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Ballast Water: Ecological and Fisheries Implications

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Ballast Water: Ecological and Fisheries Implications

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Foreword

James T. Carlton and Janet Kelly

Introduction

The first international scientific meeting addressing the role of ballast water and sediment discharge in the introduction of non-native (exotic, non-indigenous) species was convened on September 21, 1995 at the Annual Science Conference of ICES (83rd Statutory Meeting), in Aalborg, Denmark. The Session was co-sponsored by the International Maritime Organization (IMO) and the International Oceanographic Commission (IOC). Seventeen papers and posters representing eight countries and the IMO were presented. The Theme Session was immediately preceded by the Open Lecture in the General Assembly, on "Ballast Water: The Ecological Roulette of Marine Biological Invasions" by Dr J. T. Carlton.

The present proceedings, while delayed in publication, provide valuable overviews on the science and management of ballast water and invasive species. We are grateful to Ms. B. Holohan in aiding with the final preparation of these proceedings.

Background

Since the 1980s, ballast water and associated sediments have become increasingly recognised as the most important modern vectors for the transoceanic and interoceanic transport of neritic (shallow-water coastal) organisms, in particular those species associated with the estuarine ecosystems typical of many ports and harbours. Although biogeographers and ecologists recognised that many species invasions within the last two decades could be linked to ballast water, it was not until several high impact invasion events occurred in the late 1980s that new levels of interest occurred in the science and management of ballast water. These invasions included:

- The appearance of several species of North Pacific toxic dinoflagellates in southern Australia, known causative agents of paralytic shellfish poisoning (PSP), a human illness previously unknown in Australia.

- The appearance of six species of Eurasian invertebrates and fish in the Great Lakes of Canada and the United States, including the zebra mussel *Dreissena polymorpha*, a fouling organism which has cost industry hundreds of millions of dollars, and the ruffe *Gymnocephalus cernuus*, whose introduction has caused the precipitous decline of all resident small fish populations in southern Lake Superior.

- The appearance of the American comb jellyfish *Mnemiopsis leidyi* in the Black and Azov Seas, and the subsequent decimation of the already declining anchovy fisheries of that region.

All of these invasions were linked to the release of ballast water and sediments.

ICES concerns with the ballast water issue

ICES had noted the role of ballast water in exotic species invasions as early as the 1970s through its Working Group on Introductions and Transfers of Marine Organisms (ITMO). In 1988 at its Edinburgh, Scotland, meeting, ITMO drew specific attention to ballast water (Mariculture Committee, CM 1988/F:20):

"That attention be drawn to the dangers resulting from the increasing international movement of water as ballast in cargo vessels, and the subsequent accidental introduction of exotic fishes and zooplankton (as in the North American Great Lakes) and the potential accidental introduction of exotic phytoplankton (such as species that may cause toxic blooms) and ICES member countries be urged to examine this critical problem, to determine the scale of this activity in their countries, and to consider control measures (such as the exchange of harbour (port, estuarine, bay) water for ocean water on the high seas)."

In 1990 a special "Study Group" on ballast water was convened in association with ITMO's meeting in Halifax, and a report issued. Increasing concern and increasing numbers of invasions in Europe, the United States, Australia, and elsewhere lead to the convening of this 1995 Theme Session.

The 1995 Theme Session

The Theme Session was opened by Dr J. T. Carlton, Convener, accompanied by remarks from Dr M. Nauke of the IMO (London) and from Dr H. O. Enevoldsen of the IOC's Centre on Harmful Algae (Copenhagen). Dr J. Doyle presented the paper for Ireland in the absence of Dr D. Minchin and Mr J. Sheehan; Dr B. Howell presented the paper for England and Wales in the absence of Dr I. Laing, and Dr G. Rigby presented the paper for Japan in the absence of Captain T. Ikegami. Ms J. Kelly served as Theme Session Rapporteur. The Convener noted and thanked Australia, New Zealand, and Japan for their participation, which thus permitted review of this subject in a truly global fashion. In addition to the research and management programs presented by IMO, Australia, Canada, Germany, Ireland, Japan, New Zealand, the United Kingdom and the United States, additional remarks were made from the floor by Sweden on their research efforts. Dr. C. Eno also made remarks from the floor, and offered to contribute a summary paper on further work in the United Kingdom, which is included in the present proceedings. The Theme Session covered the biology and ecology of ballast water transport, potential control and management approaches, relationships between ballast water and mariculture, policy initiatives relative to economic theory, and the application of quantitative risk assessment to ballast water management.

Major findings and conclusions of the Theme Session

Theme session participants were asked to specifically identify what they considered to be the most important future research questions and priorities. These recommendations along with selected contributions from participants' presentations are outlined here.

International coordination, collaboration and communication

A major theme was the pressing need for immediate international coordination of the many independent research programs now underway in order to reduce duplication in research efforts. There was an additional call for international joint research projects (e.g. two countries sampling the same ships at each end of a voyage, or multiple countries sampling the same ship as it sailed around the world). All participants expressed a strong desire to continue communication within this group by way of regularly issued newsletter or e-mail network. In addition, it was noted that countries that do not yet have research programs on ballast water should be encouraged to collaborate with other regional programs already underway. While IMO is assisting in the coordination of ballast control strategies among nations of the world, ICES is in an ideal position to assist in the coordination of research efforts within ICES member countries as well as offering similar assistance elsewhere.

Standardisation of sampling methodology and data collection

Standardisation of sampling methods (types of plankton sampling devices used, whole water sampling methods, benthic and sediment sampling methods, ballast access, experimental techniques) was considered a major goal. Particular attention was paid to the need to standardise the means by which ballast is calculated, distinguishing the three different categories of ballast capacity from ballast actually carried from ballast discharged, and the need for distinguishing between last port of call (LPOC) and the actual source of the ballast water. Further, session participants emphasised the need for national documentation of ballast discharge by the appropriate authorities of the ballast activity.

Sampling design: improved understanding of the complexities involved

It was suggested that the variety of ship designs, the diversity of ballast tanks and within-tank configurations, and ballast discharge patterns may contribute to misinterpretation of sample data. The collection and analysis of water and sediment samples should be followed by verification of discharge activity so that assumptions about discharge are avoided. Further, it was noted that there may be water from different sources aboard a single ship, held in different tanks or mixed within a tank.

Identification of regional hot spots

The identification of "hot spots" was regarded as an important goal. In this respect, countries should provide timely notification of outbreaks, resurgences, blooms, and other episodes involving potentially harmful, unwanted, and nuisance species that may be transported by vessels. This may include the presence of a relatively new successful invasion which could potentially be picked up and further transported by vessels. The World Health Organization global network for human disease outbreak notification is suggested as a model system.

Increasing awareness of the presence of cholera and other bacteria in ballast

The United States, Australia, Germany, and other countries noted recent research that has established the presence of cholera bacteria in ballast water. The possible linkage of ballast-mediated transport to the global increase in cholera epidemics in susceptible nations was proposed as a reason to increase awareness by researchers for this and other known pathogens in ballast systems.

Research on ballast water biology and the diversity of ballast environments

Further research is required on the diversity of aquatic (freshwater, brackish water, and marine) organisms being transported over different spatial and temporal scales, as well as on the range of environmental conditions (salinity, temperature, oxygen, nutrients, and so forth) and their changes during a voyage transit, in different types of ballast tanks, and in different types of tanks on the same vessel.

Research on control methods

Session participants expressed the need for continuing research to develop long-term effective control technologies. On-going research on open ocean exchange, heat treatment, filtration, and chemical treatment, as well as exploring specific uptake-release management scenarios, such as the identification of hot spots, port incompatibility (for example, the release of polar water in a tropical port) and real-time decisions on ballasting during algal blooms are also strongly supported. It was emphasised that in the long run a variety of control and management options will be required as part of a larger "tool kit".

Definition and understanding of the meaning of "compliance" with ballast regulations

Most existing ballast management programs propose the use of open ocean exchange (exchanging coastal water with open ocean water) as a recommended method for minimising the introduction of non-native organisms. While a number of studies have identified the percentage of ships that have "complied" with this regulation, it is increasingly clear that compliance must be measured in a quantitative manner (how much water was exchanged) instead of a qualitative manner ("yes" or "no").

The relationship between mariculture and ballast water introductions

It was noted that mariculture operations are increasingly regulated to prevent the accidental introduction of pathogens and unwanted species, unlike ballast operations which remain largely unregulated. In many instances mariculture facilities are located in the same coastal ecosystems which are inundated by the release of species released in ballast water. It was felt that mariculturists would have an increasingly difficult time underwriting their efforts to control species invasions and associated environmental impacts if other vectors leading to species invasions remained uncontrolled. Further, considerable concern was expressed relative to the potential impact of ballast-mediated introductions on mariculture operations themselves – such as the introduction of competitors, predators, and pathogens. Unregulated ballast operations may also influence the sittings of new mariculture operations.

The need for increased attention to intranational (intracoastal) transfers of exotic species

The need for research on the role of ballast water and shipping in the movement of established introductions along a country's coastline, or between adjacent countries, was identified. Most efforts have to date concentrated on the arrival of foreign ballast water, although increasing evidence suggests that coastal traffic may also play an important role in the translocation of species.

Identification of species as introduced, and identification of ballast water as the transport vector

Session participants noted that the identification of certain species as being unequivocally introduced (such as many dinoflagellate species) was difficult. Session participants also noted that reliably identifying ballast water as the sole transport vector for certain species may also be difficult (as opposed to transport as fouling organisms on a ship's hull). It was noted that species should be more clearly treated as either native, introduced, or cryptogenic, the latter being a category of species whose endemic versus exotic status is not known (rather than cryptogenic species being treated as native species). It was further noted that the concept of the ship as a total "biological island" should be more thoroughly addressed, with the realisation that at any one time a ship may carry living organisms in ballast water and sediments, in its sea chests (the inlets in the vessel where water is taken in), in anchor chain lockers, as well as on the hull. In addition, it was felt necessary to keep ballast and other ship-related vectors in perspective relative to other pathways for introductions such as mariculture, the movement of species for direct human consumption, and the movement of bait worms and seaweed for packing.

The use of quantitative risk assessment (QRA) techniques

QRA is an iterative and educational process that permits identifying the detailed steps in ballast and invasion processes and identifying the level of risk associated with each. It would be valuable to undertake a detailed case study of one or more species applying the methods of QRA in order to expand our understanding of the use of these techniques in ballast water management.

Linkage with biodiversity issues

Species invasions are known to significantly impact biodiversity through competition, predation, and disturbance, altering both the diversity and abundance of the native biota. Recent international policy efforts aimed at addressing biodiversity issues provide an additional venue for exposure for the issue of ballast introductions.

International and national co-ordination with systematic biology

As an increasing number of countries recognise the need to undertake ballast research, there exists a growing demand for "global taxonomic expertise". Session participants suggested the need for a network of taxonomists including those experienced in the analysis of ballast samples who would be willing to participate in ballast studies.

The need for education programmes

The issues and challenges associated with ballast and ballast management should be incorporated into broader public and industry educational programs. Australia, Canada, and the United States have established educational programmes, ranging from wallet-size cards to leaflets to videos, that could provide model systems for other nations.

Joint Working Group of IMO, IOC, and ICES on ballast water introductions

It was noted that the IOC has proposed that a joint working group, consisting of IMO, IOC, and ICES members, be convened to discuss their mutual interests in the subject of ballast water as a vector in the release of harmful algae as well as other organisms. IMO already has in place a Working Group on Ballast Water under its Marine Environment Protection Committee; IOC noted in June 1995 in Paris its growing interest and involvement with the ballast issue, and ICES has been involved with ballast water issues for several years. It was felt that the time was right for bringing the groups together to formulate joint strategies.

Summary and action plan

It was agreed that this, the first international scientific meeting on ballast water biology and management, had more than successfully reached its goal of bringing all research groups together to discuss communication, collaboration, and standardisation. Continued correspondence was considered of the utmost importance. Cross-comparison of sampling strategies, data collection methods, and data analyses were emphasised as international co-operation increases. The continued joint association of ICES, IMO, and IOC in ballast water overview and co-ordination was seen as an important goal, with an eye toward identifying the need for a joint Study Group on Ballast Water. The ballast issue was considered to be critical in terms of ICES involvement on the impacts of human activities on coastal fisheries and coastal zone management.

Ballast water and non-indigenous species in US Coastal waters

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Introduction

Non-indigenous species (NIS) are increasingly conspicuous in marine habitats throughout the world, as the number, variety, and effects of these species continue to accrue. For marine communities in which NIS have been surveyed, the number of known NIS range from tens to hundreds of species and includes all major taxonomic groups (e.g., Por, 1978; Carlton, 1979; Boudouresque, 1994; Ruiz, 1996; Thresher, 1996). Furthermore, it is clear that some of these NIS have significant ecological impacts on invaded communities and significant economic consequences for surrounding industries (e.g., Nichols, 1990; Harbison and Volovick, 1994; Cohen and Carlton, 1995).

Most invasions by NIS result from human-mediated transfer. For centuries, common mechanisms for species transfer around the globe have included (1) movement of organisms in or on ships, (2) intentional release of commercial species (along with associated species), (3) connection of waterways through canals, and (4) release of species associated with pet industries and management practices (e.g., Elton, 1958; Carlton, 1989, 1992). However, the relative importance of these transfer mechanisms exhibits both spatial and temporal variation (Carlton, 1979; Cohen and Carlton, 1996; Ruiz, unpublished data).

On a global scale, the movement of ballast water by ships appears to be the single largest vector for marine NIS transfer today. For example, a single ship can carry > 150,000 metric tons of ballast water, and a single port system can receive thousands of ships per year with foreign ballast (e.g., Carlton, 1995). Because water is often ballasted from bays and estuaries, rich in holo- and meroplankton, most ships carry a diverse assemblage of organisms in their ballast water. These organisms are variously released at ports of call, thus creating a large scale dispersal process by which NIS can invade new regions (e.g., Carlton, 1985; Williams, 1988; Carlton and Geller, 1993).

Although the importance of ballast water in NIS transfer is clear, the relationship between transfer rate (=supply) and invasion rate remains unresolved for marine habitats and invasion biology generally. There is no doubt that many invasions throughout the world have resulted from ballast transfer (e.g., Carlton and Geller, 1993). Furthermore, the frequency of ballast-related invasions in some estuaries has increased through time with increasing ballast water delivery (e.g, Mills, 1993, Cohen and Carlton, 1995). Nevertheless, despite theoretical predictions (MacArthur and Wilson, 1967; Simberloff, 1986; Robinson and Edgemon, 1988), we simply do not know whether invasion rate across many communities is correlated strongly to ballast water supply. While supply is necessary for invasions, the success of arriving propagules may be influenced by other factors (e.g., particular attributes of source communities, condition of arriving propagules, or interactions with the recipient communities).

Our goal in this paper is twofold. First, we wish to describe the current state of knowledge about ballast water in the United States, describing research on both the transfer and invasion of NIS. Second, we call for increased international coordination of existing research efforts to test hypotheses about invasions using comparisons across many communities.

Ballast water research in the US

The largest ballast water research program within the US is now centred at the Smithsonian Environmental Research Center (SERC) in Edgewater, Maryland on the upper Chesapeake Bay. A major goal of this program is to measure the transfer and invasion of NIS associated with ballast water. We are using Chesapeake Bay as a model system for this research, because it is one of the biggest recipients of foreign ballast water in the US (see below). Importantly, our approach develops and tests hypotheses about patterns of transfer and invasion success within the Chesapeake region as well as other regions.

We review here the major elements of our research program and the current understanding of ballast-mediated transfer and invasion in the US In so doing, we have tried to include previous and on-going research on marine invasions by others that is directly relevant to the topic and that extends our perspective to include multiple sites.

Ballast water volume

Commercial ports in the US received > 79,000,000 metric tons of foreign ballast water in 1991 (the equivalent of 11,000,000 litres/hour; Carlton, 1995). Most of this water arrives in bulk cargo carriers, which carry and release relatively large volumes of ballast near or at ports of call.

Not surprisingly, the volume and source region of ballast arriving in commercial ships exhibits considerable variation among major US ports (Carlton, 1995). For example, most foreign ballast water arriving in ports along the Pacific coast derives from the northeastern Pacific, whereas that arriving in ports along the Atlantic coast is of northeastern Atlantic or Mediterranean origin. The volume of ballast water delivered annually varies 2–3 orders of magnitude among ports, from a high of approximately 15,000,000 metric tons to less than 100,000 metric tons.

Chesapeake Bay is a "hotspot" on the Atlantic coast for the delivery of foreign ballast water from commercial vessels; its two major ports, Baltimore (Maryland) and Norfolk (Virginia), received > 12,000,000 metric tons in 1991 (Figure 1; Carlton, 1995). This volume greatly exceeds that arriving to any other US port with the exception of New Orleans, Louisiana. Although ballast water arrives to the Chesapeake from throughout the world, as with other Atlantic ports, the majority is from northeastern Atlantic and Mediterranean sources. This volume and pattern of delivery to Chesapeake ports appears relatively stable across years (Smith, 1996).

In addition to commercial sources of ballast, Chesapeake Bay also receives some ballast from military vessels. As home port to the US Navy's Atlantic Fleet, the level of military traffic that returns from foreign waters is relatively high compared to other US ports. This is enhanced further by the presence of US Army vessels in the region. We are currently measuring the contribution of military traffic to the total volume of foreign ballast arriving to the Chesapeake. Preliminary data suggest that the military contribution may be minor compared to that from commercial vessels (Ruiz, unpublished data).

Ballast water content

To date, there have been two extensive sampling programs that have analysed the density and diversity of species in foreign ballast water arriving to US ports, one on the Pacific coast and the other on the Atlantic. Below we review briefly highlights from each site.

Carlton and Geller (1993) sampled plankton communities in the cargo holds of 159 bulkers arriving to Coos Bay, Oregon from 25 different Japanese ports. Using a conventional plankton net (80 µm mesh), they found a total of 367 distinctly identifiable tax, representing 16 animal and 3 protist phyla and 3 plant divisions. The ballast water of all ships contained organisms, which derived from diverse habitats and represented most trophic groups. Certain taxa were present in many or most ships: copepods, polychaetes, barnacles, bivalve molluscs, gastropod molluscs, flatworms, diatoms, decapod crustaceans, and chaetognaths (Figure 2).

In the Chesapeake Bay, we have sampled plankton communities from ballast tanks and/or cargo holds from over 100 vessels (mostly bulkers) arriving from Europe and the Mediterranean, using similar sampling methods as Carlton and Geller (1993). Approximately 90% of the ships carried live organisms in their ballast water that included a diverse assemblage of organisms; barnacles, bivalve molluscs, copepods, diatoms, dinoflagellates, flatworms, and polychaete worms were among the most common organisms (Smith, 1996). To date, we have identified > 280 distinct taxa in our samples.

