for regulators and ship owners to estimate the potential utility of ABSF as an approach to shipboard ballast filtration. However, this research is also informative on the prospective effectiveness of filtration, generally, against a range of taxonomic categories often encountered in harbors of ballast uptake at a variety of pore sizes in high flow situations.

The present study of ABSF effectiveness was conducted using two distinct experimental platforms: the commercial bulk cargo vessel, the *MV Algonorth*,

Fig. 1. (a) The *MV Algonorth*, a Seaway-sized dry bulk carrier used to evaluate the biological effectiveness of a deck-mounted ABSF ballast water treatment system with nominal filtration options of 25, 50 and 100 μm. (b) Overview of the deck-mounted ABSF ballast water treatment system used evaluated onboard the *MV Algonorth*, a Seaway-sized dry bulk carrier.

and the stationary barge moored in Duluth-Superior Harbor of Lake Superior (Figs. 1a,b-2). The *MV Algonorth* offered advantages in that its voyage pattern between the Gulf of St. Lawrence and the western-most Great Lakes ports provided real shipboard conditions in both fresh and salt-water environments. In contrast, the barge offered a more controlled testing environment, and exposed the filtration system to heavier loads of sediment and algae typical of many shallow-water harbors. The shipboard analysis was conducted first. Based on the preliminary information on the operational feasibility and biological effectiveness of ABSF at a

Fig. 2. The barge platform, moored in the Duluth-Superior Harbor of Lake Superior, used to evaluate the biological effectiveness of an ABSF ballast water treatment system with nominal filtration options of 25 or 50 μm.

variety of pore sizes in the shipboard context, investigators refined the treatment system configuration and pore size range to optimize the system from an engineering and biological standpoint. This optimized configuration was subjected to more controlled study in the barge-based context. Together the two testing venues provided a rich opportunity for exploring potential effectiveness of ABSF as a component of a ballast treatment system.

2. Methods

2.1. Treatment system

The automatic backwash screen filter (ABSF) tested was an Ever-Clear Filter designed by Ontario Hydro Technologies, Inc. to remove zebra mussel veligers from high flow intake streams for power production facilities. The prototype ABSF unit consisted of a cylindrical filter element 76 cm in diameter contained within a 1.48 m long by 0.94 m diameter cylindrical steel canister. The filter element was removable facilitating the installation of various mesh screen sizes. The unit was designed for a flow rate of 341 $m^3\ hr^{-1}$ to provide flow conditions in the range of those encountered in ballast systems of some Seaway-sized ships. A Godwin 20 cm × 15 cm HL6 Dri-Prime pump driven by a John Deere 6081T diesel engine powered flow conditions of 341 $m^3\ hr^{-1}$ at 483 kPa; shut-off head 827 kPa. Water entered and exited via 20 cm inlet and outlet connections. Periodically, the build up of filtered material on the inside of the filter element would cause a pressure drop, activating a backwash process involving the rotation of suction heads within the filter element to suction-off the filtered material and discharge it into the source water system.

2.2. Shipboard tests

2.2.1. MV Algonorth experimental platform

The ship platform for the experiment was the *MV Algonorth*, a Seaway-sized bulk carrier managed by Algoma Central Marine (now Seaway Marine Transport) of St. Catharines, Ontario. Flagged in Canada and built in 1971, the vessel is 222 m long by 23 m wide. It has a depth of 13 m, a gross registered tonnage of 18,496 MT, a total cargo capacity of 26,000 MT, and a dedicated ballast tank capacity of 10,600 MT. The vessel ballast system comprises five pairs of port and starboard wing tanks, with upper and lower structural components, one fore peak, and one aft peak tank. Two pumps deliver a combined ballast pumping capacity of 1998 $m^3\ hr^{-1}$.

At the time of the testing, the vessel was employed in the Great Lakes/Gulf of St. Lawrence bulk trade. A typical voyage pattern involved the movement of iron ore from ports in the Gulf of St. Lawrence to ports in the Great Lakes via the St. Lawrence Seaway, and the return movement of grain from upper Great Lakes ports to the Gulf of St. Lawrence.

Matching No. 3 upper wing ballast tanks of 220 m^3 capacity each were used as the dedicated treatment (port) and control (starboard) tanks. Temporary steel extensions and covers were fitted to the upper end of the lower portions of the ballast tanks so that the sections could function independently, essentially turning the upper portions of the wing tanks into separate topside tanks. Raised manhole hatches were retrofitted to facilitate frequent access to the tanks from the deck for biological sampling. Steel platforms were installed below the access hatches to support the operator while collecting biological samples. Plankton net trolleys were installed within the tanks to facilitate replicate and spatially comprehensive biological sampling. Trolley cables ran along identical 10 m transects in the treatment and control tanks from the lower aft to the upper forward corners of each tank.

Two ABSF filter units—a 250 μm prefilter and either a 25, 50, or 100 μm screen polishing filter—were installed in series and contained within a 6 × 2 × 1.5 m container module located on the *MV Algonorth's* deck, near amidships on the port side. The diesel pump was located directly across the deck from the container module. The filter backwash discharge lines exited the container low on the outboard side and were directed overboard. Dedicated 20 cm steel intake pipes were installed to allow withdrawal of water for experimental purposes from the No. 4 starboard ballast tank (1999 m^3 capacity) using a 20 × 30 cm reducer bell mouth located near the bottom of the tank, or directly from a dedicated sea suction. Intake flow could be directed—through the filter units (in series) or bypassing them—into the matched ballast tanks. Alternatively, flow could be sent directly overboard via 15 cm diameter discharge piping. The diesel pump was also used to empty the tanks. The engineering details of the shipboard test platform design are described by the designers in Parsons et al. (1997).

2.2.2. Experimental design

The matched treatment and control tanks were filled during vessel transits specifically for experimental purposes using the deck mounted pump. Table 1 details the location within the Great Lakes-Saint Lawrence Seaway System of each trial. Control water bypassed the

Table 1
Location of shipboard treatment trials conducted on board the *MV Algonorth* using ABSF at various pore sizes (25, 50, and 100 μm)

Location	Date	Trial#	Filter screen size (μm)
Lake Huron	3-Oct	1	25
Lake Michigan	4-Oct	2	25
Gulf of St. Lawrence	20-Oct	3	25
Lake St. Clair	27-Aug	1	50
Lake Huron	28-Aug	2	50
Lake Ontario	23-Oct	3	50
Gulf of St. Lawrence	27-Sep	1	100
Gulf of St. Lawrence	28-Sep	2	100
Lake Ontario	1-Oct	3	100

treatment system, while test water was routed through the treatment equipment into the test tank. Treatment and control tanks were filled to one-third capacity in sequence and then topped up to two-thirds capacity (approx. 200 m^3) allowing room in the upper portion of the tank for the sampling operator. This filling scenario was especially important to help assure homogeneity between the test and control source water when the ship was in transit during ballasting. In some cases, the No. 4 starboard tank was used as a common source reservoir for the treatment and control tanks. In these instances, the flow was diverted over the side of the vessel for at least 5 min prior to filling the test and control tanks to eliminate settled materials which could be picked up by the initial flow. The time required to fill the two experimental tanks was approximately 1.5 h, i.e., 45 min per tank.

Each of the three polishing filter screen mesh sizes—25, 50, or 100 μm—was tested at least three times for its effectiveness at reducing plankton abundance in ballast water compared to non-treated ballast water. In order to avoid distortions resulting from test tank contamination by residual water from previous tests, screen mesh sizes were tested in cycles from smallest to largest, and the tanks were cleaned with high pressure water before the ascending order of tests was repeated.

2.2.3. Biological sampling

Three replicate samples were collected from each tank first with an 80 μm mesh standard 0.5 m diameter and 1.5 m long plankton net, and then with a 20 μm mesh net of the same dimensions. Both types of net were towed along the 10 m diagonal transect trolley cable at a consistent velocity of approximately 0.5 m s^{-1} filtering approximately 0.64 m^3 of water into a 1 L sample collected in a terminal cod end. Each plankton net tow lasted about 5 min from start to finish (including rinsing and replacing the net for the next tow) and was conducted at least 5 min after the prior tow to allow the water column to return to relative equilibrium. All samples were immediately immobilized with 1 mL Lugol's solution, and preserved in 10% Lugol's solution following collection of all samples (within one hour).