A direct comparison of samples from the cargo holds suggests that the prevalence of major taxonomic groups is similar between Chesapeake and Coos Bay (n= 24 and 159 respectively; Figure 2). However, densities appear higher in Coos Bay samples. We are now increasing our sample size for Chesapeake samples to control for effect of season in statistical comparisons.

Unlike the previous study, the Chesapeake program includes analysis of whole water for micro-organisms (e.g., viruses, bacteria, ciliates) and analysis of sediments for a broad array of taxa. These additional analyses reveal a relatively high prevalence and density of ciliates, bacteria, and viruses that arrive in ballast tanks (Ruiz, unpublished data). This transfer of dense microbial communities (> 10^5 cells/ml) has received very little attention to date, especially with respect to possible control measures to minimize transfer rates.

Transoceanic transit success in ballast

As part of the Chesapeake research program, we are measuring survivorship of organisms during transit in ballast water. The density and diversity of organisms that arrive in ballast water to the Chesapeake is highly variable among ships and decreases with increasing voyage duration (Smith., 1996). This variation reflects differences in the initial community that is entrained and/or variation among ships and taxa in survivorship during the voyage (or transit success).

To measure variation in transit success, we are comparing initial densities in ballast tanks before departure from a foreign port to final densities in the same tanks upon arrival to the Chesapeake. Our preliminary data indicate that transit success is often very low (< 5% survival) for zoo – and phytoplankton on voyages of < 30 day duration. In contrast, it appears that transit success is relatively high for microbial organisms in these same voyages. Using similar measurements among many ships, we intend to test for effects of various ballast tank conditions (e.g., food density, physical and chemical characteristics, voyage duration) and biological attributes (e.g., taxonomic group, life history, life stage) on transit success.

Viability and tolerance of arriving propagules

Many organisms arriving in ballast water to US ports are viable at the time of release: (1) Numerous recent invasions are attributed to ballast water discharge in our waters (e.g., Mills, 1993; Cohen and Carlton, 1995) and (2) in both the Coos Bay and Chesapeake Bay ballast water studies, larval invertebrates were maintained and reproduced successfully in laboratory culture, sometimes across multiple generations (Carlton and Geller, 1993; Smith, 1996; Ruiz, unpublished data).

To develop predictions about the risk of successful invasion following release from ballast tanks, we are conducting laboratory experiments that measure the tolerance of arriving organisms to ambient conditions of Chesapeake Bay. Specifically, we expose replicate groups of single species cultures to each of 3 salinities (5,15,25) and 3 temperatures (5,15,25°C) that represent a range of conditions present in the Chesapeake. Survival and growth is monitored for at least a 2-week period, and some cultures are maintained for months. Our data indicate that most organisms arriving in ballast survive best at high-to-mid salinities and temperatures, suggesting that the risk of invasion may be greatest in high salinity regions of Chesapeake Bay and in warmer months.

We are simultaneously testing some of these predictions by measuring temporal and spatial distribution patterns of NIS in the Chesapeake Bay fouling community. We are examining both the distribution of established NIS and of new invasions, following some of the methods of Hewitt (1993).

Geographic variation in extent and rate of invasions

In excess of 300 NIS that are known to have invaded marine habitats of the continental US in the past few centuries from a variety of human-mediated transfer mechanisms. We derive this number primarily from a few regional surveys (below), which we (Carlton, Ruiz, Cohen, Fofonoff, and Hines) are compiling into a cumulative list for US marine and estuarine waters. These NIS include most major taxonomic groups and they originate from around the world.

Although this number of NIS is relatively large, it is an underestimate of the total number of invasions for two reasons. First, many species have simply not been examined in our inventories. Second, of those examined, the status of many species is difficult if not impossible to resolve (e.g., Carlton, 1995).

Among US estuaries, there appears to be a large degree of variation in the extent and rate of invasions. The known number of NIS ranges between 60 and 212 per estuary (Great Lakes, 137 NIS, Mills. 1993; San Francisco Bay, 212 NIS, Cohen and Carlton, 1995; Coos Bay, 60 NIS, Carlton, unpubl. data; Chesapeake Bay, 120 NIS, Ruiz, unpublished data). Furthermore, although the number of recent invasions appears to be increasing (since 1960) for the Great Lakes and San Francisco Bay, this trend is not evident in Chesapeake Bay.

Interestingly, the relationship between ballast supply and invasion rate is not clear across US estuaries. For example, although San Francisco Bay and the Great Lakes have higher rates of recent invasions attributed to ballast water compared to Chesapeake Bay, the Chesapeake receives more foreign ballast water than either of these other systems (Carlton, 1995). Furthermore, the content of ballast water arriving to the Chesapeake appears similar to that arriving to west coast estuaries based upon the Coos Bay data (Figure 2). Thus, we surmise that the Chesapeake receives more propagules in ballast (volume x content) yet has a lower invasion rate than San Francisco Bay.

A major goal of our on-going research is to use such comparisons across estuaries to examine relationships between propagule supply and subsequent invasion

(= invasion success). Our approach includes improving our estimates of ballast-mediated transfer and invasion patterns, as well as extending our estimates to additional regions of the US through collaborative research efforts. We believe this comparative approach across systems provides the most robust measure of invasion success and offers exceptional opportunities to test for specific factors (e.g., community structure, physical or chemical properties) that may influence invasion success, invasion rate, and species composition of NIS.

As a component of these cross-system comparisons, we have also begun to measure ecological impacts of NIS invasions among estuaries in two ways. First, we are measuring the relative importance of NIS in the dynamics and composition of fouling communities. Second, we are examining the impact of the same NIS in different communities (e.g., Grosholz and Ruiz, 1996). Through combining descriptive and experimental approaches to each of these directions, we wish to test for general patterns and measure variation in the performance of established NIS.

International invasion research network

Over the past decade, the extent and impact of NIS invasions has received increasing attention throughout the world. For aquatic (marine and freshwater habitats), this has resulted in a series of parallel studies in many different countries that examine patterns and consequences of various (intentional and unintentional) NIS transfer mechanisms and subsequent invasions. While the intent of this theme session is to present a "state of our knowledge" in our respective regions of the world, it also offers an opportunity to compare our results and develop a co-ordinated approach to research in marine invasion biology.

The information now emerging from numerous ballast water studies and NIS inventories begin to provide exciting comparisons across a global network of sites. As discussed above, it is only through such a comparative approach that we can truly derive generalities from individual studies, allowing us to extrapolate our results and make predictions about the invasion processes. Development of effective management strategies to reduce the risk and impact of invasions must rely upon understanding of both generalities and sources of variation (i.e., those factors that influence the success and impact of invasions).

We propose establishing a "global network" of sites to further co-ordinate our respective studies of ballast water and invasion biology of marine habitats. Specifically, we propose development of ways to collect some standard data across many of our on-going studies that improves opportunities for broader-scale comparisons and collaborations. Over the next year, we will explore various strategies for implementing a network approach with each of the symposium participants, and we invite other interested researchers to contact us and participate in this dialogue.

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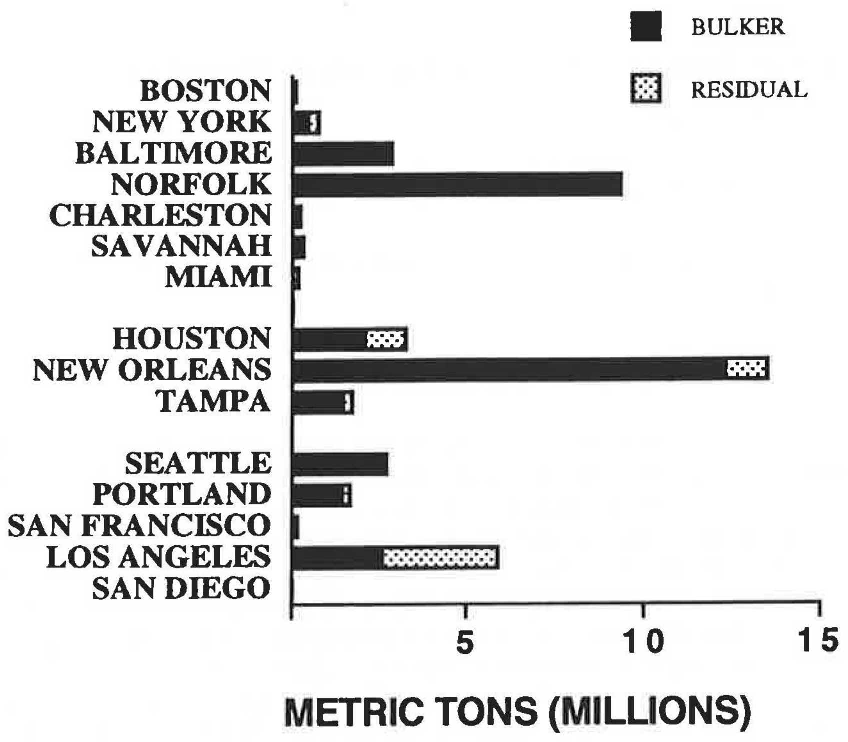

Figure 1 Comparison of ballast water volumes (in millions of metric tons) released at ports on the Atlantic, Gulf, and Pacific coasts of the United States in 1991 by commercial vessels. (Carlton *et al.*, 1995). Histograms distinguish contributions of bulk carriers (solid) from all other vessel types (stippled).

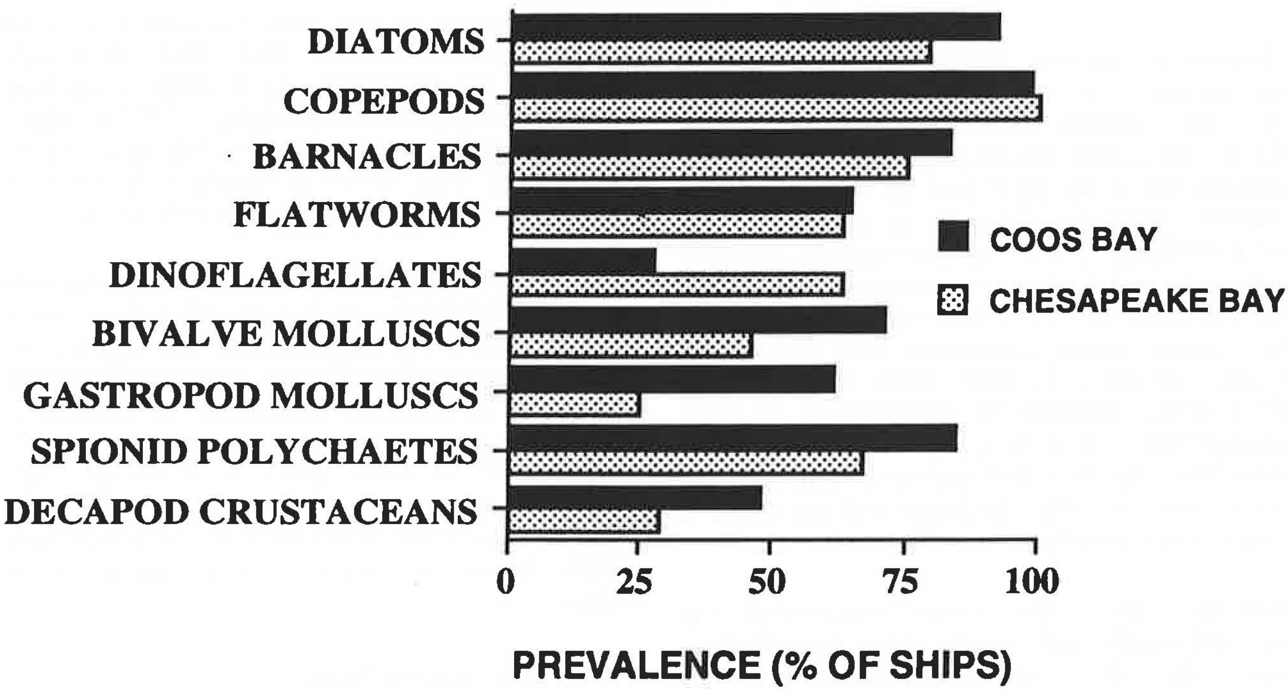

Figure 2 Comparison of major taxonomic groups collected from ships' ballast water at Coos Bay, Oregon (Carlton and Geller, 1993) and Chesapeake Bay (Smith *et al.*, 1996) expressed as a percentage of ships (n=159 and 24, respectively) in which the taxon was present.

The significance of ballast water in the introduction of exotic marine organisms to Cork Harbour, Ireland

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This paper reviews the occurrence of exotic species within one Irish port and examines the growing importance of ballast water discharges. Twenty-four exotic organisms known from Cork Harbour have been assigned according to their method of introduction. Six clam and oyster species have been used in aquaculture and unwanted species have been associated with these. At present aquaculture introductions and transfers are governed by a code of practice and this will reduce the risk posed by unwanted biota in the future. Eight of these introductions took place prior to 1972 and four of these are likely to have been introduced as fouling on ships. Antifouling applications on ships generally included TBT from 1972 and subsequently its use will have considerably reduced the risk of introductions by fouling organisms. There has been an overall increase in ballast water discharges with estimates of less than 20,000 tonnes in 1955 to almost 200,000 tonnes or more in each year since 1970. The origin of ballast water in 1993 was principally from Northern Europe and the UK, Australia, Egypt, the French and Spanish Mediterranean. There is a significant threat of establishment of non-native species, that survive in ballast water and are established elsewhere in Europe, becoming introduced to Cork Harbour.

Introduction

Introductions can have serious social and economic consequences. For example, the western Atlantic ctenophore, *Mnemiopsis leidyi*, introduced to the Black Sea from the western Atlantic in ballast water became so abundant that it has resulted in the collapse of some otherwise profitable fisheries by its predation of fish larvae (Harbison, 1993). The zebra mussels, *Dreissena polymorpha* and *D. bugensis*, introduced to the Great Lakes of North America in ballast water from the Black Sea, caused trophic competition and fouling and blockages of pipes (Kershner, 1993). Hallegraeff and Bolch (1992) demonstrated transportation of viable dinoflagellate cysts of toxic species in ships' ballast tanks. Some blooms in port areas may result from cyst inoculations from ballast discharges and may spread to compromise inshore fisheries and aquaculture activities.

Over the 20th century marine transportation has expanded rapidly, with shorter transit times between ports. The risk of unintended introductions has increased with faster travel. Boudouresque (1994) has indicated that most exotic species in southern Europe have become established since the 1950s, with the principal sites of establishment being in lagoons (23 to 24 species) and ports (13 to 14 species).

Some species considered as exotics may be previously unknown natives or have arrived as part of a natural range expansion. Others have been deliberately introduced for aquaculture and in certain cases have been the vectors of unwanted species. A third group is those species introduced by shipping. The increasing use of water as ships' ballast is thought to be the most important vector of exotic organisms in the future.

Cork Harbour, a large natural sheltered bay on the south coast of Ireland, has some features not unlike a coastal lagoon and is also an important port. This area contains a significant number of exotic species. This paper examines the historical information on aquaculture, shipping movements, estimates of ballast water and the literature on the exotic species to ascribe the likely means by which these exotics arrived. This paper explains why ballast water poses the most significant means for the introduction of exotic species in the future.

Materials and methods

Cork Harbour is a large natural sheltered bay and the principal port on the south Irish coast (Figure 1). It has a cool temperate climate with sea temperatures ranging from 5–19°C and with estuarine to coastal marine conditions. The Harbour is regularly dredged to provide ship access to Cork city. There are deepwater berths at Cobh and at industrial centres. Oyster culture has also been developed (Figure 1).

The occurrence of exotic species in the harbour was sourced from the literature and unpublished observations. The accumulated net registered tonnage (NRT – a volumetric measurement calculated from the capacity in cubic feet of spaces within the hull, and of enclosed spaces above the deck available for cargo stores and fuel, divided by 100 (Anonymous, 1991)) and number of vessels were obtained for the period 1928–1993. The NRT does not provide a direct measurement and does not relate to weight of exports because it is a capacity measurement. Dead or gross weight tonnage (DWT) was not recorded because this was not available for the period 1928–1993. A regression of changes in NRT and exports since 1955 gave a high correlation of 0.916 (using MINITAB), demonstrating that a reasonable estimate of exports over that period could be calculated based on NRT values.

By using back extrapolations of numbers of vessels both import/exporting or just importing, the proportion of vessels exporting could be calculated, based on the records of shipping activities for 1993. It has been assumed that the relative proportions in 1993 were the same to 1955 and that all exporting vessels were of the same size. The tonnage exported was calculated as follows:

Total pure exports = (Total exports/Total number of exporting vessels) (x) Total number of pure exporting vessels.

Pure exports refer to those products that were exported from Cork Harbour in ships that arrived carrying ballast water. To calculate annual ballast water discharge volume a conversion factor from NRT to dead weight tonnage of approximately 2.0 was obtained from a random selection of ships from the maritime directory. This figure was then was multiplied by 0.35 to obtain the total ballast capacity (mean value of 0.32 to 0.38 for various vessels including tankers) and then by 0.24 to calculate ballast water on arrival (a mean value based on volumes carried in tankers 0.13, and container vessels 0.35) (Carlton *et al.*, 1995). Estimates of ballast discharges may be compromised because vessel ballast volumes depend on ship design, weather conditions and planned cruise track. The origin of ships arriving with ballast to Cork Harbour was examined for 1993. In this exercise the estimates of ballast water discharges from all sources have been combined.

Results

Exotic species were classified as either deliberate or unintended introductions (Table 1a and 1b) Some species are known to have been present over a short time and may not have become established. The distribution of those species considered to have become established are recorded for three regions of Cork Harbour (*Figure* 2).

Intended introductions

With the exception of the rice grass, *Spartina x townsendii*, introduced from Poole in Britain to stabilise mud flats near Lough Mahon in 1925 (Cummins, 1930), all intentional introductions were for aquaculture.

Oyster cultivation began following a decline of production on public beds, from 1860 in Lough Mahon (47 hectares), the Middleton River (10 hectares), Owenboy Estuary (31 hectares) and elsewhere in the Harbour from 1873 (48 hectares) (Wilkins, 1989). Beds were restocked using half grown flat oysters, *Ostrea edulis* regularly imported from France. From 1882 half-grown American oysters, *Crassostrea virginica*, were introduced, approximately 600,000 were laid on the Middleton bed in 1895. Half-grown Portuguese oysters, *Crassostrea angulata*, were laid from 1892 to 1898, 5,000 at Lough Mahon, and later >8,000 within the Owenboy Estuary. The extent of the oyster fisheries at the turn of the century was recorded by Brown (1900) who refers to young native oysters, *O. edulis*, from the natural settlement area of Arcachon being re-laid at the Middleton and Owenboy layings (*Figure* 1). With up to 300,000 transferred in any one year from elsewhere in France and from the Netherlands, American oysters continued to be imported until the 1920s but overall numbers imported are unknown. Oyster culture in the harbour then declined and ceased although licensed areas were in existence.