2.2.4. Zooplankton analysis

The zooplankton samples were counted, sorted into taxonomic categories and measured at a shore-side laboratory. Prior to analysis, samples were decanted through a 20 μm lab filter, rinsed into a beaker and diluted with tap water to obtain between 200 and 500 organisms per 1 mL subsample. The diluted sample was stirred in a figure eight motion with a Henson-Stempel pipette prior to removing three 1 mL subsamples and placing them in Sedgewick-Rafter counting chambers. One subsample was taken from near the top of the well mixed sample, one from the middle, and the third from near the bottom. Using a stereomicroscope, subsamples from the 20 μm net sample were analyzed for microzooplankton and subsamples from the 80 μm net samples were analyzed for macrozooplankton. Microzooplankton consisted entirely of rotifers which were identified to genus. Macrozooplankton species were sorted by major taxonomic/morphological category: bivalve larvae, copepod nauplii, immature copepodites, adult copepods, and cladocerans. Following analysis, concentrations in the subsamples were averaged and converted to number per liter of original water sample. A subset of organisms from each sample (approx. 100 individuals) was also measured for length at this time using a calibrated eyepiece micrometer at 100× magnification.

2.2.5. Phytoplankton analysis

Following zooplankton analysis, portions of the 20 μm net samples were transferred to a second shore-side laboratory for phytoplankton analysis. Phytoplankton were sorted into six taxonomic/morphological categories and counted. The categories were: diatoms <50 μm, centric diatoms (including the genus *Cyclotella*), pennate diatoms (including the genera *Synedra*, *Asterionella*, *Navicula*, *Cymbella*, *Gyrosigma*, *Gomphonema*, *Epithemia*, *Nitzschia*, *Cymatopleura*, and *Surirella*), "spiny" dinoflagellates, "round" dinoflagellates, and the colonial green alga *Pediastrum*. Algal particles were identified and enumerated using a Sedgewick rafter counting chamber (total volume 1 mL) and a Zeiss Axioskop 20 (Carl Zeiss, West Germany) microscope using brightfield and differential interference contrast optics at 200× magnification. Samples of water treated by the 25 μm mesh ABSF were not diluted due to the low abundance of particles.

Samples of water treated by larger ABSF mesh sizes (50 and 100 μm mesh) were diluted 5–10 times to facilitate counting. Cell counts were performed by counting a portion of the Sedgewick rafter to ensure that more than 100 cells were counted for each group when possible. Rare genera or groups were counted by examining the entire rafter. The total cell counts were then converted to cells per liter.

2.2.6. Data analysis

In light of the variation in ambient assemblage and density across trials, treatment performance was evaluated and cross compared for the most part in terms of mean removal efficiencies, i.e. % reductions. Absolute densities were also determined across treatments and controls, and maximum densities in treated discharge were reported for purposes of comparison with proposed or existing treatment performance standards. Treatment effects on the zooplankton taxonomic categories, and phytoplankton taxonomic categories were analyzed separately.

Within each trial, zooplankton and phytoplankton counts for each taxonomic category within the three plankton net samples of treated water and three plankton net samples of control water were averaged separately. For a given filter pore size, mean percent reductions were calculated across replicate trials for each taxonomic category with adequate densities for statistical analysis. For a given trial, only those taxonomic categories whose mean densities were equal to or greater than 5% of the mean densities of total zooplankton or phytoplankton present were included in statistical analysis. Differences in mean removal efficiencies across screen pore sizes were detected using t tests with $p \leq 0.05$ as the criterion for a statistical significance. All density results were reported as the mean value of the triplicate samples within a trial ± 1 standard error.

Size data relative to specific taxonomic categories were similarly averaged across trials for a given screen size. Filtration efficiencies were compared within size classes across control and filter-treated samples for statistical significance. Only size classes of a taxonomic category comprising organism densities of at least 5% of the mean densities of the organisms of that taxonomic category in the control samples were subjected to statistical analysis.

2.2.7. Quality assurance/quality control

Testing was conducted consistent with the U.S. Environmental Protection Agency's quality assurance program protocols, including standard biological and operational protocols and procedures relative to experimental design and replication, sample collection, field data completedness, sample handling and chain of custody requirements, data analysis, and instrument and equipment calibration, inspection and maintenance, etc.

2.3. Stationary barge experimental platform

2.3.1. Experimental infrastructure

Following completion of the shipboard trials, the supply pump module and filter container module were transferred to a 20×8 m stationary barge platform moored at the Port Authority of Duluth in Duluth-Superior Harbor of Lake Superior. Based on operational results of the shipboard trials, the 250 μm prefilter unit was considered unnecessary to improve operational performance, and not included in the barge-based filtration system (Parsons and Harkins, 1999). Instead, the pump suction (used for both treatment and control water intake) was fitted with a 0.05 m perforated screen intake to strain out larger particles that could damage the filters. The rest of the instrumentation and flow conditions were configured as on board the *MV Algonorth*. Water depth was 6–7 m, and the suction pipe depth was adjusted to maintain a level of 1–2 m from the harbor bottom. The flow of water from the intake line could be directed through or by-pass the filter. Flow downstream of the filter/bypass was subdivided by piping and valves into three outlet streams of equivalent volume and flow rate. Three 700 L cylindrical cone-bottom catchment tubs each with a 10.2 cm diameter drain pipe at the bottom were installed downstream of the subdivision. The subdivided discharge streams were directed into the three catchment tubs for near simultaneous filling. Preliminary tests revealed equivalent particle distribution among the three catchment tubs upon filling. Parsons and Harkins (1999) detail the design and engineering of the barge test platform.

2.3.2. Experimental design

Prior to each trial, the system was flushed for 15 min. Flow was then directed through the ABSF and discharged into the three catchment tubs, filling them simultaneously to an overflow condition within 5 min. Flow was stopped and the tubs were immediately drained completely from the bottom through 20 μm mesh plankton nets fitted with 1 L cod ends. The samples were immobilized immediately with 1 mL Lugol's solution, and preserved within one hour using 10% Lugol's solution for later analysis of zooplankton and phytoplankton. The mechanical system was then adjusted to by-pass the filter, the untreated water directed into the catchment tubs, and after overflow, drained and sampled through the 20 μm mesh nets.

Following each test, the filter screen was removed for cleaning and replaced with a clean filter screen for the next day's testing. Catchment tubs and plankton nets were rinsed with city water filtered to 1 μm between control and test runs. Four trials were conducted using the 25 μm ABSF, and three trials using the 50 μm ABSF.

2.3.3. Zooplankton analysis

At a shoreside facility, the 700 L catchment tub samples, concentrated into a 1 L cod end on the barge, were further concentrated through a 20 μm lab filter and processed for sorting, counting and sizing as described above for the *MV Algonorth* zooplankton samples. As before, rotifers were identified to genus, cladocerans to family or genus, and copepods to suborder and developmental stage (nauplius, immature, adult). Abundance data was converted to number per liter of original water sample.

After identification and enumeration, up to 50 intact specimens of each taxonomic category were measured for detailed size analysis from each treatment on each sampling date for length and width using a calibrated eyepiece micrometer at 100× magnification. The spines of the rotifers *Keratella* and *Kellicottia* were included in the measurements since these spines were rigid and generally intact, thus increasing the effective size of the organism. The flexible ''paddles'' of *Polyarthra* were found in various positions and were not included in determining body size. *Synchaeta* and *Conochilus*, being soft-bodied, were often found in a contracted form. Tail spines of cladocerans were not included in the length measurements because they were usually broken. Lengths of copepods did not include the terminal setae on the caudal rami.

2.3.4. Phytoplankton analysis

Phytoplankton analysis (counting, sorting and sizing) for the barge-based tests was also similar to the methods used for the *MV Algonorth* trials. In the case of the barge tests, based on the range of organisms present and abundant, algal particles were sorted into twelve taxonomic/morphological categories. The categories were: unicellular pennate diatoms (including the genera *Navicula*, *Cymbella*, *Gyrosigma*, *Gomphonema*, *Epithemia*, *Nitzschia*, *Cymatopleura*, and *Surirella*), unicellular centric diatoms (including the genus *Cyclotella*), filamentous centric diatoms (including the genus *Aulacoseira*), *Fragilaria*-like colonial diatoms (including the genera *Fragilaria*, *Meridion*, *Diatoma* and *Tabellaria*), colonial green algae (including the genera *Eudorina*, *Pleodorina*, *Micractinium* and *Coelastrum*), filamentous green algae (including the genus *Spirogyra*), *Pediastrum* (all species), colonial cyanobacteria (including the genera *Anacystis* and *Gomphosphaeria*), filamentous cyanobacteria (including the genus *Anabaena*), chrysophytes (including the genus *Dinobryon*), dinoflagellates (including the genera *Ceratium* and *Peridinium*), and protozoa (including the genera *Codonella, Tintinnidium* and *Tintinnopsis*).

Cell measurement was performed on a Zeiss Axioskop 20 microscope (Carl Zeiss, West Germany) using a 10 X objective with an eyepiece micrometer at a total magnification of 200 X. Unicellular pennate diatoms, colonial cyanobacteria, colonial green algae, filamentous diatoms, dinoflagellates, and protozoa were all measured by length (longest axis) and width (longest axis perpendicular to the length). Unicellular centric diatoms and *Pediastrum* were measured by diameter. *Fragilaria*-like diatoms were measured by the width (i.e. cell length) and the length of the colony. Filamentous cyanobacteria were measured by filament length only, the width of the filament cells being very small and uniform (∼5 μm). Chrysophytes were measured by the number of loricae in the colony.

2.3.5. Data analysis and quality assurance

All data analysis and quality assurance measures for the barge-based tests were consistent with those used for the *MV Algonorth* tests, described above.

3. Results

3.1. MV Algonorth tests

3.1.1. Zooplankton

Three trials at each of the three filter pore sizes provided sufficient data for determining estimates of filter efficiency at removing macrozooplankton and total zooplankton. Microzooplankton were present in adequate densities for separate analysis in all three 50 μm filter trials, but in only two out of three trials of the 25 μm filter, and one out of three in the 100 μm trials. Table 2 summarizes mean densities of organisms in control samples for each taxonomic group subject to analysis.

Both the 25 and 50 μm filters significantly reduced macrozooplankton and total zooplankton densities compared to non-treated (control) densities with the 25 μm ABSF delivering 94 and 91% reductions compared to controls, respectively; and the 50 μm ABSF delivering 94 and 89% reductions, respectively. The 100 μm caused an 83 and 79% reduction in macrozooplankton and total zooplankton abundance, respectively, but did not significantly reduce either

Table 2
Average densities of zooplankton (mean ± S.E.) in control samples and % reduction by treatment relative to control densities (mean ± S.E.) for each taxonomic group subject to analysis in trials conducted on board the *MV Algonorth* and the barge platform using ABSF at various pore sizes (25, 50, and 100 μm)

Platform	Filter screen size (μm)	Taxonomic group	Average number of organisms per L ± S.E.	*N*	Mean% reduction by ABSF relative to control densities ± S.E.
MV Algonorth	25	Microzooplankton	4 ± 1	2	85
	25	Macrozooplankton	4 ± 3	3	94 ± 3
	25	Total zooplankton	7 ± 2	3	91 ± 5
	50	Microzooplankton	6 ± 3	3	81 ± 0
	50	Macrozooplankton	9 ± 2	3	94 ± 4
	50	Total zooplankton	15 ± 4	3	89 ± 3
	100	Microzooplankton	17 ± 0	1	68
	100	Macrozooplankton	9 ± 8	3	83 ± 9
	100	Total zooplankton	15 ± 13	3	79 ± 4
Barge platform	25	Microzooplankton	314 ± 58	4	81 ± 1
	25	Macrozooplankton	81 ± 100	4	100 ± 0
	25	Total zooplankton	395 ± 64	4	85 ± 1
	50	Microzooplankton	272 ± 60	3	71 ± 3
	50	Macrozooplankton	82 ± 26	3	97 ± 1
	50	Total zooplankton	353 ± 36	3	78 ± 1

density relative to controls, largely due to the wide variation in performance by this filter screen size across trials compared to controls.

All three filters appeared to remove macrozooplankton more efficiently than microzooplankton (Fig. 3), and the 25 and 50 μm filters appeared more efficient than the 100 μm filter at removing microzooplankton. However, these differences were not statistically significant because microzooplankton were present in inadequate densities for statistical analysis in trials testing the 25 and 100 μm filters. Trials for which there were adequate densities of microzooplankton showed a mean reduction of 85% due to 25 μm filtration ($N = 2$), 81% due to 50 μm filtration ($N = 3$, Table 2), and 68% due to 100 um filtration ($n = 1$).

The average absolute concentrations of zooplankton in water treated with 25 and 50 μm ABSF were 1 ± 0 and 2 ± 1 organisms per liter, respectively. Maximum

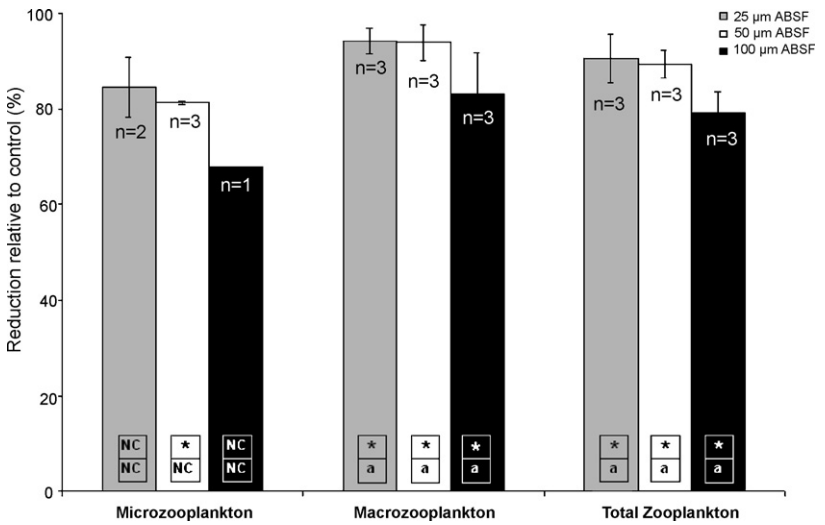

Fig. 3. Relative efficiency of 25, 50, and 100 μm ABSF at reducing densities of microzooplankton, macrozooplankton and total zooplankton relative to controls in trials conducted on board the MV Algonorth (mean ± S.E.). Within zooplankton categories, different letters (a, b, c) indicate significantly ($p < 0.05$) different ABSF performance. Asterisks indicate significant reductions ($p < 0.05$) relative to controls. NC = not calculated (data were insufficient).

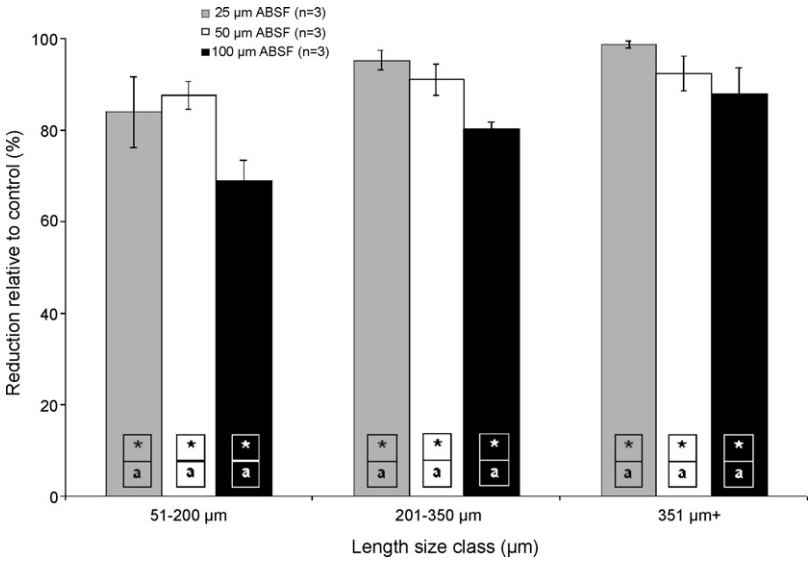

Fig. 4. Relative efficiency of 25, 50, and 100 µm ABSF at reducing zooplankton densities by length size class in trials conducted on board the MV Algonorth (mean ± S.E.). Within length size classes, different letters (a, b, c) indicate significantly ($p < 0.05$) different ABSF performance. Asterisks indicate significant reductions ($p < 0.05$) relative to controls.

zooplankton densities in treatment samples were to 1 and 3 organisms per liter, respectively.

In terms of zooplankton size, the effectiveness of all three filter pore sizes tended to increase as length size class increased (Fig. 4), but the differences were not statistically significant. The 25 µm filter removed more than 84% of organisms with lengths between 50 and 200 µm, and more than 95% of organisms with lengths greater than 200 µm. The 50 µm filter removed more than 87% of organisms with lengths between 50 and 200 µm, and more than 91% of organisms with lengths greater than 200 µm. The 100 µm filter removed more than 68% of organisms with lengths between 50 and 200 µm, and more than 80% of organisms with lengths greater than 200 µm. There also was no significant difference between the performances of the 25 and 50 µm screens at removing zooplankton in any of the length size classes. However, the 50 µm filter removed zooplankton with lengths between 51 and 200 µm significantly better than the 100 µm filter, and both the 25 and 50 µm filters removed zooplankton with lengths 201–350 µm better than the 100 µm filter.