Oyster cultivation did not again take place until 1969 when *O. edulis* settled as spat in ponds beside the North Channel, were laid on the seabed, or ongrown in bags on trestles. The broodstock was sourced from public oyster fisheries in Ireland, principally Tralee Bay. Pacific oysters, *Crassostrea gigas*, previously quarantined in Conwy, were cultured on trestles in the same area from 1976, and their production rapidly expanded and new oyster growing areas evolved. Because this species rarely spawns in Irish waters, spat for culture are produced in hatcheries and most are imported from Britain and Guernsey. In 1993, as a result of EU legislation to promote free trade (Anonymous, 1991), half grown Pacific oysters were transferred to Ireland from France.

Other exotic molluscs were used in aquaculture trials; the hard shell clam, *Mercenaria mercenaria*, not currently in culture, and the Pacific clam, *Tapes philippinarum*, are cultivated in small quantities. Both were quarantined in Conwy. The soft shell clam, *Mya arenaria*, has been established in some European ports for some centuries, and is established in Cork Harbour.

Table 1a Species introduced intentionally to Cork Harbour.

SPECIES	ABUNDACE	VECTOR	COMMENT
Spartina x townsendii	Abundant	Ship transfer	Arrived in Cork Harbour 1925.
Mya arenaria *	Generally distributed	Unknown	Widely distributed about Ireland.
Crassostrea virginica	Abundant in years 1880–1920	Aquaculture	Never became established. Relaid and sold.
Crassostrea angulata	1890s	Aquaculture	Never became established. Relaid and sold.
Crassostrea gigas	Abundant	Aquaculture, introduced in 1970s	Part of current large scale aquaculture.
Mercenaria mercenaria	Rare or no longer present	Aquaculture trials in 1960s and 1980s	Not established.
Tapes phillippinarum	Frequent	Aquaculture, introduced in 1980s	Small scale aquaculture activities.

* *M arenaria* may have been introduced as ships' fouling.

Table 1b Species unintentionally introduced to Cork Harbour. Most likely vectors of introduction to Cork Harbour are shown in bold print.

	SPECIES	ABUNCANCE	**VECTOR**	COMMENT
1	*Bonamia ostreae*	Frequent Established	**Oyster transfers. Ship transfer**	Identified 1987, oyster disease organism.
2	*Gyrodinium aureolum*	Common Established	**Range extention. Unknown**	Forms algal blooms.
3	*Cryptonemia hibernica*	Abundant Established	**Ships fouling. Ships ballast**	New species, now spread to Oysterhaven, first record 1971.
4	*Bonnemaisonia hamifera*	Present Established	**Ships fouling. Unknown**	Cullinane, 1973 generally distributed.
5	*Colpomenia peregrima*	Frequent Established	**Drift Oyster transfer. Ships fouling**	Cullinane, 1973 generally distributed.
6	*Cladophora sericea*	May be common	**Ships fouling. Ballast water. Oyster transfers**	Cullinane, 1973.
7	*Codium fragile subsp. tomentosoides*	Occasional Established	Unknown	Parkes, 1975 generally distributed.
8	*Ficopomatus enigmaticus*	Occasional Established	**Ships fouling**	In Ireland only known in Cork Harbour. First record 1972.
9	*Elminius modestus*	Abundant Established	**Ships fouling**	Causes extensive fouling in brackish areas, first record 1972.
10	*Mytilicola intestinalis*	Frequent Established	**Ships fouling in mussels**	Gut parasite in mussels, recorded since 1947.
11	*Mytilicola orientalis*	Rare	**Oyster transfers**	Briefly introduced on oysters in 1993.
12	*Herrmannella duggani*	Occasional	**Native species? Oyster transfers**	New species, causes gill damage to oysters.
13	*Myicola ostreae*	Rare	**Oyster transfers**	Briefly introduced on oysters in 1993.
14	*Corophium sextonae*	May be common	**Ships fouling**	First recorded by Costello.
15	*Styela clava*	Frequent Established	**Ships fouling**	First recorded in 1972.

It is not clear whether this species was intended as food when introduced to Europe.

Unintended introductions

Introduced species associated with aquaculture

Uncontrolled movements of molluscs may result in the establishment of undesirable species, for example the sporozoan *Bonamia ostreae*, which infects the blood of *O. edulis*, may have been introduced with contaminated oysters in 1986 (McArdle *et al.*, 1991). In 1980, an eroded gill condition was found in up to 6% of *O. edulis* in the North Channel, similar to that produced by an elusive poecilostome copepod, *Herrmannella duggani* (Holmes and Minchin, 1991) known from Ireland and Brittany. Its status as an exotic species is not certain but may have become established in Ireland following earlier oyster transfers from continental Europe.

A consignment of half-grown Pacific oysters from France in 1993 were laid in the harbour and were removed some weeks later. They contained two copepods, *Myicola ostreae*, attached to gills, and *Mytilicola orientalis*, a gut parasite of molluscs. These species are not known to have become established in Cork Harbour.

Introduced species associated with shipping

It is not clear whether many of the exotic marine algae, such as *Bonnemaisonia hamifera* found at Camden (Cullinane, 1973) were introduced by shipping but they may have been transported as attached plants on ships' hulls. The first Irish specimens of *B. hamifera* were washed ashore in Achill Sound in 1911 (in the National Herbarium, Dublin, DBN) and so the species is likely to have been present before this date elsewhere, at a time when little or no ballast water was used by ships for stability. Similarly *Codium fragile tomentosoides*, found at Corkbeg by Cullinane (1973), has been known from Ireland since 1833 (DBN). A further species, *Colpomenia peregrina*, had become established in France by 1905 and was first found in Lough Hyne, Ireland in 1939. This species may have reached Ireland as drift because it has a light thallus which when filled with air or gasses can float proud of the water and so become easily dispersed by wind. It may also have been transported in well boats involved with exports of lobsters from the Irish south coast. In 1971 a foliose red alga, *Cryptonemia hibernica*, was described for the first time from Cork Harbour (Guiry *et al.*, 1973); it has since been recorded from nearby Oysterhaven (Cullinane and lan, 1980). It is not known elsewhere in Europe, but its abundance and highly localised distribution and affinities with Pacific species strongly suggest that it is an introduction.

The New Zealand barnacle, *Elminius modestus*, and the Korean sea-squirt, *Styela clava*, were probably introduced as fouling. *E. modestus* is the most frequent barnacle in Lough Mahon and North Channel and is common at the Harbour entrance. The first Irish record was from Lough Hyne (Beard, 1957); it was probably established in Cork Harbour before then, and was first seen in the Owenboy Estuary in 1968. Crisp (1958) records its expansion on the south coast of Britain from 1946 (*Figure* 4), where it is thought to have been established since 1939.

Styela clava became established on the south coast of Britain and is thought to have been introduced by returning warships following the Korean War. It was already established in Cork Harbour in 1972 (Kilty and Guiry, 1972). In 1987 it was widely distributed within the upper Harbour and was also found to be common on the hull of a moored vessel (Minchin and Duggan, 1988).

Mytilicola intestinalis, a gut parasite of mussels, was first found in Ireland in 1947 from Fountainstown and Church Bay in Cork Harbour (Grainger, 1951); it is now well established. It is likely that it was introduced from larval releases from its host *Mytilus edulis*, a known fouling organism of ships. The first record outside of the Mediterranean was from the North Sea (Caspers, 1939). More recently its status as an exotic species has been questioned, but it sporadic occurrence, principally within Irish bays with ports and earlier absences, provide evidence that it is an introduction close to its northern range (Grainger, pers. comm.).

The serpulid *Ficopomatus enigmaticus*, which may form extensive intertwining masses in estuarine areas, is considered to have been introduced to Europe from the Indo-Pacific (Fauchald, 1977) as ships' fouling during the first world War (Zibrowius, 1994). It was first recorded from Cork Harbour by Kilty and Guiry (1973) near Cork city, further specimens were seen in Lough Mahon in 1986 and 1993. This species may have been introduced directly from Swansea where there is a local population (Kilty and Guiry, 1973) by the regular ferry service between Cork and Swansea.

The species *Gyrodinium aureolum* described from the western North Atlantic by Hulbert was first recorded in the eastern Atlantic by Braarud and Heimdal (1966) on the SW coast of Norway and may have been introduced to Europe as ballast water. Since then it has been observed at a number of other localities and probably arrived by spreading at coastal fronts. There is, however, some taxonomic confusion with a form from the Pacific. Its initial appearance in Europe may have been due to ballast water. It was first noticed on the south Irish coast in 1976, when it formed blooms. Although it has appeared in water samples since 1981 in Cork Harbour, it is not known to have bloomed there.

Alexandrium tamarense forms blooms in coastal areas and may cause paralytic shellfish poisoning. A bloom, of low toxicity, of this species was first recorded in Cork Harbour in the spring of 1985 in the North Channel, Owenboy Estuary and near Spike Island. No cysts of this genus were found in a 1993 study. It is not clear whether this species is native to Cork Harbour or was transferred or introduced in ballast water at some former time.

Quantifying the relative risk from shipping

Estimated annual discharges of ballast water into Cork Harbour rose from 1955 to 1971. During the 1970s much of the ballast water entering the harbour would have been as a result of the extensive dredging as a result of harbour developments. These vessels will have taken on ballast on return to the harbour following disposal of spoil at the nearby dumping ground. The ballast discharges again rose consistently from 1982 (*Figure* 4). Increases of ballast discharge relate to periods in the development of and export of specialised products such as oil, steel, chemicals and livestock (Table 2). In 1993 the majority of vessels carrying ballast were associated with oil products and consequently the opening of the Whitegate oil terminal in 1959 is a significant factor in the volumes of ballast discharged.

Patterns of shipping entering the port of Cork show an obvious decline in the gross tonnage of liners to 1972 (*Figure* 3). Liners, which are unlikely to hold significant quantities of ballast, when entering Cork Harbour were principally in transit to and from North America. When disembarkation took place liners either anchored south of the Harbour entrance or when conditions were suitable smaller liners anchored off Spike Island or berthed at Cobh for short periods of time. The large volume of liners until the 1960s may have been significant for inoculations of fouling organisms to have taken place. Although the shorter time spent by liners may have meant that the risks were reduced. Nevertheless, changes in temperature and salinity on entering the harbour may have promoted spawnings that could have led to recruitment. The greatest changes in temperature and salinity would have been at the berths in Cork city where in the earlier years, and before the development of the Tivoli and Ringaskiddy dock sites were developed, most of the non passenger shipping traffic would have gone.

The net rate tonnage (NRT) of merchant vessels trading with the U.K. has been 500,000 tonnes or less from 1928, declining during the Second World War. Following the war tonnage increased to 2,500,000 tonnes in 1974 and then generally declined. There has been a continual trend of increased NRT with continental Europe and elsewhere to 4,000,000+ tonnes in 1992. With the increase in NRT, from a wider range of ports, the potential of an exotic inoculation has increased. Pre and post war port facilities were not as efficient as in present times and the turnaround time of trading vessels, then principally centred at Cork city, was some days. The efficient biocidal antifoulant TBT paints, widely available to shipping since 1972, may have significantly reduced the potential for dispersal of fouling organisms, by reduction of fouling biomass. Although the International Maritime Organization have recommended further controls on its general use by shipping, whatever replaces it will need to be as effective.

In Ireland there are presently no general controls on segregated ballast water or procedures for managing discharges with the exception of controls on oily ballast. Ballast water was first regularly used in the 1880s (Carlton and Geller, 1993). This was a more economic method of ballasting as it was rapidly done and required less labour than stone ballast. The sites where deballasting takes place and the volume discharged depends on ship design, sea state and the nature of the cargo. Vessels normally discharge at the first available opportunity so as to reduce time spent in port. Oil tankers, in particular, can discharge ballast near their destination while under way and most usually before berthing, because oil products are rapidly loaded, providing insufficient time to enable deballasting, while berthed in port. On older ships ballast water would be taken on in empty oil tanks. However, there are facilities at Whitegate to pump dirty ballast water to tanks ashore, where oil can be removed before the water is discharged. The greater proportion of trading vessels in Cork Harbour are associated with oil products and since the terminal is near the Harbour entrance some deballasting may commence while at sea and so may reduce the efficacy of a potential inoculum.

Since the 1970s, the usage of TBT antifouling paints, has had a major impact on transfers of fouling organisms on ships. This biocide may modify the viability of inocula from ships' ballast water. Discharges of fine sediment from ballast tanks may become deposited along with fine sediments known to act as a sink for TBT in port areas. Polychaetes and other soft sediment fauna and possibly some algal cysts, settling in these areas, may consequently become constrained from establishment. It may also influence previously established populations.

The last port of call (LPC, being the port at which the ballast water was loaded), by region, of vessels visiting Cork Harbour in 1993 containing ballast water is shown in Table 3. The risk of introductions may be greater where there is much traffic throughout the year from the same LPC, particularly for those species that have seasonal cycles of abundance. Future introductions to Cork Harbour, will as a consequence, be likely to evolve following their establishment in northern European port areas, for example Glasgow, Liverpool, ports along the Bristol Channel and Rotterdam. It should be noted that the LPC does not always provide an accurate account of the ballast water transported, because deballasting and ballasting may take place while in transit or may have been contained from earlier visits. Sediments will accumulate from several ports in ballast tanks.

Table 2 Development of Port of Cork facilities.

Year	Port Area	Product	Development
1946	Haulbowline	Steel	Steel first made
1959	Whitegate	Oil, oil products	Oil refinery opens
1960	Haulbowline	Steel	Steel plant modernised
1969	Tivoli	Cars, passengers	Car ferry terminal opens
1970	Tivoli	Livestock	Livestock terminal opens
1970	Ringaskiddy	Containers	Container terminal opens
1972	Haulbowline	Steel	Modernisation of steel plant
1979	Marino Point	Ammonia, urea, fertilisers	First production of natural gas products
1981	Ringaskiddy	Timber, wood products	Berthing facilities open
1982	Ringaskiddy	Cars, passengers	Car ferry terminal opens
1986	Ringaskiddy	Containers	Deepwater berthing, terminal opens

Table 3 Origin, by area of ships carrying ballast water to Cork Harbour for 1993.

Commodity	**Origin of ships carrying ballast water**								
	Ireland (+N. Ireland)	UK	Northern Europe	Eastern Mediterranean	Western Mediterrean	Southern Mediterranean	Eastern Atlantic	Other	Total
Oil	181	92	12	0	0	0	0	0	285
Chemicals	95	53	3	0	1	0	0	0	152
Steel	62	22	9	0	0	0	0	0	93
Wood	41	35	2	0	0	0	0	0	78
Livestock	0	1	0	2	1	42	2	2	50
Foodstuffs	9	4	7	0	2	0	1	1	24
Total	**388**	**207**	**33**	**2**	**4**	**42**	**3**	**3**	**682**

In 1993, vessels arrived from elsewhere in Ireland and Britain, Continental Europe, North Africa, the Middle East and Australia. It is clear from Table 3 that vessels distributing oil products discharge the largest volume of ballast water into the Harbour. This is followed by ships exporting chemicals and steel. Almost all the vessels arriving in ballast, that load ammonia, are from Belfast. This route could result in the introduction of species to Cork Harbour previously introduced to Belfast Lough. Forty-two ships arrived carrying ballast water from North African ports (33 from Alexandria and 7 from Tripoli) to export livestock. This route may permit access of Mediterranean biota to Cork Harbour.

Discussion

High exploitation of oysters during the mid-nineteenth century resulted from the rapid and reliable steam transportation by rail and sea, and improved marketing. Depletion of oysters lead to several introductions to Ireland of half-grown *O. edulis*, often in large numbers, from France, Britain and the Netherlands into the 1950s in order to enhance stocks and maintain oyster production. There were also extensive and sustained introductions of American oysters to Ireland and Britain during 1880–1920, from Long Island Sound, which were laid in several areas including Cork Harbour. Importations from the same source resulted in the establishment of slipper limpets, *Crepidula fornicata* and the American tingles *Urosalpinx cinerea* to the South East coast of Britain (Utting and Spencer, 1992).

C. fornicata spread throughout much of northern continental Europe in the following hundred years, principally with oyster transfers. As its range expanded within Europe the risk of it becoming introduced with relayed oysters from the continent increased (Minchin *et al.*, 1995).

Several organisms have been moved unintentionally with introductions and transfers of oysters. These risks are greatest with movements of half-grown oysters. Parasites and diseases, intimately associated with molluscs, are likely to be transferred. Three (*B. ostreae, M. intestinalis* and *H. duggani*) are thought to be established in Cork Harbour.

It is likely that associated biota arrived in Cork Harbour with the large volumes of American oysters introduced and may include species that have now become established within natural communities, possibly including planktonic species. Asian coastal copepods have appeared in California, USA and in Chile, all in areas of Pacific oyster cultivation (Omori *et al.*, 1994). The implication is that Pacific oyster cultivation has resulted in the introduction of Asian coastal copepods to these areas. Such planktonic species may survive being transferred in the liquor within the mantle cavity, as is known for *Myicola ostreae*.

Prior to 1993, shellfish and fish importations to Ireland were refused from unrecognised or uncleared areas, because being an island there was some freedom from pests, parasites and diseases. However, under EU Directive 91/67/EEC designed to improve trade within Europe, free movement of Pacific oysters not subjected to listed diseases, in Europe was allowed. The subsequent importations resulted in additional species being introduced to Ireland (Minchin *et al.*, 1993), including a short appearance of *M. ostreae* and *M. orientalis* not previously known to have appeared in Cork Harbour.

It has been an aim of the International Council for the Exploration of the Sea to reduce risks associated with aquaculture introductions and with trade. A code of practice has recently been updated (Anonymous, 1995) to take account of such shellfish movements, and to address the planned development of new species for aquaculture within ICES member countries. This code covers not only the consequences of the introduced species but outlines measures for prevention of release of associated species, by recommended procedures in quarantine. Intended molluscan introductions themselves seldom result in negative effects and correct implementation of the ICES code considerably reduces the risk of unwanted effects.

Tenacious species and associated biota may become widely distributed on ships' hulls. The ascidian *S. clava*, a frequent fouling organism in the Northwest Pacific, has spread within northern Europe since 1952. It had become established in Cork Harbour by 1972 and can only have colonised Cork Harbour between these dates (*Figure* 3). Similarly, *E. modestus*, introduced during the second world war to Britain from New Zealand, rapidly expanded its range in Europe and had become established in Cork Harbour before 1968, when it was first recorded (*Figure* 3). The serpulid *F. enigmaticus* may have been introduced to Ireland between the end of the First World War to 1972. Although trade with Britain was relatively low prior to the Second World War, there may have been a better opportunity for its establishment due to the slower turnabout times in port. The introduction of *M. intestinalis* clearly occurred before 1947, and as the shipping traffic at this time was very low, due to the Second World War, it is likely that it became established prior to 1941.

The estimated volumes of ships' ballast discharges into Cork Harbour will merely reflect a general trend, which demonstrates that there is indeed an increase in annual ballast water discharges from a low level in 1955. The estimates have not included ballast discharges from vessels other than those with a net export from the harbour. Many other ships will have discharged ballast water and consequently the figures are under-represented. In addition, ballast discharges of tankers following the opening of the Whitegate Refinery are likely to provide lower figures than shown in Figure 4. If these were known, this is because, the ballast water on arrival will be less than the ballast capacity of the ship, and this can vary widely from 0.13 of the gross tonnage of tankers and is lower than the mean value of 0.24 used in all annual calculations. Since the expansion of the port facilities (Table 2) the container vessel traffic has increased and the ballast water on arrival of such vessels approximates to 0.35.

Cork Harbour has acquired marine biota from aquaculture, ships' fouling and possibly ships' ballast. The ICES Code of Practice first adopted in the 1970s has resulted in much tighter controls on species introductions associated with aquaculture, and so the risks of undesirable species' introductions are considerably reduced.. The use of TBT antifouling paints on ships' hulls since the 1970s is also likely to significantly reduce the risk of introductions via ships' fouling. Ballast water, however, has increased in importance since the 1960's and may act as the main source of future introductions. The question of the control of ballast is under discussion by ICES and the International Maritime Organization (IMO) with a view to finding adequate control methods, using either continuous exchange of ballast at sea, biocidal methods or contained ballast transfers.

In this exercise it has not been possible to quantify accurately the volumes of ballast discharged and the development of a register of source, volumes, times and dates of taking on ballast by compartment by port authorities would greatly aid management. Technological developments and data bases of nuisance species distributions and algal bloom events may aid in the treatment of ballast once effective and practical methods of controlling nuisance species in ballast have been developed.

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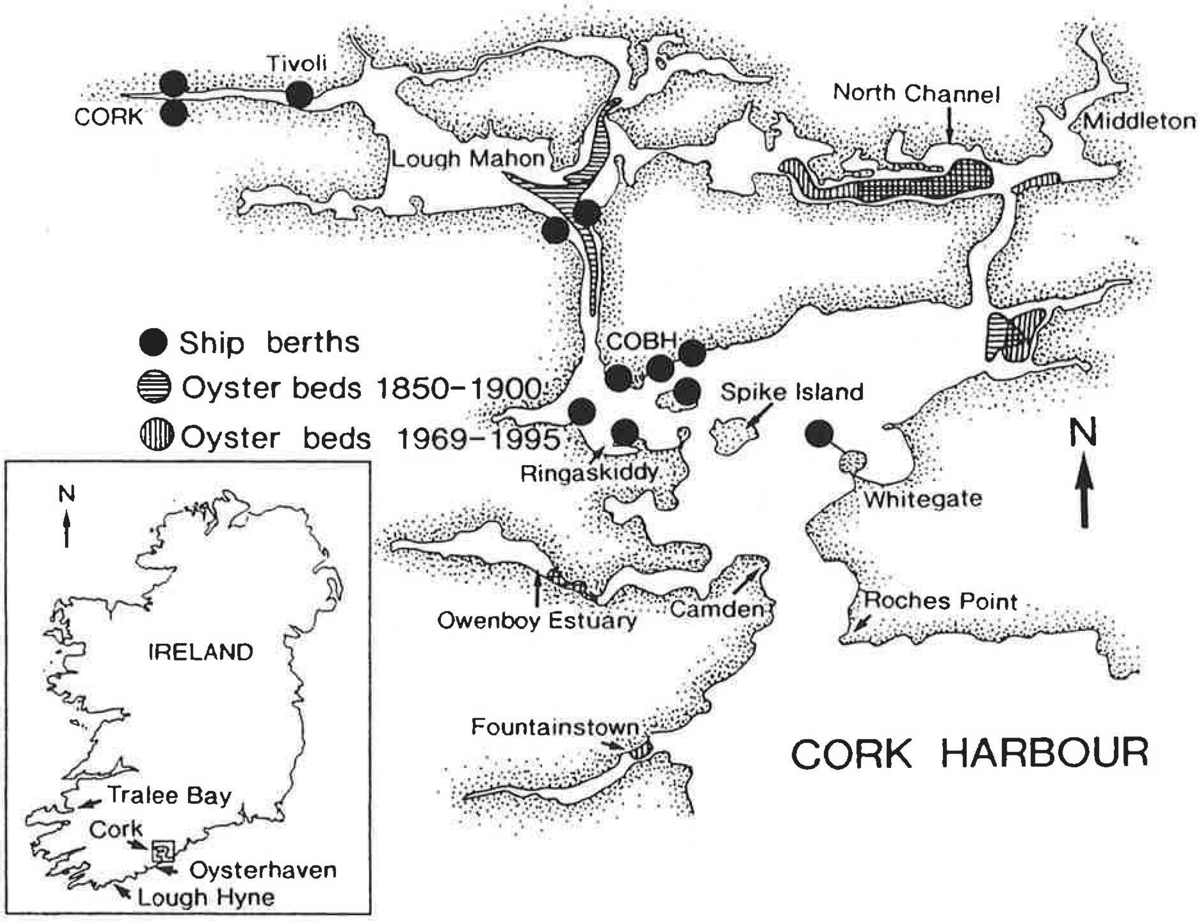

Figure 1 Distribution of shipping berthing areas and oyster growing areas.

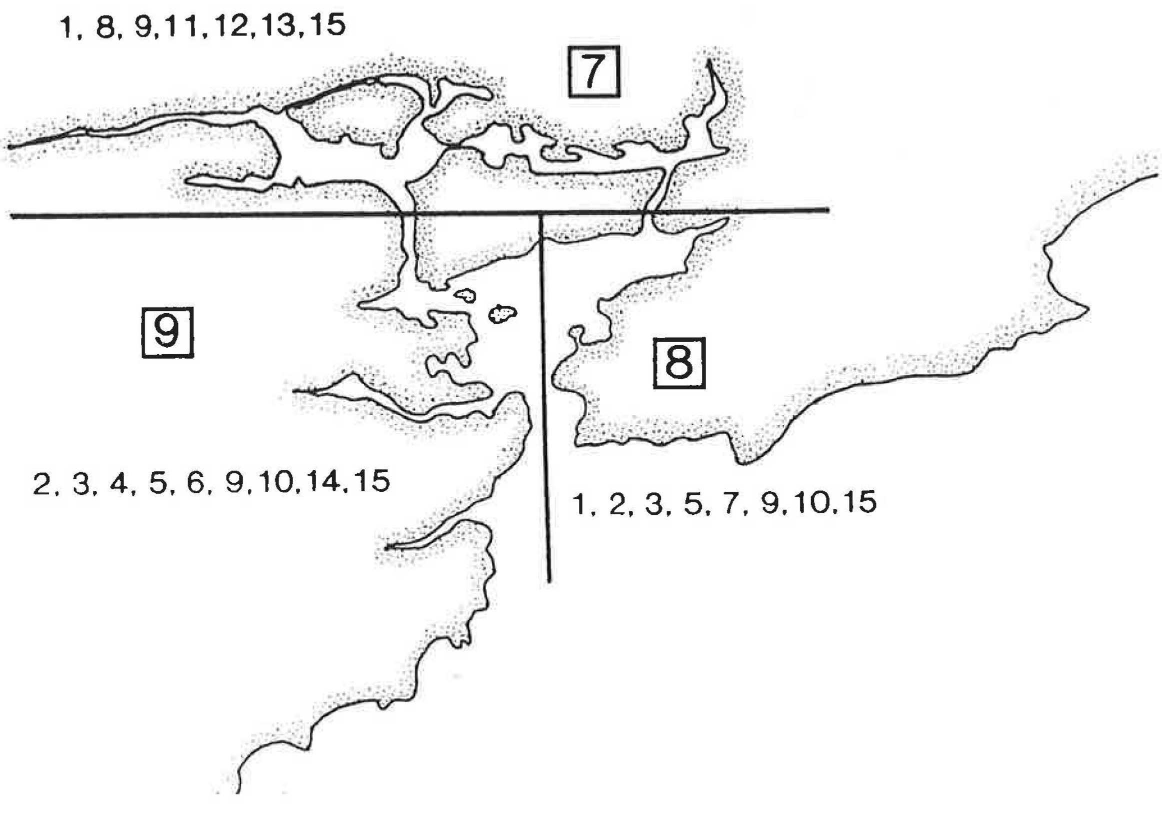

Figure 2 Distribution of unintended introductions of exotic species within three regions of Cork Harbour. The total numbers for each region are shown within squares. Numbers refer to those species coded in Table 1b.

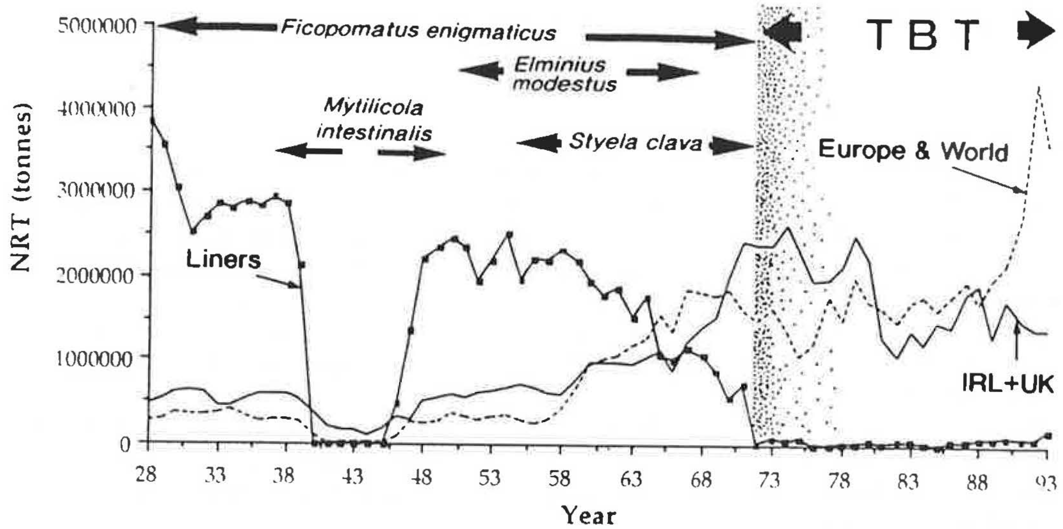

Figure 3 Trends in shipping volume 1928 to 1993 for Cork Harbour. The period over which four exotics became established are indicated with arrows. The use of TBT may have had an important effect on reducing the opportunity for exotic species to become established.

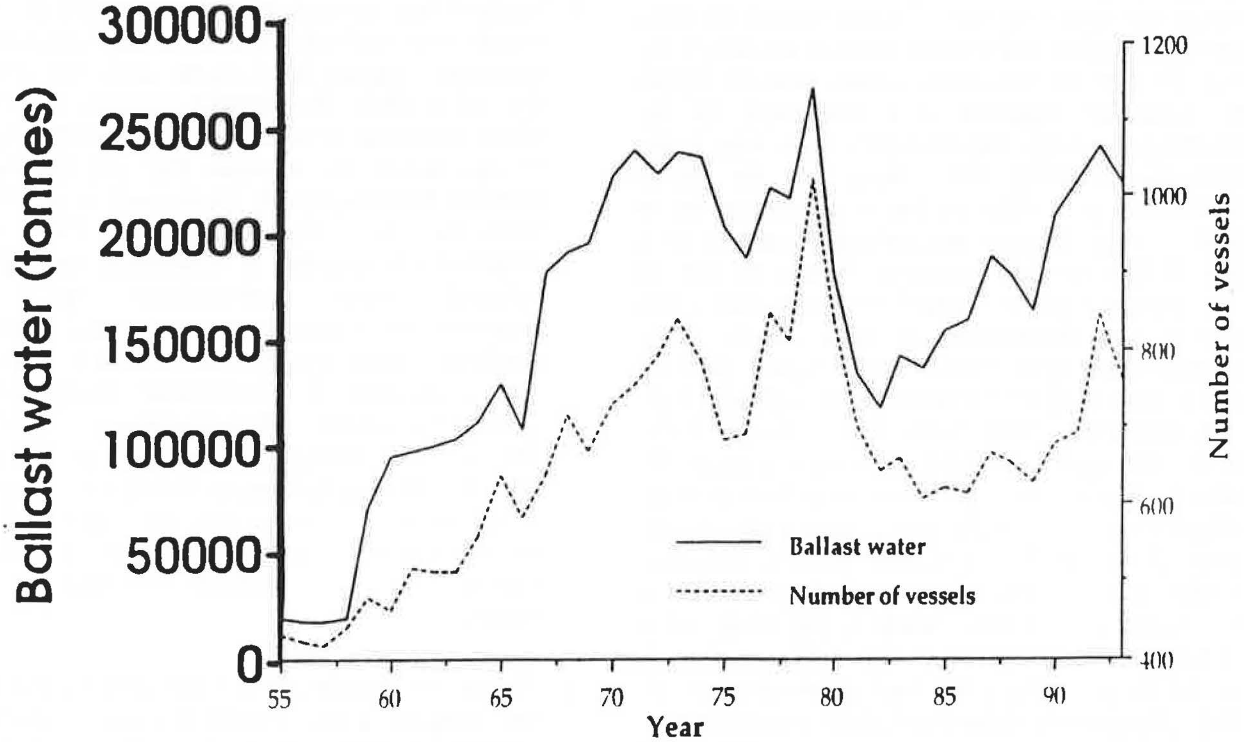

Figure 4 Number of vessels discharging ballast and estimated volume of ballast water discharged in Cork Harbour from 1995 to 1993.

Dinoflagellate resting cysts and ballast water discharges in Scottish Ports

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During the last 20 years, observations of the harmful impacts of non-native aquatic species being transported worldwide in ships' ballast waters and sediments appear to have increased. Until 1993, very little was known about ballast water operations in Scottish waters, but the increasing significance of problems worldwide, coupled with growing national awareness of these problems prompted the inception of a research programme to investigate non-indigenous or harmful planktonic organisms in ballast discharges to Scottish waters. The results from an earlier desk study were used to design an ongoing field programme which is primarily concerned with the ballast water transport of potentially harmful phytoplankton. Field and laboratory work is still underway, but preliminary findings are reported here. Sediment samples have been collected from the ballast tanks of oil and gas tankers discharging ballast water in Scottish ports. Dinoflagellate cysts were found in 90% of samples examined and were most numerous during spring and autumn months. Cysts provisionally identified as Alexandrium minutum, a PSP toxin producing species, were found in four samples. The possibility that these cysts may not be viable in Scottish waters due to unsuitable environmental conditions is discussed.

Introduction

Ships require ballast to adjust stability and trim when sailing without cargo or only partially laden. By 1850, vessels had begun to use seawater instead of solid materials as ballast and this was common practice by the mid-1870s. By the turn of the century, seawater ballast was tentatively suggested as a mechanism for the spreading of a large marine diatom from Asia to the North Sea (Ostenfeld, 1909). Since then, the role of ballast water as a vector for the accidental transfer of aquatic species between geographically separate areas received relatively little attention. Within the last 20 years, increasing research effort has been directed at this problem and observations of alien species being transported in ships' ballast water appear to have increased (Medcof, 1975; Carlton, 1985; Williams *et al.*, 1988; Hutchings, 1992; Kelly, 1992). Much of this research has been motivated by the variety of potentially harmful effects that may result from ballast water introductions. For example, native species may be out-competed and possibly replaced by the non-indigenous invader. Commercially important shellfish stocks may be affected by Paralytic Shellfish Poisoning (PSP) (Hallegraeff *et al.*, 1990) or fish resources may be affected by competition for food (Studenikina *et al.*, 1991). There may be detrimental effects for human users of the marine environment (Boalch and Harbour, 1977), or human health may be at risk (McCarthy and Khambaty, 1994).

Until recently, the majority of ballast water research had been carried out in the USA and Australia (Hallegraeff, 1992; Carlton and Geller, 1993), but increasing global awareness of the potential problems has prompted worldwide proliferation of research effort in this field. In Scotland, there are three main reasons for establishing a programme of ballast water research:

1. Scotland has economically valuable fisheries for finfish and shellfish and a rapidly developing aquaculture industry involving the cultivation of both fin and shellfish. The shellfish industry, like most others worldwide, is vulnerable to the harmful effects of algal toxins, for example, PSP and Diarrhetic Shellfish Poisoning (DSP) (Hallegraeff *et al.*, 1988; Subba Rao *et al.*, 1994; Chang *et al.*, 1995). The dinoflagellates regarded as responsible for PSP in temperate waters (*Alexandrium* spp. and *Gymnodinium catenatum*) can, under certain conditions, form resting cysts allowing them to survive periods of unfavourable environmental conditions (Anderson, 1984; Anderson *et al.*, 1988). This survival strategy makes these species well suited to ballast tank transport. Whilst PSP – thought to be caused by *Alexandrium* spp – and DSP are known in Scottish waters, other forms of shellfish toxicity which cause problems elsewhere are not known.

2. The oil and gas industry is responsible for much of the shipping tragic around Scotland's coastline, involving tankers arriving "in ballast" which is discharged prior to loading cargo for export. The frequency of these operations combined with the size of the vessels involved results in considerable quantities of ballast water being discharged (Macdonald, 1994). Additionally, coastal quarrying for aggregates, and further applications for licenses to develop such quarries may, if permission is

granted, result in frequent movements of bulk carriers to remote areas of coastline previously unaffected by large scale shipping operations. Ballast water management and monitoring plans are essential to any new coastal shipping developments, and research is required to develop those management strategies.

3. The UK wishes to meet the International Maritime Organization's (IMO) request for member states to investigate ballast water introductions (MEPC, 1991); additionally, the UK Government is responding to recommendations following the Braer tanker accident to encourage ballast water studies (Donaldson, 1994).

This paper discusses a field and laboratory research programme that is currently underway to study planktonic organisms transported in both ballast water and sediments. Some preliminary results concerning the transport of dinoflagellate resting cysts in ballast water and sediments are reported.

Methods

Ballast water and sediment sampling

Field sampling based on results from a previous desk study (Macdonald, 1994) began during 1994 and the programme is still underway. Water and sediment samples are collected from ships discharging ballast water in Scottish ports previously identified as important areas for ballast water discharges (Figure 1). Net and integrated water samples are taken to examine zooplankton and motile phytoplankton present in ballast water these data will be presented elsewhere. The methods described here concern the collection of sediment from ballast tanks to examine the presence or absence of dinoflagellate resting cysts. In all cases the samples were collected from tanks of segregated ballast water.

Sample collection

Sediment samples were collected from the deck of oil and gas tankers by deploying a weighted hose to the tank floor through a deck hatch. The hose was connected to a hand-operated pump and water and sediment from the tank floor were pumped to deck level, where approximately 20 litres was collected in polycarbonate carboys. The contents of the carboys were kept cool and dark and transported back to the laboratory where they were stored at 4°C in darkness. The sediment was allowed to settle for 48-72 hours before the overlying water was siphoned off. The remaining sediment/water mixture was concentrated by centrifuging at 2,000 rpm for 16 minutes followed by carefully removing the supernatant by syringe leaving sediment and a small volume of overlying water. Final volumes of sediment obtained ranged from 10 cm^{-3} when particulate material was very sparse, to approximately 800 cm^{-3}. The resultant sediment was split into two aliquots, one half was frozen at -20°C for heavy metal analysis, the remaining half stored in the dark at 4°C prior to microscopic examination for dinoflagellate cysts.