3.2. Phytoplankton

Filter effectiveness relative to total phytoplankton and particular phytoplankton categories at each of the three filter pore sizes was difficult to assess due to large variations in control densities between trials. For example, densities of phytoplankton in ballast water not subject to treatment in *MV Algonorth* trials ranged from 71 to 4602 cells per liter for the 25 µm ABSF trials, 7–31 cells per liter for the 50 µm ABSF trials, and 31–590 cells per liter for the 100 µm ABSF trials. There also were insufficient numbers of individuals within trials to determine if any of the screen sizes reduced phytoplankton cell concentrations significantly differently than the other sizes, with the exception of diatoms <50 µm and total density counts (all taxonomic categories combined) where there were no significant differences in performance among screen sizes (Fig. 5). Mean removal efficiencies for total phytoplankton by the 25 and 50 µm filter screens were 37.5%, and 8.3% respectively. Maximum phytoplankton densities in ballast water discharge treated by 25, 50, and 100 µm ABSF were 1382, 21, and 168 cells per liter, respectively.

3.3. Stationary barge platform

3.3.1. Zooplankton

In the barge-based tests, four trials of the 25 µm ABSF and three trials of the 50 µm ABSF provided adequate data for determining relative filter efficiency at removing total zooplankton, and macro- and microzooplankton specifically. Table 2 summarizes densities of organisms in control samples for each taxonomic group subject to analysis.

Both the 25 and 50 µm ABSF significantly reduced macrozooplankton, microzooplankton and total zooplankton densities relative to control densities, and the

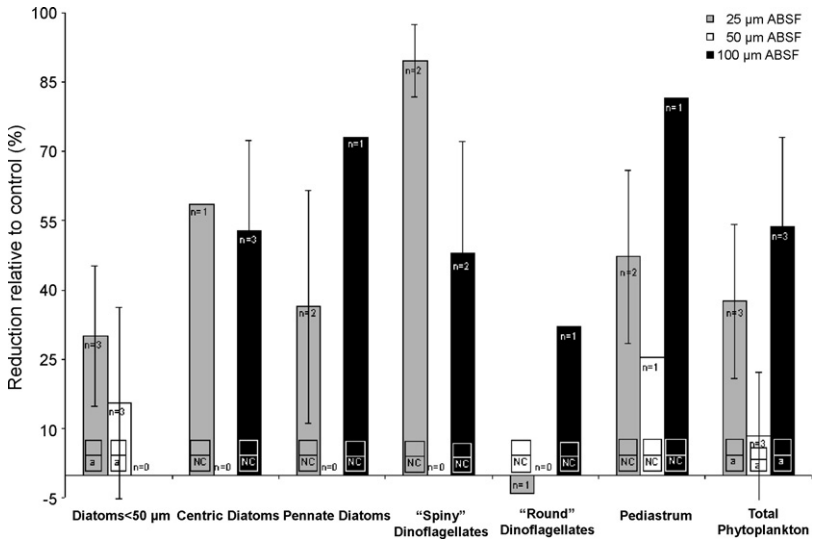

Fig. 5. Relative efficiency of 25, 50, and 100 μm ABSF at reducing densities of diatoms <50 μm, centric diatoms, pennate diatoms, ''spiny'' dinoflagellates, ''round'' dinoflagellates, *Pediastrum*, and total phytoplankton relative to controls in trials conducted on board the MV Algonorth (mean ± S.E.). Within phytoplankton categories, different letters (a, b, c) indicate significantly ($p < 0.05$) different ABSF performance. NC = not calculated (data were insufficient).

25 μm ABSF was significantly more effective than the 50 μm ABSF (Fig. 6). Macrozooplankton densities were reduced by over 99% of the control density with the 25 μm filter and by 97% with the 50 μm filter. The 25 μm filter reduced microzooplankton densities by 81% compared to a 71% reduction with the 50 μm filter. Overall, the 25 μm filter resulted in an 85% removal of zooplankton while the 50 μm filter achieved an average reduction of 78%.

Maximum residual concentrations of macrozooplankton in water treated with 25 and 50 μm ABSF were to 1 and 6 organisms per liter, respectively. Maximum residual concentrations of microzooplankton in water treated by 25 and 50 μm ABSF were to 86 and 90 organisms per liter, respectively. Mean absolute concentrations of zooplankton (macro- and microzooplankton) with widths >50 μm in discharge from the 25 and 50 μm filters were 21 and 55 per liter, respectively.

The analysis of filter efficiency relative to organism length and width revealed organism width to be more determinative than length. Filtration using this ABSF system caused a greater than 90% reduction in zooplankton densities compared to control densities only in length size classes more than four times the

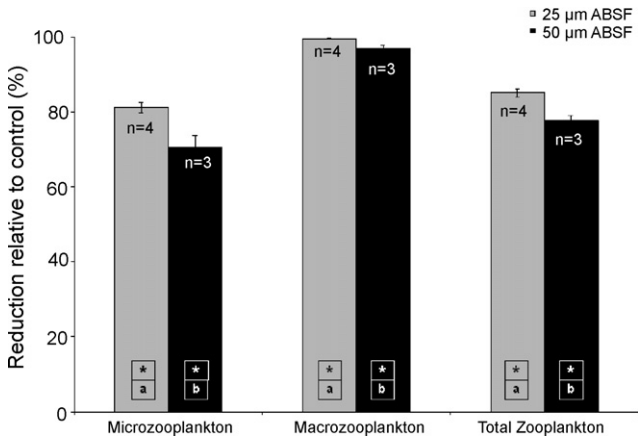

Fig. 6. Relative efficiency of 25 and 50 μm ABSF at reducing densities of microzooplankton, macrozooplankton and total zooplankton relative to controls in trials conducted on board the barge-based platform (mean ± S.E.). Within zooplankton categories, different letters (a, b) indicate significantly ($p < 0.05$) different ABSF performance. Asterisks indicate significant reductions ($p < 0.05$) relative to controls.

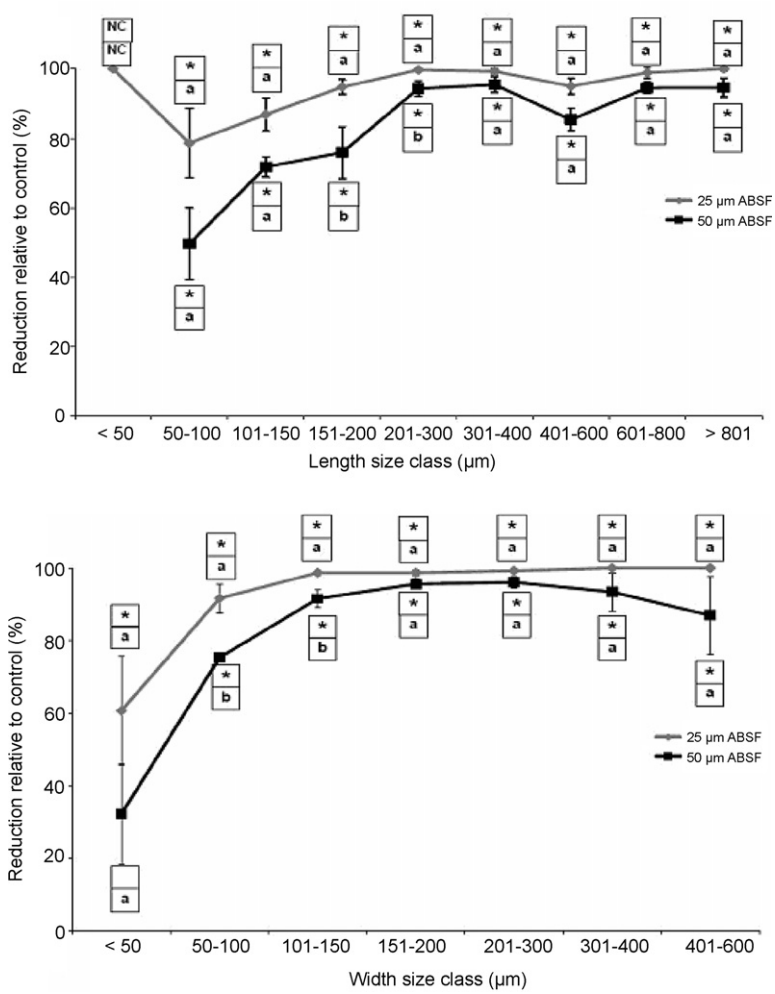

Fig. 7. Relative efficiency of 25 and 50 μm ABSF at reducing zooplankton densities by length (top) and width (bottom) size class in trials conducted on board the barge-based platform (mean ± S.E.). Within size classes, different letters (a, b) indicate significantly ($p < 0.05$) different ABSF performance. Asterisks indicate significant reductions ($p < 0.05$) relative to controls. NC = not calculated (data were insufficient).

nominal filter pore size (i.e., 151 μm length size class and greater for the 25 μm ABSF, and 201 μm length size class and greater for the 50 μm ABSF, respectively; Fig. 7). In contrast, both filter sizes (25 and 50 μm) reduced concentrations of organisms by greater than 90% in width size classes equal to twice the nominal filter pore size (i.e., 50 μm width size class and greater for the 25 μm ABSF, and 101 μm width size class and greater for the 50 μm ABSF, respectively; Fig. 7). The 25 μm filter was significantly better than the 50 μm filter at reducing zooplankton with widths in the 50–100 μm size range and the 101–150 μm size range. Above these width classes, the two filter sizes did not perform statistically differently.