Sediment processing and microscopy

Sediment samples, or aliquots if material was plentiful, were sonicated for two minutes in a Kerry Instruments ultrasonic bath to break down aggregated material and remove detrital particles from cyst walls. The sonicated sediment was washed with 0.2µm filtered seawater and fractionated through 70µm and 20µm sieves. The material retained on the 20µm sieve was washed with approximately 200 ml of filtered sea water, backwashed into a beaker and made up to a known volume. Aliquots of the final suspension were examined using a Zeiss Axiovert-10 inverted microscope using brightfield, phase contrast and differential interference contrast illumination. All cysts - both full and empty/cysts or cyst remains - observed were identified and counted.

Results

Ballast water sampling programme

Ballast water sampling aboard vessels docking in Scottish ports began in the summer of 1994. To the end of July 1995, samples have been collected from 32 ships visiting four ports (Figure 2). Ballast water origins include ports in northern and southern Europe, USA and the UK (Table 1).

Dinoflagellate cysts in ballast tank sediments

Ten of the 24 sediment samples collected to date have been analysed for the presence of dinoflagellate cysts. Nine of these samples contained both full cysts and empty cysts or remains of cysts. The abundance of full cysts ranged from 7 to 1450 cysts cm^{-3}. The highest concentration of full cysts was found in a sample with ballast originating from Hamburg, and 55% of these cysts were round brown peridinoid dinoflagellate cysts.

Table 1 Vessels sampled in current ballast water programme, May 1994-July 1995.

Sampling number	Date sampled	Port of sampling	Vessel DWT	Location BW loaded	Region
number		sampled	sampling	DWT	
BW/001	05 May 94	Braefoot Bay	22600	La Pallice, France	S Europe
BW/002	30 Jun 94	Hound Point	285000	Le Havre/R'dam	N Europe
BW/003	15 Aug 94	Sullom Voe	135000	Le Havre	N Europe
BW/004	17 Aug 94	Sullom Voe	283861	Immingham	UK
BW/005	18 Aug 94	Sullom Voe	82279	Gdansk	N Europe
BW/006	18 Aug 94	Sullom Voe	90000	Shellhaven	UK
BW/007	18 Aug 94	Sullom Voe	90000	Shellhaven	UK
BW/008	20 Sep 94	Hound Point	131400	St James Mississippi	
BW/009	20 Sep 94	Hound Point	131400	St James Mississippi	
BW/010	20 Sep 94	Hound Point		Hamburg	N Europe
BW/011	21 Sep 94	Hound Point	82279	Bilbao	S Europe
BW/012	12 Oct 94	Hound Point	88821	Pembroke	UK
BW/013	27 Oct 94	Hound Point	88821	Milford Haven	UK
BW/014	25 Jan 95	Hound Point	97002	Europort	N Europe
BW/015	08 Feb 95	Hound Point	278220	Fos, Marseille	S Europe
BW/016	19 Feb 95	Hound Point	261913	Fos, Marseille	S Europe
BW/017	08 Mar 95	Hound Point	135271	Malaga	S Europe
BW/018	28 Mar 95	Hound Point	152109	Wilhemshaven	N Europe
BW/019	21 Apr 95	Hound Point	306000	Fawley	UK
BW/020	05 May 95	Hound Point	306430	Rotterdam	N Europe
BW/021	11 May 95	Hound Point	83107	Rotterdam	N Europe
BW/022	24 May 95	Hound Point	147500	Malta	S Europe
BW/023	04 Jun 95	Sullom Voe	387858	Rotterdam	N Europe
BW/024	05 Jun 95	Sullom Voe	88836	Hamburg	N Europe
BW/025	07 Jun 95	Sullom Voe	97693	Tranmere	UK
BW/026	08 Jun 95	Sullom Voe	124502	Rotterdam	N Europe
BW/027	15 Jun 95	Hound Point	97602	Livorno	S Europe
BW/028	20 Jun 95	Montrose	960	Seaham	UK
BW/029	22 Jun 95	Braefoot Bay	9384	Antwerp	N Europe
BW/030	30 Jun 95	Braefoot Bay	28840	Bay of Biscay	S Europe
BW/031	12 Jul 95	Hound Point	88836	Rotterdam	N Europe
BW/032	12 Jul 95	Hound Point	86943	Immingham	UK and Ireland

Table 2 Summary of dinoflagellate cysts found in ballast sediment samples.

Tank number	BW origin	Date sampled	Full cysts per cm^{-3}	Empty cysts per cm^{-3}
BW/005	Gdansk	18 Aug	20	120
BW/010	Hamburg	9 Sept	1450	500
BW/012	Pembroke	12 Oct	700	1200
BW/013	Pembroke	27 Oct	550	775
BW/014	Europort	25 Jan	250	1400
BW/015	Marseille	8 Feb	0	0
BW/018	Wilhemshaven	23 Mar	750	813
BW/024	Hamburg	6 Jun	115	198
BW/027	Livorno	15 Jun	45	5
BW/030	Bay of Biscay	30 Jun	7	13

Table 3 Occurrences of dinoflagellate cyst species in ballast sediment samples.

Species	Samples with full cysts	Samples with empty cysts
Alexandrium cf. *minutum*		
cf. *Alexandrium margalefi*	1	0
Cyst remains	0	9
Diplopelta parva	1	9
Gymnodinium cf. *catenatum*	0	1
cf. *Gymnodinium* spp.	2	0
Lingulodinium machaerophorum	2	2
Lingulodinium spp.	0	2
Multispinula sp.	0	1
Operculodinium centrocarpum	3	2
Operculodinium sp.	0	1
Pentapharsodinium dalei	1	0
Pheopolykrikos hartmannii	0	1
Polykrikos schwartzii	1	3
Protoperidinium avellana	0	1
Protoperidinium compressum	0	1
Protoperidinium conicum	1	7
Protoperidinium leonis	0	2
Protoperidinium minutum	1	0
Protoperidinium oblongum	1	1
Protoperidinium pentagonum	0	1
Round brown (Peridinales)	6	0
Scrippsiella crystallina	0	1
Scrippsiella larbrymosa	1	0
Scrippsiella precaria	1	0
Scrippsiella rotunda	2	0
Scrippsiella trifida	1	0
Scrippsiella trochoidea	5	1
Scrippsiella sp.	1	0
Spiniferities spp.	1	4
Spiniferities bentori	1	0
Spiniferities bulloides	0	1
Spiniferities mirabilis	0	1
Unidentified cyst	5	0

Table 4 Other taxa found in ballast tank sediment samples.

Diatoms	Motile dinoflagellates
Actinoptychus senarius	*Gonyaulax* sp.
Asterionella glacialis	
Asterionella kariana	
Chaetoceros spp.	**Other taxa**
Coscinodiscus spp.	a) Fresh water algae
Cyclotella spp.	*Pediastrum boryanum*
Ditylum brightwelli	*Scenedesmus quadricauda*
Grammatophora serpentina	
Leptocylindrus minimus	b) Protozoa
Melosira granulata	Ciliata
Navicula spp.	Foraminifera
Nitzschia longissima	Tintinnida
Odontella alternans	
Odontella aurita	c) Others
Odontella rhombus	Nematoda
Odontella sinensis	
Paralia sulcata	
Pleurosigma/Gyrosigma spp.	
Raphoneis amphiceros	
Rhizosolenia alata	
Rhizosolenia delicatula	
Skeletonema costatum	
Stephanodiscus spp.	
Thalassionema nitzschiodes	
Thalassiosira spp.	

Five other samples had >100 full cysts cm^{-3} (Table 2). This compares with Hallegraeff and Bolch's (1992) data where they selected nine samples with high cyst abundance, where numbers ranged from 40 to 22,500 cysts cm^{-3}. Thirty-one different cyst species were identified, most commonly represented being *Scrippsiella* and *Protoperidinium* (Table 3). In addition to dinoflagellate cysts, a motile *Gonyaulax* sp. was observed in one sample. Highest numbers of full cysts were found in samples taken during March and September/October (Figure 3). Square root transformations were carried out on full cyst numbers and a two sample t-test showed a significant difference ($P=0.044$, $n=10$) between numbers of full cysts in sediment collected from September to March than in samples collected from April to August.

Cysts resembling descriptions of *Alexandrium* spp. (Fukuyo *et al.*, 1990; Hallegraeff *et al.*, 1991) were found in five samples. These cysts were typically smooth- walled and covered with a layer of mucilage. In three samples, these cysts were hemispherical and most closely resembled *Alexandrium minutum.*, In another sample where they resembled *A. minutum* in most respects, the cysts were rather smaller (15 µm diameter) than the size range of 20-25 µm reported in the literature for this species (Erard Le-Denn *et al.*, 1993). The *Alexandrium* type cysts in the remaining sample were approximately 25 µm diameter, but were spherical and had yellow accumulation bodies as opposed to the red ones common to some species of *Alexandrium*. These cysts resembled descriptions of *Alexandrium margalefi* (Hallegraeff *et al.*, 1991), but were slightly smaller than the size range reported (28-34 µm). The highest concentration of *Alexandrium* cysts was 50 cysts cm^{-3}.

In one sample with ballast water originating from Hamburg, an empty cyst resembling descriptions of *Gymnodinium catenatum* (Anderson *et al.*, 1988) was found. The distinctive microreticulate cyst wall was observed and the archeopyle was similar to that described by other workers (Blackburn *et al.*, 1989; Carrada *et al.*, 1991). At 26 µm diameter, this specimen was much smaller than the average 50 µm diameter reported in the literature by workers in Japan (Fukuyo *et al.*, 1990), but only slightly smaller than the 30-38 µm found for specimens from German sediments (Nehring, 1995).

Other taxa in ballast tank sediments

All sediment samples examined were found to contain other taxa (Table 4), with diatoms being found in every sample. Entire diatom cells complete with contents and diatom frustules or remains were found and at least 25 species were represented. Both centric and pennate diatoms were found, but diatom resting spores were rare. Some fresh water algal species were observed, particularly the centric diatom *Melosira granulate* and the colonial alga *Pediastrum boryanum*. Living ciliates were observed in some samples. In three samples, live nematode worms were seen moving in the sediment material.

Discussion

The present study has shown that a wide diversity of planktonic organisms can be transported in the segregated ballast tank sediments of oil and gas tankers. Similar species assemblages have been recorded in sediments from bulk carriers' ballast tanks (Hallegraeff and Bolch, 1992). The range of algal species found to date is consistent with the results of other researchers – Hallegraeff and Bolch (1992) found 53 dinoflagellate cyst species and many diatom species from ballast tank sediment samples. Many of the cysts observed in the current study have been shown to represent the resting stages of temperate dinoflagellates species (Dale, 1983; Lewis *et al.*, 1984, Lewis, 1988; Lewis, 1991) many of which are already found in UK sediments (Lewis *et al.*, 1984; Higman *et al.*, 1996, Macdonald, unpublished). The presence of full dinoflagellate cysts in the samples indicates that cysts are present in ships discharging ballast water at Scottish ports, and this may have implications for the spread of non-indigenous or potentially toxic species presently not known in this country. It is difficult to ascertain at this stage whether the cysts were entrained into ballast tanks from the water column or by resuspension of sediment during ballasting. A significant difference was found in the number of full cysts in ballast sediments sampled between September and March than from April to August, although it should be noted that the sample size was small. Cysts were found to be most numerous during spring and autumn months, when in the Northern Hemisphere, cyst numbers in the environment are expected to be maximal (Higman *et al.*, 1996).

Of potential concern were the observations of cysts which preliminary studies identified as resting stages of potential PSP-producing motile dinoflagellates. Further taxonomic investigations should be attempted to confirm the thecal affinity of these cysts, identified as closely resembling *Alexandrium minutum* and possibly *Alexandrium margalefi*. If these are indeed resting cysts of *Alexandrium* spp, they may represent a potential problem in terms of PSP toxin production. Toxin studies on Australian strains of *A. margalefi* showed them to be non-toxic (Hallegraeff *et al.*, 1991), but *A. minutum* has been associated with PSP intoxication in France (Erard Le-Denn *et al.*, 1993) and Australia (Hallegraeff *et al.*, 1991). Higman *et al.* (1995) and Macdonald (unpublished) in recent studies of dinoflagellate cysts on the east coast of Britain found concentrations of a cyst closely resembling, but larger, than known specimens of *A. minutum*. Although presently unidentified, Higman *et al.* (1995) report its thecal affinity is likely to be with *A. minutum*. These cysts were most numerous in sediments of the Firth of Forth. This area has a history of PSP toxicity (SOAFD data) – usually attributed to *Alexandrium tamarense* – and also has a high density of shipping due in part to the presence of both oil and gas terminals. Cysts of *A. tamarense*, the dinoflagellate normally associated with PSP events in Scotland and abundant in parts of the Firth of Forth (Lewis *et al.*, 1995) were not found in any of the ballast sediments. Whilst cysts resembling *A. minutum* have been observed in the Firth of Forth and in ballast sediments of ships discharging there, motile cells of *A. minutum* have not been observed in the Firth of Forth. Also, they have not been observed in the waters off Sullom Voe, the other port where these cysts were observed in ballast sediments. Efforts should be made to germinate both the cysts found in the current study and those from the Firth of Forth to ascertain their respective motile stages, and genetic studies might help establish any relationships between them.

Laboratory studies have shown that germination of *A. minutum* cysts is maximised at temperatures of around 16°C and at salinity values ranging from 14-26 (Cannon, 1993). Maximum bottom temperature in the outer Firth of Forth occurs during August when the mean value is only 12.97°C, whilst mean bottom salinity never goes below 34 throughout the year (Turrell and Slesser, 1992). If *A. minutum* cysts are being transported to the Firth of Forth, conditions may be unsuitable for their germination, so the cysts may simply remain dormant in the sediment or become non-viable.

One empty cyst was observed which resembled *Gymnodinium catenatum*, but was smaller than those observed by other workers. This cyst may have been the resting stage of another similar species of *Gymnodinium*, or a very small specimen of *G. catenatum*, which perhaps occurs as smaller cells in colder waters. The distribution of this species in European waters has traditionally been associated with southern European countries (Blanco, 1989; Carrada *et al.*, 1991). However, the appearance of living *G. catenatum* cysts in recent surveys off both the German (Nehring, 1993) and Danish (Ellegaard *et al.*, 1993) coasts coupled with the findings of Dale *et al.* (1993), who presented evidence for prehistoric blooms of *G. catenatum* in the Skagerrak/Kattegat, suggest that either parts of the North Sea are being newly colonised by *G. catenatum*, or that the cysts may be a relic from prehistoric times (Nehring, 1995). Whichever is the case, it is clear that northern European countries should not discount the threat of this potential PSP producing dinoflagellate becoming endemic to their regions.

Hallegraeff and Bolch's (1992) research found cysts only in vessels originating from Japan or South Korea. In this study, cysts were observed in samples taken from ships that had loaded their ballast in a variety of northern and southern European countries. Sediments may have accumulated over a period of time, depending on when the ship was last in dry dock or when the tanks were completely cleaned out, so samples might therefore reflect an accumulation of material from many ports. For safety reasons, samples were collected from deck. It was therefore not possible to assess the nature of the sediment, to note if large accumulations were present, or if the state of the tank suggested that sediment was flushed out regularly.

Northern European ports are the most common origins of ballast water discharges to Scottish ports (Macdonald, 1994). This might imply that introductions of non-indigenous species are unlikely to occur, as the differences in flora and fauna between origin and discharge ports may be small. However, there are harmful algal species found in northern European waters not yet observed in Scotland (Nehring, 1995). Environmental conditions in waters of relatively close proximity are likely to be more similar than those which are geographically distant, so it could be argued that the chances of survival in adjacent or nearby "new areas" may be enhanced.

Conclusions

Preliminary analyses of ballast tank sediments demonstrate that dinoflagellate cysts are commonly found in tankers visiting Scottish ports. If these cysts are discharged to the environment and survive in their new location, it is possible that shellfish resources in particular could be affected if toxin-producing species are involved. However, introduced cysts may not germinate if environmental conditions are unsuitable, but remain dormant or be rendered non-viable. Efforts should be directed at investigating the taxonomic relationships with other cyst species known in Scottish waters and the viability of ballast tank cysts should be assessed. Further studies will be carried out to extend our knowledge of the ballast water transport of planktonic organisms to Scottish ports.

Acknowledgements

I wish to acknowledge R Davidson for laboratory analysis, J Dunn and M Robertson for assistance with field sampling, A Gallego for help with preparation of figures and A Shanks for statistical advice. This work is funded by The Scottish Office Agriculture, Environment and Fisheries Department, Department of Transport/-Marine Safety Agency and is partly based on research commissioned by Scottish Natural Heritage as part of its programme of research.

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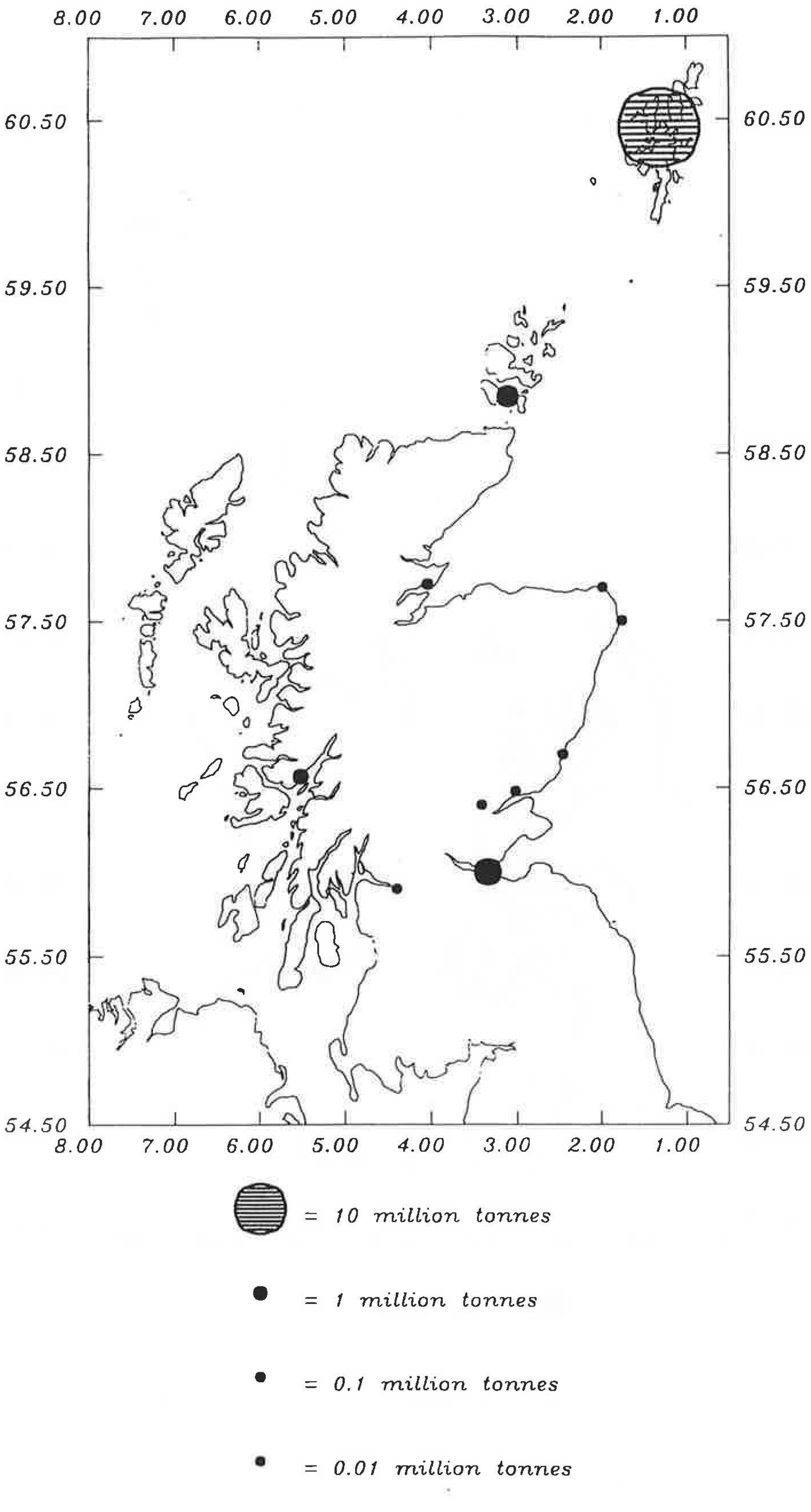

Figure 1 Estimated ballast water discharges to Scottish ports.

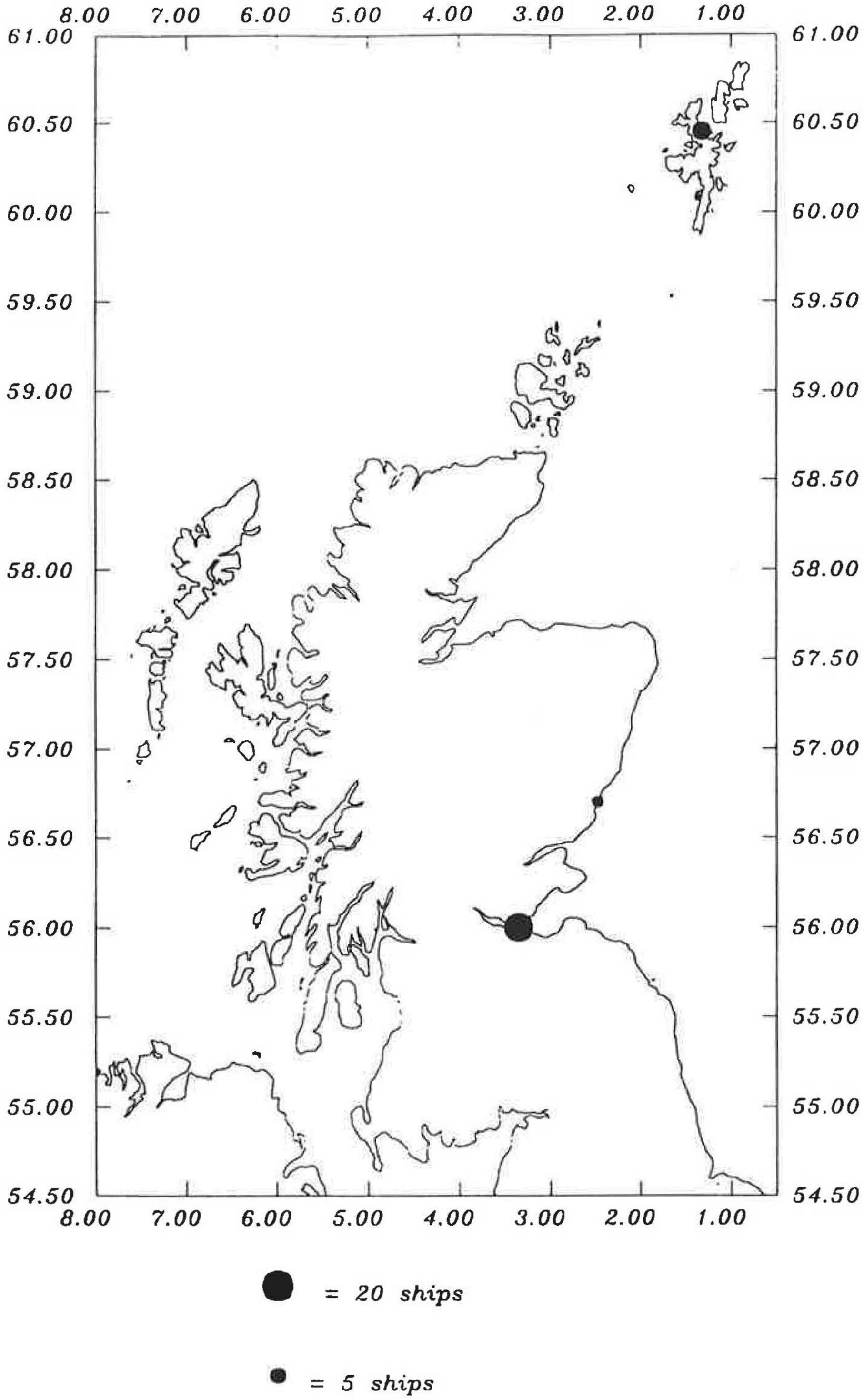

Figure 2 Ships and ports sampled to date during Scottish ballast water research porgramme.

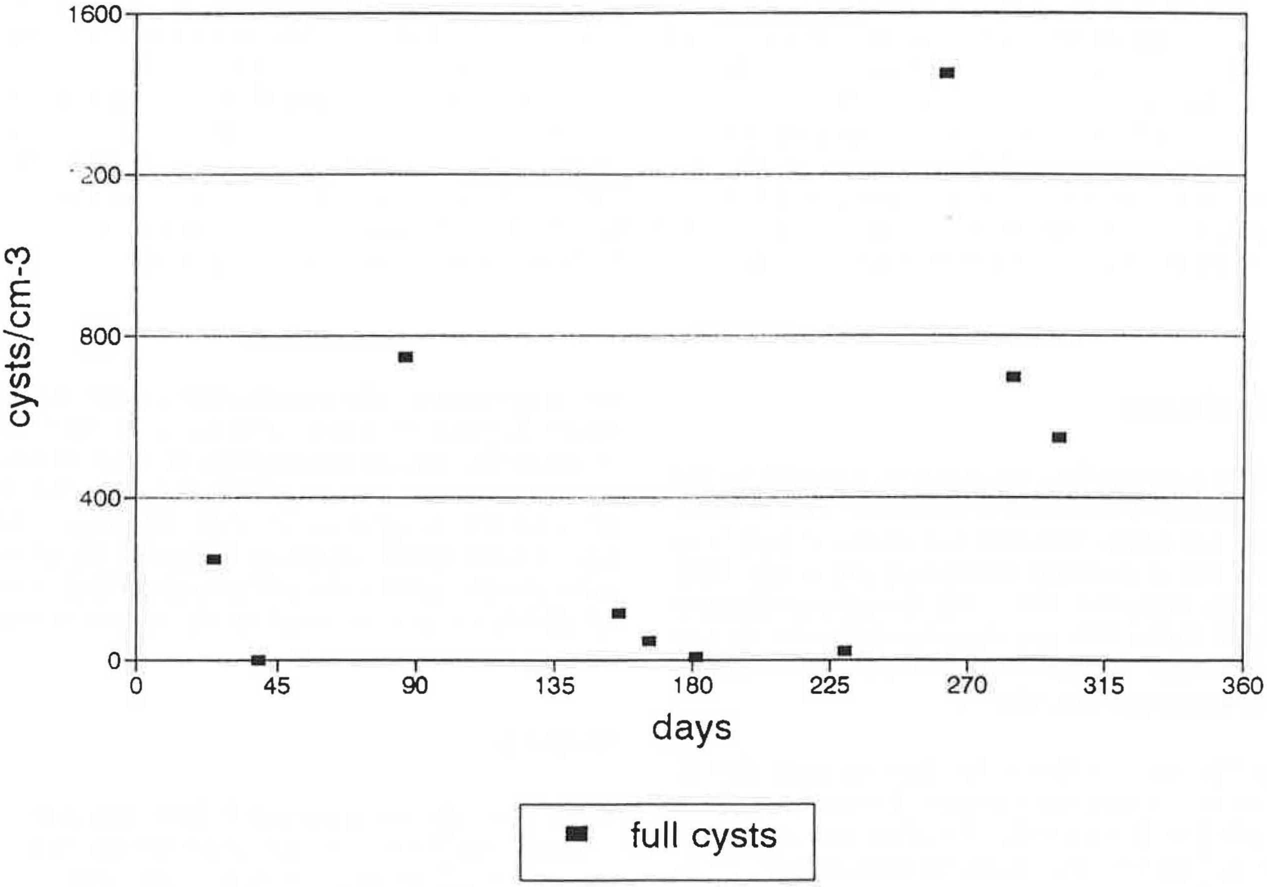

Figure 3 Full cyst counts in ballast tank sediment samples, January-December.

Ballast water discharge into coastal waters of England and Wales

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A questionnaire was designed to assess the risk of introductions of alien marine organisms into coastal waters of England and Wales through discharge of ballast water from ships. It was sent to 127 ports in England and Wales in order to identify the areas of greatest risk, which will be further assessed in a future sampling survey. Replies were received from 111 (87.4%) of ports. Ballast water is discharged into just under half (48.7%) of ports in England and Wales. Few accurate records are kept by these ports but it is possible to gain a general overall picture of the current situation from the information supplied. It is estimated that there are more than 16,000 ballast water discharge operations annually and an estimated 16.8 million tonnes of ballast water is discharged. Oil and gas tankers contribute over 75% of this total. Only four ports (Bristol, King's Lynn, Middlesborough, and Milford Haven) reported discharge of ballast water originating from outside continental Europe. By volume, ballast water from this origin accounted for about 11% of the total for all ports, compared with 47% at ports where discharge originated only from other United Kingdom and Northern European ports. Most ports (79%) have no policy or regulations on management of ballast water discharge. Of the 13 ports which do have regulations, these are mainly related to operational safety. Only five ports request compliance with IMO guidelines on ballast water management.

Introduction

Ballast water has been implicated as a medium for the introduction of alien marine organisms, some of which have had serious biological and economic impacts in their new environment (Hallegraeff and Bolch, 1992; Carlton and Geller, 1993). The International Maritime Organization (IMO) has adopted guidelines for the safe management of ballast water (IMO, 1991) and is considering issuing regulations.

For UK coastal waters, it has been suggested that 42 alien species have been introduced since 1830, 18 of which have had some harmful effect, and 11 of these harmful species have become widespread (Eno, 1995). Nine of the 42 introductions may have been secondary, that is they were originally introduced (from outside Europe) into other European ports. Convincing evidence for the means of introduction is generally lacking, but ballast water is suggested as the vector in three cases, compared with 21 introductions through transport on the outside of ships' hulls and 12 introductions, both deliberate and accidental, associated with mariculture. There is no known mechanism for the remaining six introductions, and ballast water cannot be ruled out in these cases. These results compare with the documented introduction from ballast water of 14 species into Australia (Anderson, 1992) and 10 species out of a total of 20 unintentional introductions into the Baltic Sea (Jansson, 1994).

This report presents the findings from a questionnaire survey designed to obtain information to assist in assessing the risk of introductions of alien marine organisms, and the areas of greatest risk. The strategy for a sampling programme, in which the number and type of viable marine organisms transported in ballast water into the coastal waters of England and Wales will be determined, will be based on the results of this survey.

Methods

Names and addresses of port and harbour authorities in England and Wales were obtained from information supplied by Lloyds Register and Marine Offices. A questionnaire was designed, based on that used by the SOAFD Marine Laboratory, Aberdeen for a survey of Scottish ports and harbours (Macdonald, 1994). The purpose of the questionnaire was to gather information on amounts of ballast water and associated sediments discharged and loaded in coastal waters around England and Wales and the sources of discharged ballast water. Information on current ballast water management practices and any policies or regulations covering the loading or discharge of ballast water was also sought. This questionnaire, together with a covering letter, was distributed to 127 ports and harbours. Some ports either forwarded the forms to operators of shipping terminals in their area or provided the information for this to be done. Other ports suggested various shipping companies as possible sources of further information. Minor revisions were made to the questionnaire and a pilot survey was made of 35 of these shipping companies. Reminders and spare questionnaire forms were sent out to ports from which no reply had been received after six weeks.

Results

Response

Replies were received from 111 ports (87.4% of those surveyed) or their associated terminals. The response from the pilot study of shipping agents was lower. Of the 35 surveyed, 12 replied (34%), of which 9 were responsible for vessels that were involved in ballast water exchange. The detailed information that 7 of the shipping agents supplied on a total of 1.153 million tonnes of ballast water discharge in 1,368 operations was useful, together with that supplied by the ports, in estimating average amounts of ballast water exchange by different types and sizes of vessel.

Ports where ballast water is exchanged

Of the 111 ports that responded, 63 (56.8%) reported some ballast water exchange operations. At nine ports (8.1%) this involved loading of ballast water only, giving 54 ports (48.7%) at which ballast water is discharged . The status of all ports surveyed in relation to ballast water operations is shown on Figure 1.

Amounts of ballast water discharged at ports

Many of the 36 ports that supplied information on the amounts of ballast water exchanged commented that this information was based on estimates and that accurate data could only be obtained by consulting ships' log books. Eleven ports were only able to supply estimates of the numbers, type and size of vessel involved in ballast water exchange operations and the remaining 16 ports where ballast water is exchanged did not supply any data. The total number of ballast water exchange operations reported (from 47 ports) was 23,815 per annum. Of these, 13,214 (55.5%) were ballast loading and 10,601 (44.5%) were ballast discharging operations. Extrapolating these data to all ports with ballast water discharge, including those from which no data were supplied and those from which no reply was received (assuming the same ratio of ports with ballast water discharge as those that did reply), give an estimate of over 16,000 ballast water discharge operations annually.

A reported total (from 36 ports) of 15.52 million tonnes of ballast water is exchanged annually at ports in England and Wales. Of this total, 61.4% (9.529 million tonnes) is loaded and 38.6% (5.992 million tonnes) is discharged. This load to discharge ratio of 1.6:1 compares with a ratio for Scottish ports of 0.03:1 (Macdonald, 1994). For ballast water discharge, it is possible to make an estimate for the 11 ports that only supplied numbers, types and sizes of ships involved in ballast water exchange operations, using this information and the calculated average amounts of ballast water discharged by these vessels (see below). This calculation gives an additional 4.935 million tonnes, making a total of 10.927 million tonnes. The relative amounts of ballast water discharged at individual ports in England and Wales is shown on Figure 2. Amounts ranged from 2.38 million tonnes per annum at terminals in the Tees (Middlesborough) to less than 1,000 tonnes at smaller ports such as Littlehampton. Extrapolating the data to obtain a total figure, as for the number of ballast water discharge operations above, gives an estimated figure of 16.8 million tonnes of ballast water discharged annually into ports in England and Wales. It is recognised that this is a very approximate value, which compares to an estimate of 25.7 million tonnes of discharge into ports in Scotland (Macdonald, 1994).

Amounts of ballast water discharged, by vessel

Ports and shipping agents were asked to record the types of vessel involved in ballast water exchange and to classify them, by size, into one of three groups: (a) less than 10,000 tonnes; (b) 10,000 to 100,000 tonnes; and (c) greater than 100,000 tonnes. Five categories of vessel type were recorded; bulk carriers; tankers (oil and gas); ferries; general cargo vessels; and other vessels (barges, tenders, tugs, etc.). Records were obtained for 8,816 ballast water discharge operations of which 94.5% were by ships in the smallest size group (a). Ships of size groups (b) and (c) accounted for only 4.3% and 1.2% of ballast water discharge operations respectively. All ships in the largest size group were tankers, and these accounted for 3.6% of ballast water discharge operations by all tankers. The average amounts of ballast water discharged by each type and size of vessel are shown in Table 1. Tankers of less than 10,000 tonnes are responsible for the most ballast water discharge operations. Large tankers make only a small contribution to the total number of discharge operations but because of the large volumes transported the amount discharged is significant. All tankers account for over 75% of the total volume of discharge. A high proportion of discharge operations is by ferries, but this is to maintain trim of the vessels and as the amounts involved in each operation are small the contribution to the total volume is low.

Table 1 Average volume (tonnes) of ballast water discharged by various types and sizes of vessel involved in this operation at ports in England and Wales. The proportional contribution (percentage) made in terms of number of discharge operations and volume of ballast water discharged annually are also given.

Type of vessel	Size of vessel	Average discharge (tonnes)	Percentage of total discharge operations	Percentage of total volume discharged
Bulk carrier	a	660	18.31	10.35
Tanker	a	1,230	31.53	33.22
	b	7,330	1.88	11.80
	c	28,500	1.24	30.27
General Cargo	a	630	17.45	9.42
Ferry	a	90	19.74	1.52
	b	110	2.40	0.27
Other	a	500	7.45	3.19

Amounts of ballast water discharged by origin

Information on origin of discharged ballast water was not always provided and was not sufficiently detailed to obtain accurate estimates of volumes from specific countries of origin. The data were divided into four categories, according to ports in areas of origin: United Kingdom only; UK and Northern Europe; some ships from elsewhere in Europe; some ships arriving from outside Europe. The origin of ballast water discharged at ports in England and Wales classified according to these categories is shown on Figure 3. Only four ports reported discharge of ballast water from ports outside continental Europe viz., Bristol, King's Lynn, and certain terminals at Middlesborough and Milford Haven. Ships arrive in ballast at these ports from the Americas, Australasia, Africa, India, and the Far East. From such information as was provided by these ports it was estimated that about 11% of the total discharge volume for all ports originates from outside Europe. This compares with 47% of the total volume discharged with a known origin of other United Kingdom and Northern European ports only. These results must be treated with caution as ballast water may have been loaded at a site other than the previous port of call.

Ballast water management

Most ports (79%) have no policy or regulations on management of ballast water discharge. Of the 13 ports which do have regulations, these are mainly related either to operational safety or to preventing chemical pollution. In the latter case ballast water from cargo tanks cannot be discharged or, in the case of some oil terminals, can only be pumped into dedicated on-shore facilities. No consideration is taken of potential biological content. Only five ports request compliance with IMO guidelines on ballast water management. Sampling of ballast water is carried out at only five ports and again this is related to chemical rather than biological content. Some respondents were aware that the National Rivers Authority took water samples in the vicinity of the port. Only three of the 111 respondents were aware of any problems associated with the discharge of ballast water.