Microzooplankton data within the two smallest width size classes were further analyzed for 25 and 50 μm filtration efficiency relative to hard-bodied (loricate) versus soft-bodied (aloricate) rotifer genera. There was no difference in control densities of either morphological category across the width size classes analyzed. Both the 25 and 50 μm ABSF screens reduced loricate rotifers significantly more than aloricate rotifers with widths <50 μm and between 51 and 100 μm (Fig. 8).

3.3.2. Phytoplankton

The stationary barge platform afforded greater consistency in intake densities across taxonomic categories of phytoplankton than the shipboard platform. As a result, each of the three trials at each filter pore size (25 and 50 μm) provided sufficient data for determining algal removal efficiency. In these tests, 25 and 50 μm ABSF significantly reduced algal densities relative to controls across all taxonomic groups with the

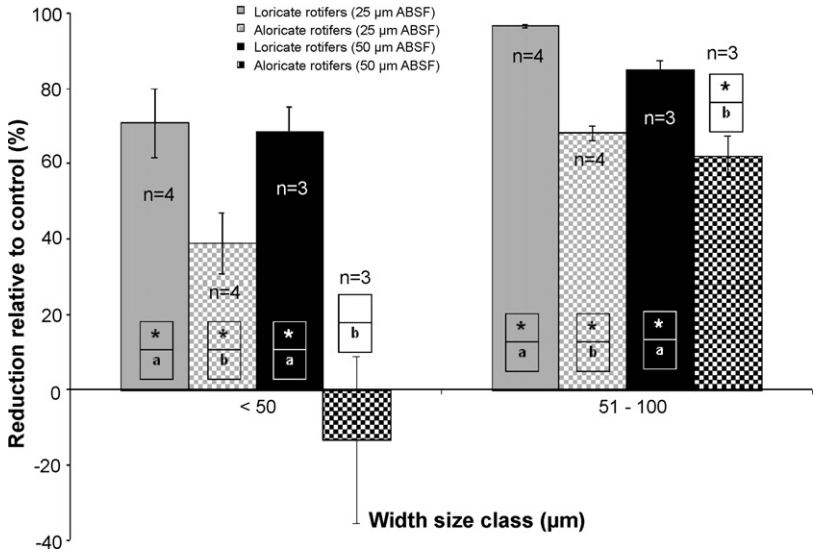

Fig. 8. Relative efficiency of 25 and 50 μm ABSF at reducing hard-bodied (loricate) and soft-bodied (aloricate) rotifer densities relative to controls by width size class in trials conducted on board the barge-based platform (mean ± S.E.). Within size classes, different letters (a, b) indicate significantly ($p < 0.05$) different ABSF performance. Asterisks indicate significant reductions ($p < 0.05$) relative to controls.

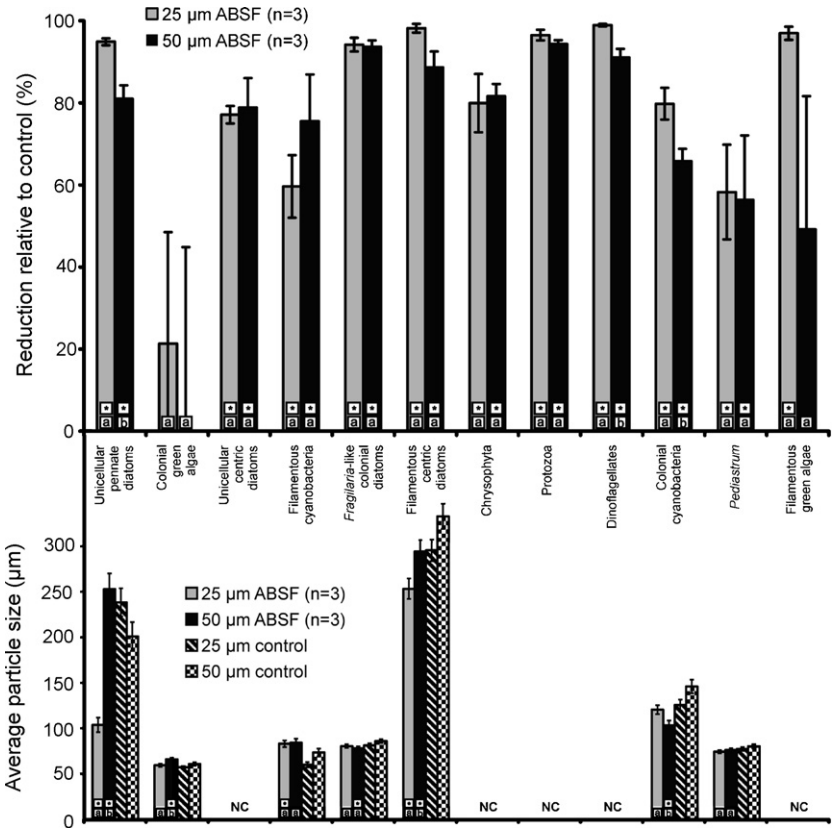

Fig. 9. Relative efficiency of 25 and 50 μm ABSF at reducing phytoplankton densities (top) and eliminating particular particle sizes (bottom) across taxonomic categories relative to controls in trials conducted on board the barge-based platform (mean ± S.E.). Lowercase letters denote similar (a/a) or significantly different (a/b) results between 25 and 50 μm treatments for each phytoplankton group, and asterisks indicate significant differences from controls (*t*-test, $p < 0.05$). NC = not calculated (data were insufficient or incompatible measurement regimes were used).

exception of colonial green algae and filamentous green algae (50 μm filter only) (Fig. 9). The filters were effective at reducing algal numbers particularly within the particle size ranges above 20 μm (Fig. 10). The reductions relative to controls in taxonomic categories for which there was a significant effect of 25 μm filtration ranged from 58.3% for *Pediastrum* to 98.9% for dinoflagellates. The 50 μm ABSF caused significant reductions of 56.3% for *Pediastrum* to 94.3% for protozoans.

Data were analyzed in detail to detect possible influences of filter pore size, algal morphology, algal particle size and intake densities on filter effectiveness. Taxonomic categories included in this analysis were unicellular pennate diatoms, colonial green algae, filamentous cyanobacteria, *Fragilaria*-like colonial diatoms, filamentous centric diatoms, colonial cyanobacteria and *Pediastrum*.

Filter pore size was not a significant influence when specific size classes were tested probably as a result of the limited number of data sets ($N = 3$). However, there was a clear general class-wide increase in efficiency at removal of total algal particles by the 25 μm over the 50 μm ABSF (paired Wilcoxon, $Z = 2.67$, $p < 0.01$) (Fig. 10), and the 25 μm filter out-performed the 50 μm filter at reducing overall densities of organisms within specific taxonomic groups, namely, unicellular pennate diatoms, dinoflagellates and colonial cyanobacteria (Fig. 9, top).

Fig. 11 illustrates variations in filtration efficiency between morphological groups. Both filters tended to remove the rigid morphological categories (e.g., unicellular pennate diatoms, and *Fragilaria*-like colonial diatoms) better than more globular morphological types (e.g., colonial green algae). No difference in removal efficiency was observed between filter pore sizes and between algal forms when the algae were grouped as filamentous and colonial forms (paired Wilcoxon comparison of percent reduction in 25 and 50 μm treatments, $p < 0.01$) (Fig. 12).