Discussion

Information on ballast water exchange operations at ports in England and Wales is limited, but sufficient data has been obtained from the questionnaire survey to give a general overview of the situation and estimates of the amounts involved. The data collected will be valuable in determining a strategy for a sampling programme to assess the risk of introducing unwanted alien marine organisms.

A high proportion of the ballast water discharged originates from within the UK or Northern Europe, giving a risk of further dispersal of unwanted marine organisms that may become introduced in this region. A recent study (Sherwood, 1995) in which 7 ships from Northern Europe were sampled over a 5 month period identified 31 living species in ballast water, one of which, the diatom *Chaetoceros fragile*, may be a relatively recent introduction to European waters.

Oil and gas tankers contribute the greatest volume of discharged ballast water. The amount discharged annually exceeds one million tonnes in 4 areas, the Tees, Milford Haven, Southampton and the Tyne. The first two of these receive some ballast water from outside Europe, as do ports at Bristol and King's Lynn, which each receive over 500,000 tonnes annually.

In a UK context, less ballast water is discharged in England and Wales than in Scotland, but discharge operations are more frequent, from a greater proportion of smaller vessels, and more ports are involved. Some ports receive only small quantities, but there is still a risk of introducing any alien marine organisms contained in this ballast water.

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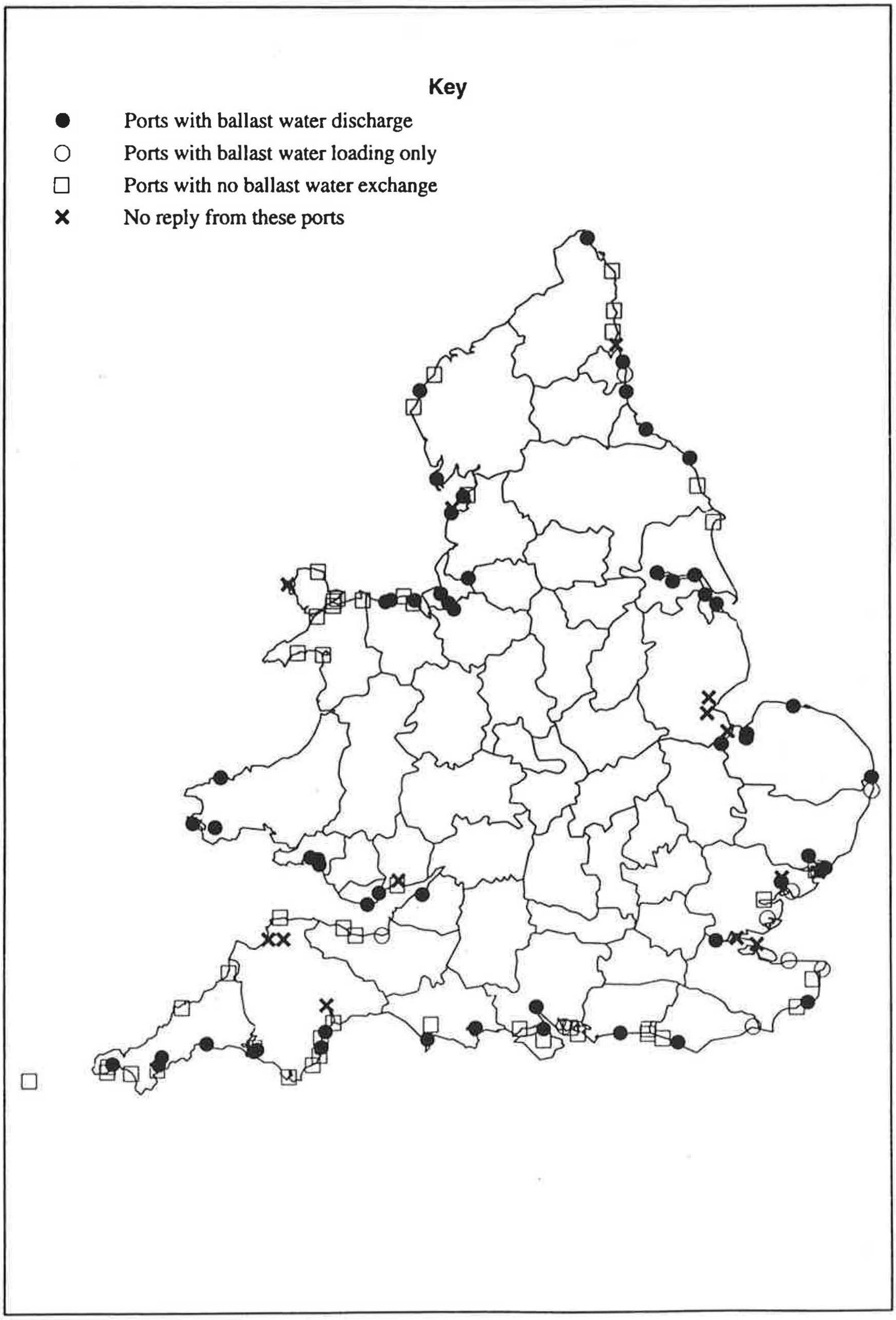

Figure 1 Ballast water exchange at ports in England and Wales. Data from replies to questionnnaire, March 1995.

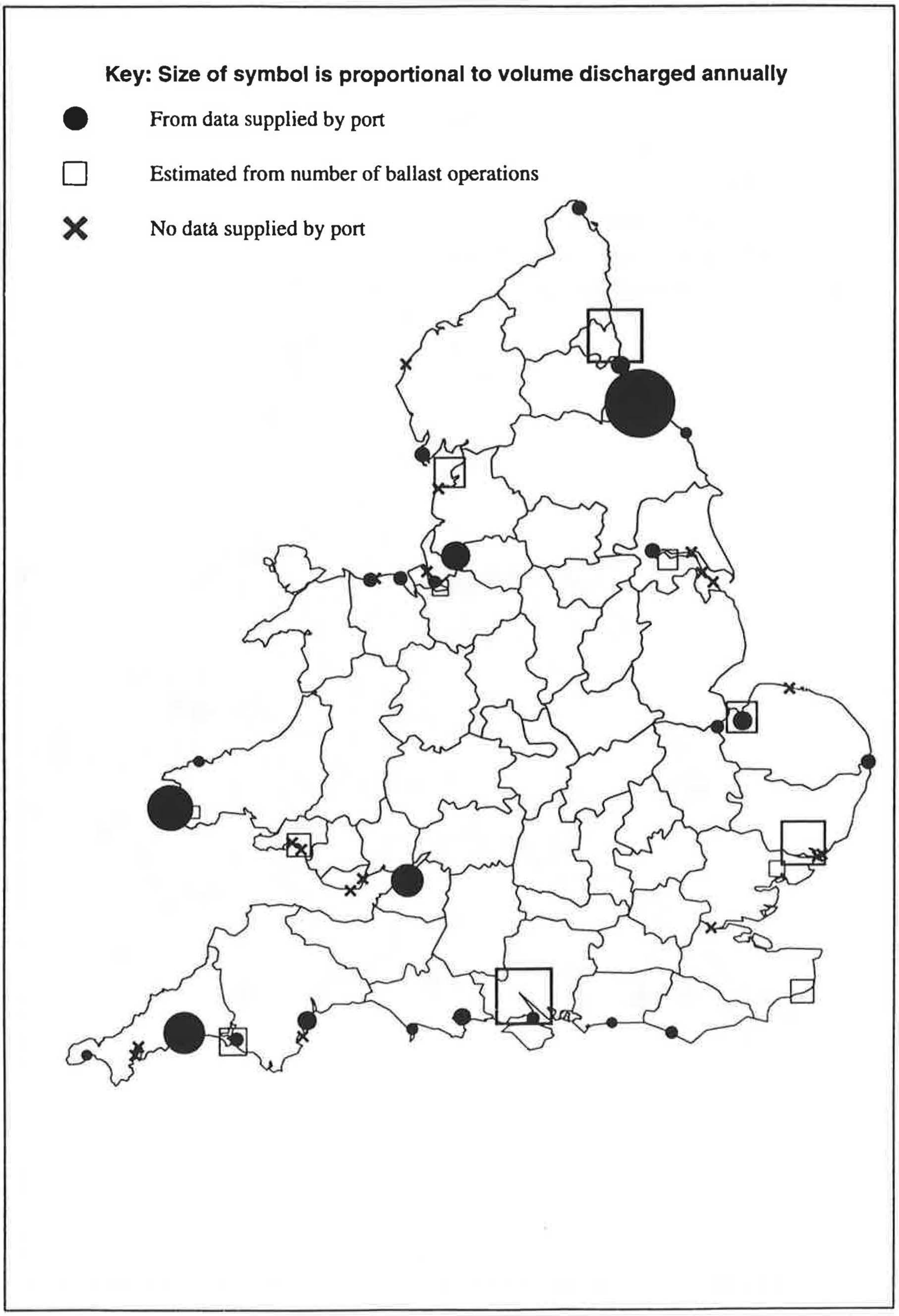

Figure 2 Relative volumes of ballast water discharged at ports in England and Wales. Data from replies to questionnaire, March 1995, for all respondent ports at which ballast water is discharged.

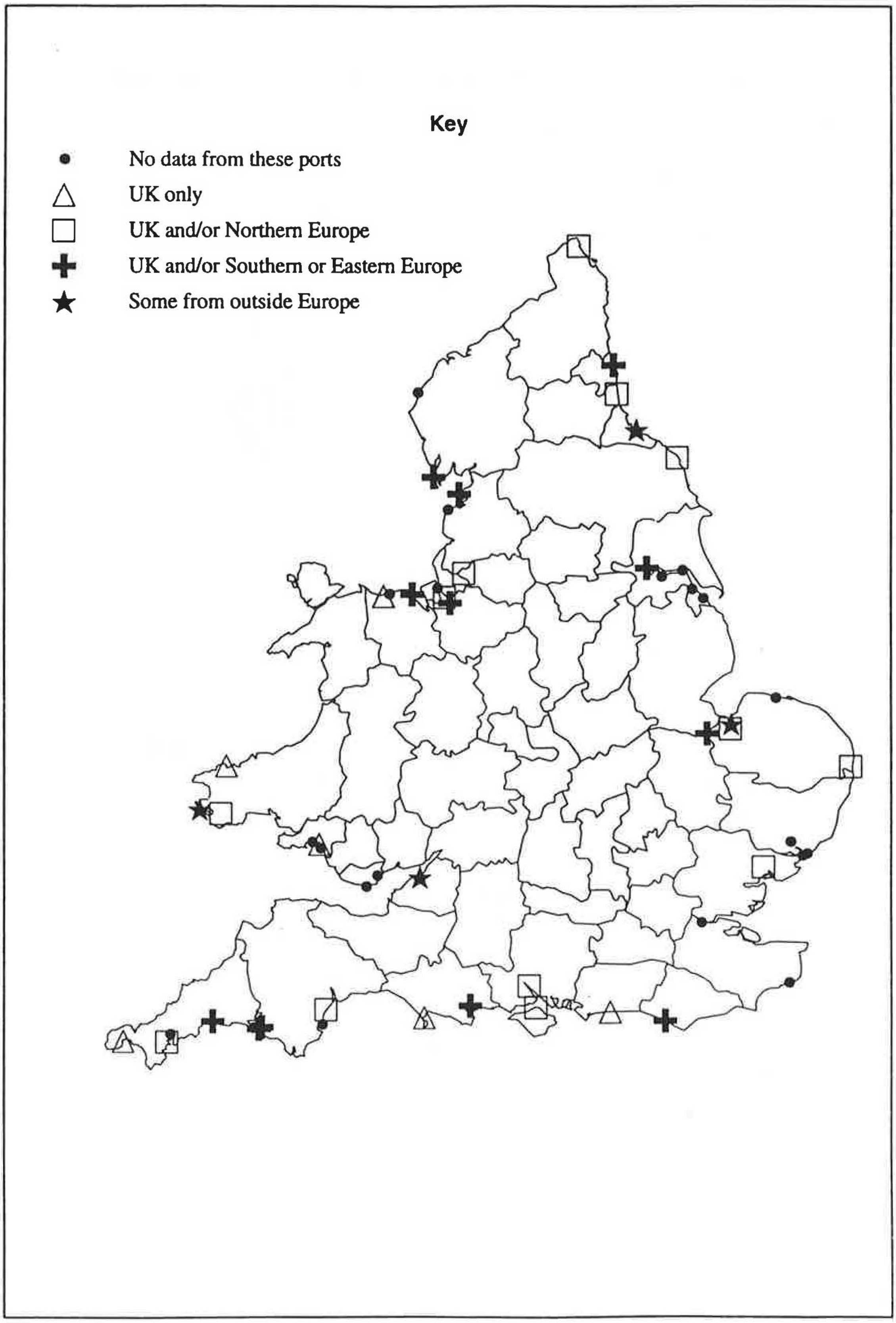

Figure 3 Origin of ballast water discharged at ports in England and Wales. Data from replies to questionnaire, March 1995, for all respondent ports at which ballast water is discharged.

Non-native marine species in British waters: ballast water introductions

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Information on non-native marine species found in British waters thought to have been introduced in ballast water or sediment contained in ballast tanks is presented. The information has been extracted from a larger study covering all methods of introduction involving human agency. Thirty of a total of fifty three species were found to have been introduced in association with shipping. Nine species were introduced in ballast and a further five were either introduced in ballast or on ships' hulls, transport on hulls was identified as the sole method of introduction for the remaining sixteen species. The species under consideration were found to have originated from all major temperate oceans. More species were introduced in the 1970s than in any other decade, which may be correlated with changes in ship and port design. A variety of effects on commercial interests were recorded and the displacement of native species was identified as the most common effect on the environment. There is a continual need for vigilance to safeguard ecological and commercial interests.

Introduction

The material presented here is part of a wider study undertaken to collate details and review information about introductions of marine flora and fauna to Great Britain (Eno, Clark and Sanderson, 1997) This paper focuses on those species identified as probably having been introduced in association with ballast. The study was undertaken for the Joint Nature Conservation Committee (JNCC), the body constituted by the Environmental Protection Act 1990 to be responsible for research, advice and the setting of common standards on nature conservation at both UK and international levels.

Traditionally, shipping has been considered a major route of introductions, and not only of marine species. However, the agents involved may have changed. The amount of transoceanic shipping increased greatly and the use of anti-fouling paints became common this century. Furthermore, modern vessels tend to move faster through the water. These factors have favoured present day transport of species in ballast tanks as opposed to on hulls. Carlton (1992 a and b) considered that ballast water probably provides the greatest flow of neritic species globally in modern times. In relation to Europe, it is noteworthy that, in particular, numerous phyto-planktonic organisms have been recorded in ballast water in vessels entering the Baltic and North Sea (Anonymous, 1994).

Methods

Collection of information

A questionnaire was distributed widely to British marine biologists including targeted marine specialists with knowledge of particular taxonomic groups. Information on marine flora and fauna introduced to British waters was also drawn from the literature. Details were compiled of species introduced with ballast, particularly in relation to other introductions associated with shipping. An evaluation was made of their origin, date and method of introduction, actual and potential effects on native ecosystems and nature conservation and effects on commercial interests. Further details of the reasons for the success of non-native marine species found in Britain, their rate of spread, current distribution, and methods of control were covered in Eno, Clark and Sanderson (1997) Micro-organisms were not considered.

Definition of non-native species

It became apparent as information was being collected on species not normally resident in British waters that they would need to be categorised according to their status. The following definition has been used to describe non-native marine species.

A non-native species is one which has been introduced directly or indirectly by human agency (deliberate or otherwise), to an area where it has not occurred since any major climatic change (5000 years before the present), and which is separate from, or lies outside, the area where natural range extension could be expected. The species have become established in the wild and will have self-maintaining populations. The term also includes hybrid taxa derived from such introductions.

Results

Methods of introduction

Thirty of the 53 introduced marine species currently established in British waters were considered to have been primarily introduced to Britain or neighbouring waters in association with shipping (see Figure 1), nine of these in ballast. Of the sixteen marine algae, five diatoms, one angiosperm and 31 invertebrates which were identified as non-native (Eno, 1995), the diatoms, angiosperm and three invertebrates shown in Table 1 were brought in with ballast. A further five species, including two Crustacea, two annelids and one alga came either on ships' hulls or in ballast, as shown in Table 2. The remaining 16 species were considered to have been introduced attached to the hulls of ships or in the case of one species, flying boats.

Origin

Species were introduced from the primary sources from which they originate, or from secondary sources to which they were previously introduced. In general, species only became established if they were introduced from similar latitudes and those possibly brought in with ballast originated from all temperate oceans, as shown in Tables 1 and 2.

Dates of introduction

Carlton (1985) pointed out that the date of first collection is not necessarily, and indeed rarely is, coincident with the date of introduction. For a number of species, introduction dates were therefore approximate. Of those species introduced with ballast six out of nine were considered to have entered British waters after the mid 1960s, with most entering in the 1970s as shown in Table 1; including those species in Table 2, five out of 14 entered in the 1970s.

Effects on the environment and on commercial interests

The effects of individual non-native marine species introduced with ballast are given in Tables 1 and 2. The most common effect on the environment was found to be the displacement of native species; this was also the case for species introduced by other methods (Eno, 1995). The effects on commercial interests were more varied and included fouling of ships, marinas, moorings, nets, shellfish and aquaculture structures, and damage to fishing nets.

Discussion

Over a quarter of non-native marine species in British waters may have been introduced with ballast, either in ballast water or in sediments transported in ballast tanks, which makes this a significant method of introduction. It is interesting to note that only a single marine macroalga of a total of 16 non–natives identified may have entered by this method (Eno, 1995). Yet all the phytoplanktonic introductions are considered to have entered with ballast (Wallentinus in press).

Historically, European major ports were some distance from the coast, often 30–40 miles from the open sea in reduced salinity waters. In the 1970s there was a rapid move to container transport by large vessels and the use of super tankers for oil which were restricted to coastal (high salinity) ports, e.g. Felixstowe, Southampton and Milford Haven. This change in practice may have accounted for an increased number of introductions and enhanced survival when ballast was discharged.

Of those introduced marine species which have become established in British waters, only a small proportion have so far proved to be a nuisance to sea users or a threat to the environment (Eno, 1995). One of the notable examples is *Spartina anglica.* This derives from hybridisation of *Spartina alterniflora* (introduced in ballast water from the East Coast of North America) with the native small cord-grass *S.maritima.* There are also a number of species which have been introduced and have not exhibited the adverse effects seen elsewhere in Europe (Eno, 1995). There is a continual need for vigilance to safeguard ecological and commercial interests. Examples of economic and ecological disasters such as those seen in the American Great Lakes following the introduction of the zebra mussel *Dreissena polymorpha* (Harbison, 1993) and in the Black Sea following the introduction of the comb jelly *Mnemiopsis leidyi* (Kershner, 1993) indicate that ballast water controls are essential.