The ratio of algal particle length to filter pore size appeared to influence filter performance but was not

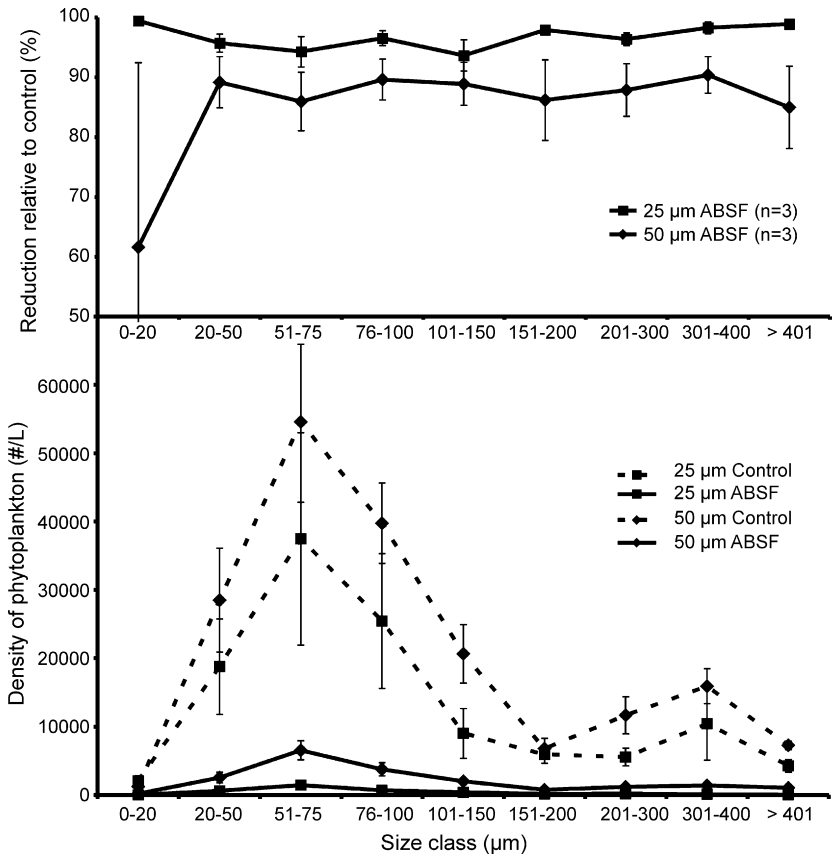

Fig. 10. Relative efficiency of 25 and 50 μm ABSF at reducing phytoplankton densities (top) and absolute phytoplankton densities in controls and treatments (bottom) in trials conducted on board the barge-based platform (mean ± S.E.). Reduction and density data are grouped by size class (maximum particle dimension).

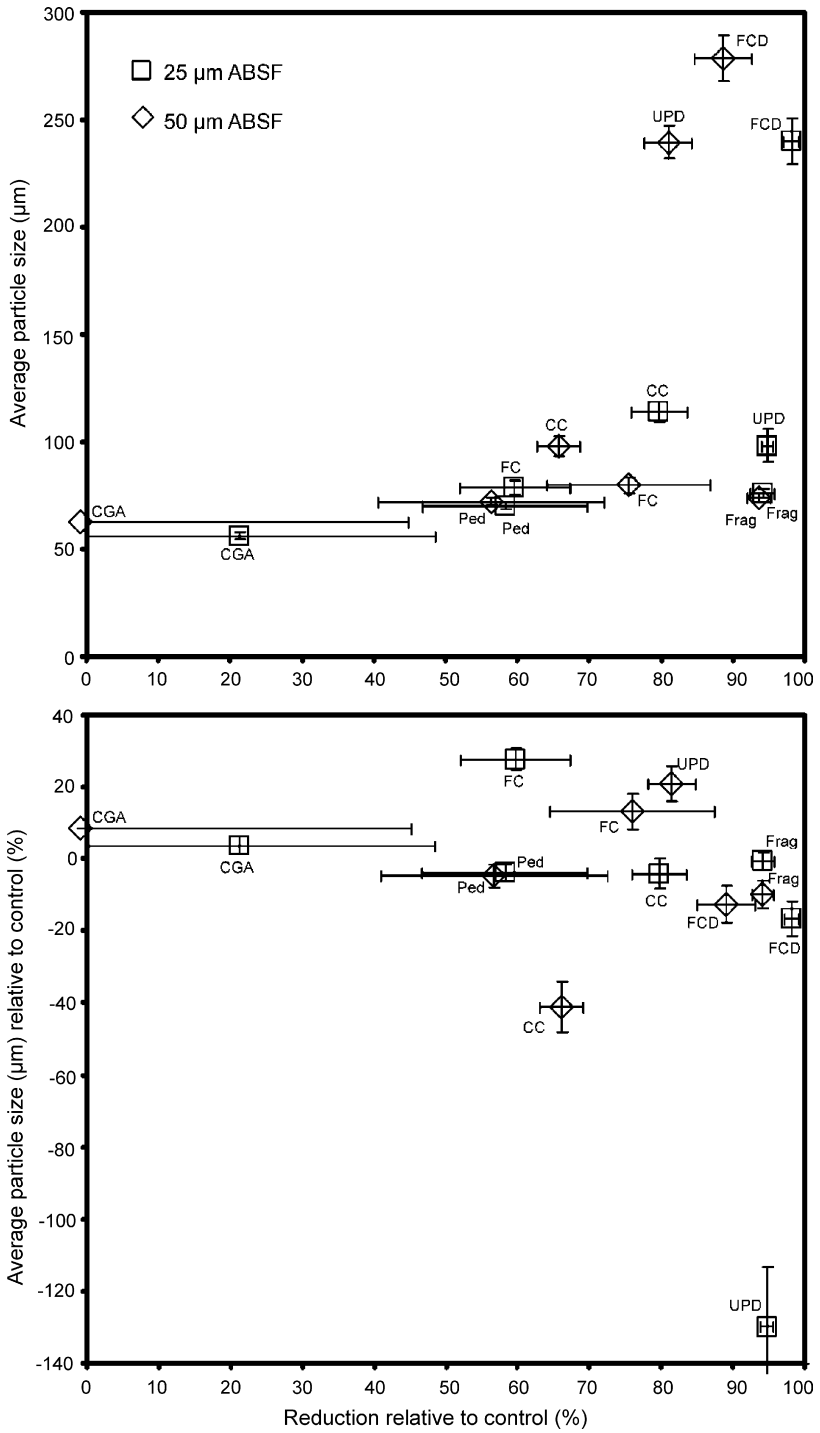

Fig. 11. Comparison of average algal particle size in treated water (top) and average change in particle size following filtration (bottom) along the gradient of filter performance in trials conducted on board the barge-based platform (mean ± S.E.). Algal groups shown are unicellular pennate diatoms (UPD), colonial green algae (CGA), filamentous cyanobacteria (FC), *Fragilaria*-like colonial diatoms (Frag), filamentous centric diatoms (FCD), colonial cyanobacteria (CC) and *Pediastrum* (Ped).

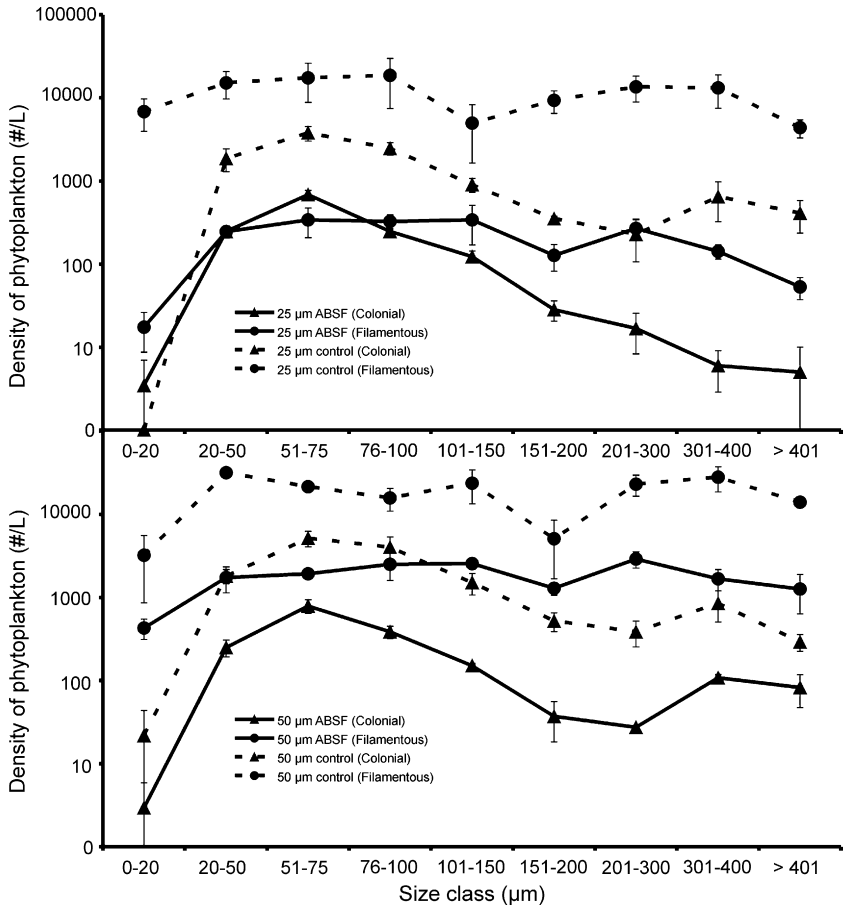

Fig. 12. Densities of colonial and filamentous phytoplankton particles in controls and water treated using 25 μm (top) and 50 μm (bottom) ABSF in trials conducted on board the barge-based platform (mean ± S.E.). Particles were grouped by size class to evaluate variations related to the maximum dimension of particles.

always determinative. The 25 μm screen was more likely than the 50 μm screen to remove large unicellular pennate diatoms (e.g. greater than 100 μm). Average particle size in discharge from 50 μm treatment was greater than 200 μm, while average particle size in discharge from the 25 μm filter was less than 100 μm. However, both screens performed similarly well relative to filamentous centric diatoms greater than 100 μm; and average particle size in discharge from both filters was greater than 200 μm.

The influences of particle morphology on algal particle removal did not appear independent of each other. Rigid particles of 101–150 μm were more efficiently removed by the 25 μm screen than the 50 μm screen (Fig. 11). Meanwhile longer filaments well above the filter pore size were removed equally well by both filters.

Finally, these tests showed no notable increases in numbers of smaller algal particles in treated versus control water. The only apparent exception was the 25 μm screen, which had a slightly higher number of colonial forms in the filtered water, relative to the control. Certain algal forms, i.e., unicellular pennate diatoms (25 μm treatment) and colonial cyanobacteria (50 μm treatment), had smaller particles in filtered water when compared to controls. However, other forms showed little change in the average particle size following filtration.

4. Discussion

This research explored the potential of shipboard filtration as a means of reducing ballast-mediated introductions of aquatic invasive species into the Great Lakes by commercial ships. Specifically, the study evaluated the effect of treatment by three pore sizes of automatic backwash screen filtration on the densities of major taxonomic groupings of ambient plankton in the shipboard context throughout the North American Great Lakes system and through more controlled experiments

on a stationary barge-based platform moored in Lake Superior.

Testing the same filter system and pore sizes on the two different experimental platforms proved useful in evaluating the relationship between screen filtration pore size and effectiveness against a variety of taxonomic categories of plankton. The shipboard analysis yielded preliminary findings to assess the workable range of effective filtration pore sizes under more "real world" conditions. The more detailed barge-based findings provided insight into the possible relationship of organism size, morphology, and intake densities to the effectiveness of screen filtration. In combination, this information serves as a basis for cautious speculation relative to prospective effectiveness of screen filters at removing ambient organisms in the Great Lakes, and beyond. Coupled with operational evaluations of the same filter systems reported by Parsons and Harkins (1999), this investigation also suggests the level of filtration which could optimize operational and biological performance, and the relationship between that nexus and what might be needed to meet current and pending ballast water treatment discharge standards.

The biological findings show that screen filtration at 25 and 50 μm had clear strengths as a potential ballast treatment. First, it can deliver significant reductions in plankton densities. Indeed, the reductions in macrozooplankton caused by ABSF in the barge-based tests were striking—greater than 99% for the 25 μm screen, and 97% for the 50 μm screen. The two filter pore sizes were capable of removing 99% and 91% of dinoflagellates, respectively, relative to controls. Moreover, filtration outcomes were quite consistent across trials. Despite the small difference in pore size between the two filters tested and the limited number of trials for each experiment ($N = 3$), the barge-based tests showed the 25 μm screen afforded significant advantages over the 50 μm screen, especially with respect to removal of microzooplankton (81 relative to 71%) and several categories of phytoplankton (unicellular pennate diatoms, dinoflagellates and colonial cyanobacteria).

However, this biological study also showed that treatment with ABSF would have to be enhanced with additional treatment to adequately minimize discharges of entrained organisms to meet prevailing international standards and to remove all risk. Specifically, these tests indicate that ABSF alone, even at 25 μm, would be unlikely to deliver ballast discharge that complies with recent International Maritime Organization standards. The IMO Convention on Ballast Water calls for ballast discharge containing no more than 10 viable organisms per m^3 of 50 μm or greater minimum dimension, a size descriptive of many zooplankton. It also limits discharge of smaller organisms (10–50 μm in minimum dimension) to no more than 10 organisms per mL, and sets specific discharge limits for selected bacteria. ABSF is limited in part because many of the organisms in the latter two regulatory categories (e.g. picoeukaryotes) are smaller than even the minimum available pore sizes for high-flow screen filtration (25 μm). However, even if requirements on organisms larger than 50 μm in minimum dimension are considered alone, the ABSF evaluated in this study would not meet the IMO standard. In barge tests, reductions relative to zooplankton width, while significant for all size bins greater than the nominal filter size, reached 90% only for organisms with widths of twice the nominal filter size and above. The 25 μm ABSF, for example, removed less than 80% of the zooplankton with widths of 50–100 μm. In terms of absolute concentrations of organisms, discharge of *MV Algonorth* ballast water treated with 25 and 50 μm ABSF averaged 90 ± 20 macrozooplankton per m^3, and 640 ± 470 macrozooplankton per m^3, respectively. Only the lowest discharge densities for macrozooplankton in the *MV Algonorth* tests approached the IMO standard (60 organisms per m^3 after treatment with the 25 μm screen, and 140 organisms per m^3 after treatment with the 50 μm screen); the maximum residual concentrations of macrozooplankton in water treated with 25 and 50 μm ABSF were 120 and 1590 per m^3, respectively. In barge-based tests, the lowest discharge densities observed were 200 macrozooplankton per m^3 after treatment with the 25 μm screen, and 870 per m^3 after treatment with the 50 μm screen; maximum discharges ranged to 580 macrozooplankton per m^3 after treatment with the 25 μm screen, and 6,110 per m^3 after treatment with the 50 μm screen. It is possible that some of these macrozooplankton ranged below the 50 μm in minimum dimension, but it is more likely that many microzooplankton in a ship's discharge will range greater than 50 μm in minimum dimension. In the barge tests, where microzooplankton were abundant, mean absolute densities of zooplankton generally with widths >50 μm in water treated with the 25 and 50 μm filters were 21,090 and 54,500 per m^3, respectively.

It should be noted that the specific filter system tested was a prototype unit, and while no correctable equipment flaws were evident during the biological tests, it is conceivable that improvements in the construction or design of ABSF system could reduce the number of larger organisms detected in treated discharge. However, even optimally designed screen

filters are expected to remove less than 100% of the particles larger than the filters' nominal rating in real world high flow applications. Indeed, Parsons and Harkins (1999) observed based on their operational evaluations relative to general particle removal that the filter units tested performed well from an engineering standpoint across platforms at a mean efficiency above the nominal pore size of 88 and 90%, respectively.

Failure to meet IMO criteria as a stand alone system in no way diminishes the potential utility of filtration as a component of an effective treatment system. If filters should be employed in this way, this research provided useful information about pore size, and organism morphology, structure, density and size as influences on filtration efficiency. In particular, our observations about the effect of specific features of organism morphology on ABSF performance could help in anticipating the potential ABSF contribution to treatment effectiveness of a compound treatment system against a variety of organisms.

For example, in this study, the same filter screen removed hard-bodied (loricate) species of rotifers more efficiently than soft-bodied (aloricate) species of rotifers within the same length and width size classes. The lower rate of removal of microzooplankton within the *MV Algonorth* tests relative to the barge based tests could be explained in part by the dominance of *Polyarthra*, a soft-bodied rotifer, in the natural assemblage associated with the shipboard tests. Accordingly, at a given filter pore size and within a given set of common algal size classes, rigid algal particles appeared more readily removed than globular forms. For example, the colonial green alga *Pediastrum* was more poorly removed than rigid filamentous phytoplankton perhaps because their softer cell walls allow colonies to distort and so pass through pores smaller than their diameter. This effect was not simply an artifact of algal particle shape as colonial forms and filamentous forms were equivalently removed by the filters. These results suggest that a secondary treatment system used to complement filtration would need to have particular effectiveness on soft-bodied plankton.

Meanwhile, organism density and particle size above the filters' nominal pore size were surprisingly weak influences on filter performance. It could be postulated that filter efficiency would improve in higher density conditions due to crowding at the filter. However, these tests suggest that filtration during algal bloom conditions will result in commensurately higher numbers of algae in filtered water with filtration efficiency relatively unchanged. It also may have been expected that larger algal particles would be necessarily more effectively captured than smaller particles by a given filter screen. Our findings show that there was no overall increase in performance efficiency across phytoplankton size classes above the nominal filter pore size. Part of the problem here may have been the expression of size for algal particles, or the fact that their morphology is not streamlined. We found that among rigid-bodied rotifers, size did influence filter effectiveness and width was far more predictive of filtration efficiency than length.

Complicating prediction of filtration efficiency on any of the above potential influences is the likelihood of their interaction with each other. For example, morphology, pore size and particle size appeared to interact to influence filter efficiency. Specifically, the ratio of algal particle length to pore size appeared to predispose certain rigid algae to selective capture by or penetration of filters, suggesting that they may be able to tip into and spear through the 50 μm pores more readily than the 25 μm pores. Meanwhile longer filaments well above the filter pore size were removed equally well by both filters. More testing regarding this issue would be necessary to generate more conclusive results.

An important consideration relative to filtration of algal particles is whether filaments and other colonies might be broken up by the filters into more abundant propagule units. These tests suggest that the filters do not have this undesirable effect. The slightly higher number of colonial forms in the 25 μm filtered water combined with the apparent poor percent reduction of algae in the smallest size class may be because the numbers counted in this size class were relatively low. We attribute the decline in the average size of unicellular pennate diatoms in treated discharge relative to controls to smaller cells passing through the filter, and not fragmentation. It is important to note that if colonies had been broken up into units well below 20 μm in size, they could have passed undetected through the 20 μm control and treatment sampling nets.

When considered in combination with operational findings of Parsons and Harkins (1999), these biological findings offer insight into ways to optimize biological performance in light of operational limitations. In operational tests conducted by Parsons and Harkins (1999) net lost flow due to backwash for the 50 μm filter screen was between 6.8 and 13.5%. In contrast, net lost flow due to backwash for the 25 μm screen was between 10.6 and 21.2%, approximately 60% more than the 50 μm screen. Use of the 25 μm filter screen also introduced a greater system pressure drop, further reducing the net flow rate or requiring a higher pump capacity to maintain the design ballast flow rate. This

lost flow rate has significant implications for ballast pump sizing to ensure that the ballast time is not lengthened. The authors therefore did not recommend use of the 25 μm screen on board a commercial vessel without significant backwash improvements. These operational findings raise the issue of how important from a biological standpoint the smaller pore size may be. Our study indicates that the 25 μm screen could well afford significant advantages, especially where smaller rigid or hard-bodied organisms are prevalent. However, the findings also show that some form of lethal secondary treatment will be necessary to enhance filtration effectiveness irrespective of filter size to achieve discharge at current and pending regulatory standards. Moreover, this lethal treatment would require effectiveness relative to the full spectrum of organisms in the water column (i.e., across all size categories). These considerations combined with the operational findings suggest that enhanced biological efficiency afforded by 25 μm using the equipment tested may not justify the operational difficulty involved at this time. However, should filtration technology improve to allow a 25 μm screen to perform equally well as the 50 μm screen tested, the smaller screen size should be used.

In conclusion, the biological findings regarding filter effectiveness relative to freshwater zooplankton and phytoplankton from the North American Great Lakes, demonstrate a strong potential value of filtration as a primary treatment method due to large and consistent removal efficiencies of taxonomic categories of known concern from ballast water. At the same time, they confirm the need for filtration to be coupled with an additional treatment step to assure inactivation of residual organism concentrations across the entire organism size spectrum.

Acknowledgments

We wish to thank the principal investigators of the operational research, Richard Harkins and Michael Parsons, who generated the designs for the test platforms, and who lent invaluable advice, assistance and companionship throughout the biological testing. We thank Algoma Central Marine (now Seaway Marine Transport) and the officers and crew of the *MV Algonorth,* as well as the Port of Duluth/Superior for providing the venues for our research. We are indebted to the Great Lakes Protection Fund for its generous funding in support of the effort. As ever, we greatly appreciate the insight and good will of Jim Carlton, who inspired, cheered and helped interpret our work. Finally, we are indebted to Gustaaf Hallegraeff for inviting our paper for inclusion in this special issue of Harmful Algae.[SS]

References

Cangelosi, A., 2002. Filtration as a ballast water treatment measure. In: Leppakoski, E., Gollasch, S., Olenin, S. (Eds.), Invasive aquatic species of Europe. Distribution, impacts and management. Kluwer Academic Publishers, Dordrecht, pp. 511–519.

Cangelosi, A., Mays, N., 2006. Great Ships for the Great Lakes? Commercial Vessels Free of Invasive Species in the Great Lakes–St. Lawrence Seaway System. A scoping report for the Great Ships Initiative. Northeast-Midwest Institute, Washington D.C.

Colautti, R.I., Niimi, A.J., van Overdijk, C.D.A., Mills, E.L., Holeck, K., MacIsaac, H.J., 2003. Spatial and temporal analysis of transoceanic shipping vectors to the Great Lakes. In: Ruiz, G.M., Carlton, J.T. (Eds.), Invasive Species: Vectors and Management Strategies. Island Press, Washington D.C., pp. 227–246.

Grigorovich, I.A., Colautti, R.I., Mills, E.L., Holeck, K., Ballert, A.G., MacIsaac, H.J., 2003. Ballast-mediated animal introductions in the Laurentian Great Lakes: retrospective and prospective analyses. Can. J. Fish. Aquat. Sci. 60, 740–756.

Holeck, K.T., Mills, E.L., MacIsaac, H.J., Dochoda, M.R., Colautti, R.I., Ricciardi, A., 2004. Bridging troubled waters: biological invasions, transoceanic shipping, and the Laurentian Great Lakes. BioScience 54 (10), 919–929.

International Maritime Organization, 2004. International Convention for the Control and Management of Ship's Ballast Water and Sediments. International Maritime Organization, London.

Johengen, T., Reid, D., Fahnenstiel, G., MacIsaac, H., Doblin, M., Jenkins, P., 2005. Assessment of Transoceanic NOBOB Vessels and Low-Salinity Ballast Water as Vectors for Non-Indigenous Species Introductions to the Great Lakes. National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Laboratory, Ann Arbor.

Kuzirian, A.M., Terry, E.C.S., Bechtel, D.L., 2001. Hydrogen peroxide: An effective treatment for ballast water. Biol. Bull. 201, 297–299.

Mills, E.L., Leach, J.H., Carlton, J.T., Secor, C.L., 1993. Exotic species in the Great Lakes: a history of biotic crises and anthropogenic introductions. J. Great Lakes Res. 19 (1), 1–54.

National Research Council, 1996. Stemming the tide: Controlling introductions of nonindigenous species by ships' ballast water. National Academy Press, Washington, D.C..

Park, J., Hushak, L.J., 1999. Zebra Mussel Control Costs in Surface Water Using Facilities. Technical Summary TS-028, Ohio Sea Grant, Columbus.

Parsons, M.G., Cangelosi, A., Harkins, R.W., Mackey, T.P., Munro, D.J., 1997. Design of the Great Lakes Ballast Technology Demonstration Project. Transactions SNAME 105, 323–348.

Parsons, M.G., Harkins, R.W., 1999. The Great Lakes Ballast Technology Demonstration Project filtration mechanical test program. Mar. Technol. 37 (3), 129–140.

Ricciardi, A., 2001. Facilitative interactions among aquatic invaders: is an "invasional meltdown" occurring in the Great Lakes? Can J. Fish. Aquat. Sci. 58, 2513–2525.

Ricciardi, A., MacIsaac, H.J., 2000. Recent mass invasion of the North American Great Lakes by Ponto-Caspian species. TREE. 15 (2), 62–65.

Sarnelle, O., Wilson, A.E., Hamilton, S.K., Knoll, L.B., Raikow, D.E., 2005. Complex interactions between exotic zebra mussels and the

noxious phytoplankter. *Microcystis aeruginosa*. Limnol. Oceanogr. 50, 896–904.

Sutherland, T.F., Levings, C.D., Elliot, C.C., Hesse, W.W., 2001. Effect of a ballast water treatment system on survivorship of natural populations of marine plankton. Mar. Ecol. Prog. Ser. 210, 139–148.

Tamburri, M.N., Wasson, K., Matsuda, M., 2002. Ballast water deoxygenation can prevent aquatic introductions while reducing ship corrosion. Biol. Conserv. 103, 331–341.

Vanderploeg, H.A., Liebig, J.R., Carmichael, W.W., Agy, M.A., Johengen, T.H., Fahnenstiel, G.L., Nalepa, T.F., 2001. Zebra mussel (*Driessena polymorpha*) selective filtration promoted toxic *Microcystis* blooms in Saginaw Bay (Lake Huron) and Lake Erie. Can. J. Fish. Aquat. Sci. 58, 1208–1221.

Waite, T.D., Kazumi, J., Lane, P.V.Z., Farmer, L.L., Smith, S.G., Smith, S.L., Hitchcock, G., Capo, T.R., 2003. Removal of natural populations of marine plankton by a large-scale ballast water treatment system. Mar. Ecol. Prog. Ser. 258, 51–63.