Table 1 **Non-native marine species introduced in ballast.**

Phylum	Species	Origin	Probable date of intro-duction to Britian	Effects on the environment and commercial interests	References
Bacillariophyta	*Thalassiosira tealata*	Unknown	1950	None known.	Wallentius (in press).
	Thalassiosira punctigera	Unknown	1978	None known.	Hasle 1983 & 1990, Wallentinus (in press), Smayda 1990
	Pleurosigma simonsenii	Indian Ocean	1966	Displacement of native species, sometimes to the point of dominating as a bloom.	Boalch & Harbour 1977a, Wallentinus 1993
	Odontella sinensis	China Sea	1903+	*Odontella sinensis* has been a prominent contributor to the winter and spring phytoplankton of the western English Channel.	Boalch & Harbour 1977a, Boalch 1987, Ostenfeld 1908
	Coscinodiscus wailesii	Indian and Pacific Oceans	1977	*Coscinodiscus wailesii* can reach high numbers for a cell of its size, produce copious mucilage which in sinking can accumulate insoluble skeletons of planktonic organisms and mineral particles, increasing its volume and density. One year British fishing trawls were reported as clogged or broken by heavy grey slime which can interfere with the hauling of fishing gear, furthermore, prolonged washing or air drying may not completely remove it.	Boalch & Harbour 1977b, Rincé & Paulmier 1986, Hasle 1990.
Angiospermae	*Spartina anglica*	North west Atlantic coasts	1971	The rapid colonisation of *Spartina anglica* over extensive flats in sites with large wintering populations of waders and wildfowl is a major concern because of their loss of habitat for feeding and roosting. It is believed that *Spartina anglica* may have helped the demise of the native *S .maritima* as the latter is much less widely spread than formerly. In addition, by taking over the mantle of the native pioneer species, *S. Anglica* has altered the course of succession. It usually produced a monoculture which has much less intrinsic value to wildlife than the normally occurring marsh. Amenity interests may be affected by *Spartina*, although it has been used in the past as an aid to saltmarsh enclosure.	Davidson *et al.* 1991, Doody 1984, Perring & Walters 1976, Stapf 1914
Annelida	*Marenzelleria viridis*	North west Atlantic coasts	1982	In the Tay *Marenzellaria virdis* occurred at grater sediment depths than other species in an intertidal mudflat, but its distribution and population densities were negatively correlated with all other species.	Atkins, Jones & Garwood 1987, Essink & Kleef 1993

Table 1 Continued					
Phylum	**Species**	**Origin**	**Probable date of intro-duction to Britian**	**Effects on the environment and commercial interests**	**References**
Crustacea	*Eriocheir sinensis*	Eastern Asia (secondary introduction from Germany)	1935	For most of its life the Chinese mitten crab (*Eriocheir sinensis*) lives in freshwater. During August adult crabs migrate seawards. They have been reported to damage the nets of eel fishermen.	Clark 1986, Ingle 1986, Panning 1939
Mollusca	*Ensis directus*	North west Atlantic coasts	1989	None known. It probably does not displace native razor shells because it typically inhabits muddy sediments.	Howlett 1990, Essink 1986.

Table 2 Non-native marine species introduced either with ballast or on ships' hulls.

Phylum	**Species**	**Origin**	**Probable date of intro-duction to Britain**	**Effects on the environment and commercial interests**	**References**
Chlorophyta	Codium fragile subsp. tomentosoides	Japan (secondary introduction from mainland Europe)	1939	Physical displacement of the native species *Codium tomentosum* although there is some recent indication that the native *Codium tomentosum* is making a comeback against this non-native.	van Goor 1923, Farnham 1980, Silva 1955, Burrows 1987
Annelida	*Goniadella gracilis*	North west Atlantic coasts	1970	None known.	Walker 1972
	Hydroides ezoensis	Japan	1976	Severe fouling organism on harbour structures and ships' hulls throughout Southampton Water.	Thorp *et al.* 1987, Zibrowius & Thorp 1989
Crustacea	*Balanus amphitrite*	Cosmopolitan species but origin of introduction unknown	1937	Fouling organism.	Bishop 1950
	Acartia tonsa	Occurs in western Atlantic and Indo-Pacific but origin of introduction unknown	Between 1916–1956	None known.	Conover 1957, Remy 1972, Taylor 1987.

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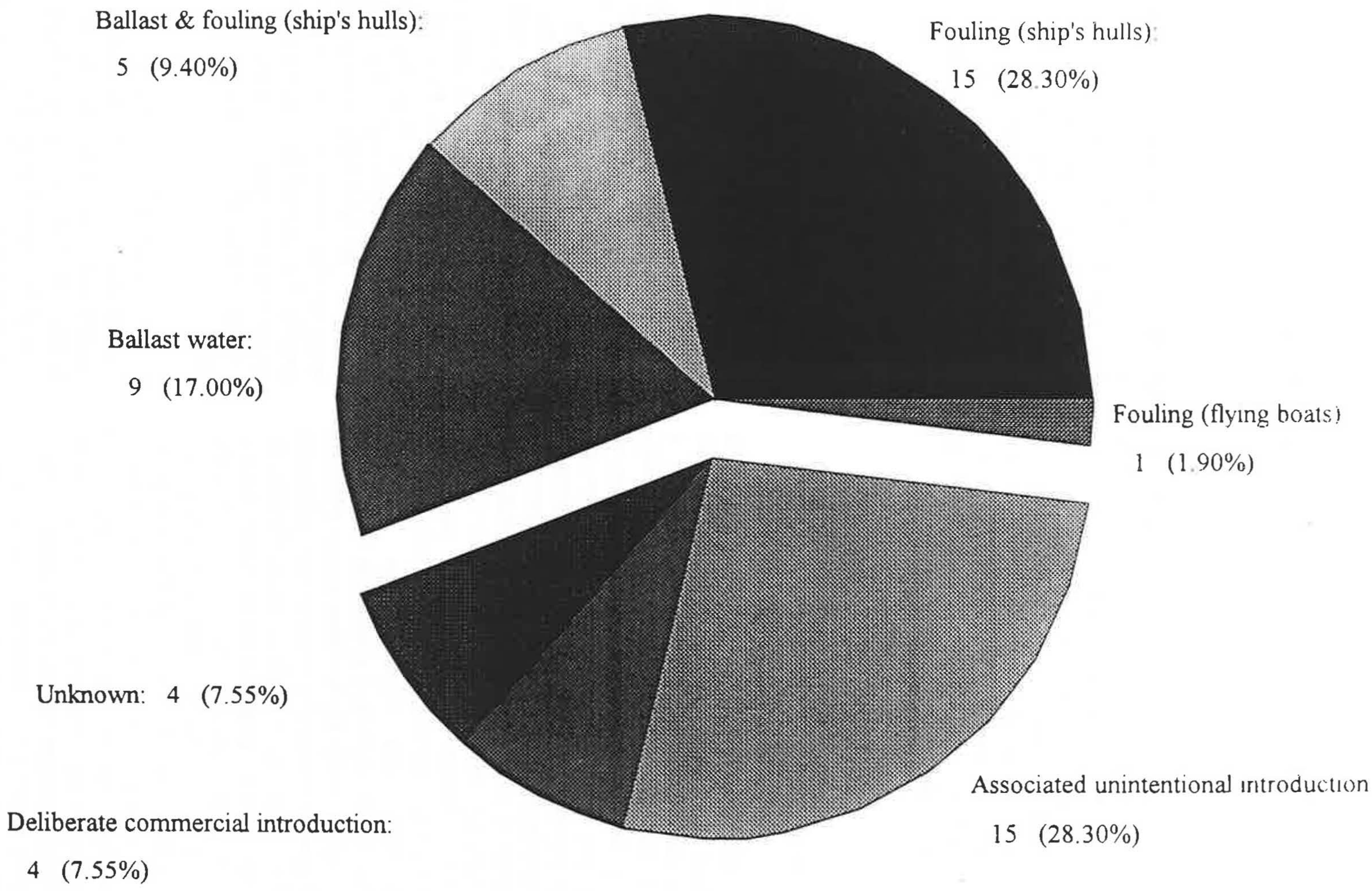

Figure 1 Primary methods of introduction of non-native marine species to British waters.

Non-indigenous organisms introduced via ships into German waters

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Ballast water has been recognised as a major vector for the introduction of non-indigenous organisms. Commissioned by the Federal Environmental Agency, Berlin, a joint research project between the Institut für Meereskunde Kiel and the University of Hamburg was initiated to provide information on possible harmful effects of non-indigenous organisms introduced into German waters by ship traffic. The study aims at a thorough taxonomic assessment of planktic and benthic organisms found in ballast water, tank sediment and on ship hulls. Over a period of three years about 300 vessels calling at German ports were visited. So far about 350 plant and animal species/taxa were found, of which roughly 30 percent comprised foreign organisms, non-indigenous to the Baltic and North Sea. In addition, the survival of plankton organisms in ballast water tanks was studied by accompanying a container vessel on its voyage from Singapore to Bremerhaven. Initial results are reported here.

Introduction

Carlton (1985) has given a comprehensive review of ballast water as a mechanism for dispersing aquatic organisms and has provided evidence that thereby a world-wide transfer of organisms between continents takes place. Recently observed mass developments of non-indigenous species in various parts of the world, causing severe ecological and even economic damage, have brought the problem of ballast water transport into general focus (Carlton and Geller, 1993; Hedgpeth, 1993). Examples are the zebra mussel (*Dreissena polymorpha*) (Roberts, 1990), the cladoceran *Bythotrephes cederstroemi* (Sprules *et al.*, 1990) and the European river ruffe (*Gymnocephalus cernuus*) (Waldichuk, 1990), which have invaded the Great Lakes in North America. While the two latter species affect the original food web structure by outcompeting indigenous species, *Dreissena* causes high economic damage by clogging pipes in water pumping and discharge systems. The ctenophore *Mnemiopsis leidyi*, a species from the southern east coast of North America, has become a dominant member of carnivorous zooplankton in the Black Sea ecosystem, affecting the recruitment of commercial fish stocks by predation on fish larvae and their prey organisms (Harbison and Volovik, 1993). Another North American species, the spionid polychaete *Marenzelleria viridis*, has established itself in the Baltic Sea (Norkko *et al.*, 1993) and almost entirely replaced the indigenous polychaete *Nereis diversicolor* in some areas (Zmudzinski, 1993). Marine aquaculture is threatened by the worldwide transport of toxic phytoplankton species in ballast water tanks, especially of cyst-forming dinoflagellates which are able to survive long periods of unfavourable conditions (Hallegraeff *et al.*, 1988, 1990).

After the occurrence of new toxic algal blooms in Australian waters, evidently established there by ballast water transport from Japan, Australian scientists have taken the lead in intensifying ballast water research (Hallegraeff and Bolch, 1991, 1992). They have urged the IMO (International Maritime Organization) to take up the ballast water problem as an official issue in regulating international ship traffic. As a first reaction the 'International guidelines for preventing the introduction of unwanted aquatic organisms and pathogens from ships' ballast water and sediment discharges were adopted by IMO (1991). The main recommendation of these guidelines was to exchange ballast water, as far as weather and safety conditions permit, when crossing deep open ocean waters. This measure would greatly reduce the danger of transferring freshwater or near-shore marine organisms to other areas, as clear nutrient-exhausted open ocean water is usually characterised by a sparse plankton community, the members of which are unable to survive under the far more changeable environmental conditions in coastal areas.

In 1992, a joint research project between the Institut für Meereskunde Kiel and the University of Hamburg commissioned by the Federal Environmental Agency in Berlin was launched to investigate flora and fauna carried by international ship traffic to German ports. The project also assessed the ecological risk arising from the introduction of non-indigenous species to German waters. The flora is identified in Kiel and the fauna in Hamburg.

Material and methods

A large variety of ocean-going vessels calling at German ports were investigated for their ballast water content. In addition, newly docked vessels were inspected for the presence of sediment and larger organisms in emptied ballast water tanks as well as for fouling organisms on the hull. The majority of samples were collected at the overseas harbours of Hamburg (76 %) and Bremerhaven (18 %). Other ports which were only occasionally visited include Rostock and Kiel (Western Baltic), Rendsburg (Kiel Canal), Brake, Elsfleth, Bremen (River Weser) and Wilhelmshaven (North Sea). The vessels investigated were mainly cargo ships, the most frequent type being container vessels followed by combi ships, bulk carriers and car transporters. A few passenger liners, research vessels and even navy ships were visited as well.

Three methods were employed for sampling ballast water. The first was opening a manhole permitting direct access to the tank and taking a sample with a small plankton net (mesh size 10 µm). Such an 'ideal' sample taking was, however, very rarely possible, a mere 8 times out of a total of 117 inspections. The reasons usually given by the ship's crew were inaccessibility of suitable manholes because of overlying cargo, a strict interpretation of safety regulations and lack of manpower needed for opening and closing a tank during the short and busy schedule in the port.

The second method, which was employed 69 times, was to pump ballast water through a sounding pipe in the tank with the help of a hand-pump. These sounding tubes have a diameter of about 6cm and a length of up to 20m. The maximum depth of water level that could be reached by the hand-pump was 9m. Very modern vessels do not have sounding tubes any more. Nowadays, water content of the tanks is controlled solely by electronic meters.

The third method, employed 43 times, was drawing water from a small tap on the ballast water pump. Water obtained by the second and third methods were filtered through a 10 µm plankton net, usually 100 liter (I) per sample, and preserved for phytoplankton and zooplankton analysis in 4 % formalin and 70 % ethanol, respectively. Depending on time and distance from the laboratory, small subsamples were left unpreserved for inspection of living organisms. On 18 occasions, when emptied tanks were inspected, it was possible to take plankton samples out of the residual bottom water.

The abiotic factors regularly measured in ballast water were temperature, salinity and oxygen by means of portable electrochemical probes and pH with a portable pH-meter.

As already mentioned, sediment and hull samples were obtained from newly docked vessels. Entering emptied tanks sometimes needs special precautionary measures, as non-ventilated tanks may contain toxic gases such as methane or hydrogen sulphide. At the beginning of the project it was therefore decided to purchase a breathing apparatus and to undergo a special training course with the local fire-brigade. A gas mask also provides protection against pathogenic germs, e.g. cholera bacteria, which might be present in ballast water. It turned out later that in most cases the inspected tanks were well-ventilated.

Sediment samples were taken from the tank bottom and from construction frames on the walls. Fouling organisms were scraped from the walls, too. Sometimes it was possible to catch larger organisms such as crabs and fish in the residual water by means of a small landing net. Preservation methods were the same as with plankton samples. Unpreserved sediment samples were stored in a refrigerator for future cyst-hatching experiments. For making a semi-quantitative comparison of fouling samples possible, a patch measuring roughly 10 x 10cm was usually scraped off the hull.

In May 1995 the German container ship 'DSR America' was accompanied during a 23 day cruise from Singapore to Bremerhaven. The survival of tropical plankton in ballast water tanks was investigated on passage to Northern Europe through a daily check of environmental conditions (temperature, salinity, oxygen and pH value) and plankton content. Environmental conditions were recorded in 4 tanks, in the forepeak and aftpeak tank and in two opposite side tanks on starboard and port side. The first tank was filled after departure from Singapore and the three others after a stop in Colombo (Sri Lanka). Plankton survival was controlled in two tanks, in the aftpeak tank and one of the later filled side tanks. 100 I samples were taken daily through opened manholes and filtered through a 10 µm plankton net. Species determination and counting were, as far as possible, completed on board

Results

Figure 1 shows the position of ballast water tanks in a modern container vessel. They consist of a series of double bottom tanks, topside tanks and a forepeak and aftpeak tank. The ballast water capacity of large vessels may exceed 20,000t. Bulk carriers, when travailing without cargo, can transport more than 100,000 t.

Vessels from almost all parts of the world connected through international ship traffic were investigated (Figure 2). 308 vessels were inspected between March 1992 and July 1995, yielding a total of 335 plankton, sediment and hull samples (Figure 3). Their geographical origin is shown in Figure 4.

Of the over 350 different species taxa recorded more than 100 comprised unicellular algae and about 250 animals. Even with the help of experts, an exact systematic identification was rather difficult in a number of cases. Therefore the genus could only be listed. The number of organisms found in 100 l of ballast water varied between one and several hundred specimens. A total of 15,000 specimens have been analysed so far, about two-thirds comprising plankton organisms and 1000 and 4000 specimens from sediment and hull samples, respectively. The main phytoplankton groups recorded are diatoms, dinoflagellates, chloro- and cyanophytes. Diatoms and chlorophytes were more common than dinoflagellates. Figure 5a shows the regional distribution of the samples and presence of the main groups. It is interesting to note that in quite a number of cases no phytoplankton was found at all, especially in samples from the Indian Ocean, South West America and the open ocean.

Sediment samples analysed so far showed the presence of empty cysts of dinoflagellates belonging mainly to the genus *Protoperidinium*. It is unknown where the hatching took place, in the tank or before ballasting.

The main group of organisms recorded in ballast water from all regions are planktonic crustaceans (Figure 5b). Mollusc, polychaete and fish larvae occurred quite frequently. What is interesting is the occurrence of rotifers and nematodes. Rotifers inhabit mainly freshwater and low-saline brackish water. Their presence can be taken as an indication of the origin of the ballast water. Nematodes are benthic organisms. Their presence points to the fact that ballasting occurred in a nearshore shallow area where the sediment was stirred up. The presence of chlorophytes (Figure 5a) may be interpreted in the same way. A classification of the salinity of the ballast water shows that in 3 % salinity was below 5 ‰, 32 % fell into the range 5–30 ‰ and 65 % contained high-saline water above 30 ‰.

The dominance of crustaceans recorded is also mirrored in their species diversity. Of 250 species taxa recorded in total for the animals, 152 species (61 %) were crustaceans with 57 copepod species encountered primarily in plankton samples. Molluscs rank second with 57 species (23 %). Cirripeds and bivalves were the predominant hull organisms. Foraminiferids occurred mainly in sediment samples.

A first estimate shows that about 30 % of the 350 organisms recorded are to be regarded as non-indigenous. Table 1 gives an overview of the systematical groups where foreign species were encountered. It is interesting to note that the plankton samples contained only 4 groups with non-indigenous species, while the number of groups found in sediment and hull samples was almost twice as high.

Table 1 Systematical groups in which non-indigenous taxa were recorded and location of records.

Systematical unit	Plankton	Sediment	Hull
Diatomophycea	+	+	
Dinophycea	+	+	
Foraminifera	+	+	+
Turbellaria			+
Rotifera	+		
Gastropoda		+	+
Bivalvia		+	+
Cladocera	+	+	
Ostracoda		+	+
Copepoda	+		
Cirripedia		+	+
Decapoda		+	+
Bryozoa			+

The study on the survival rate of plankton in ballast water tanks on board the container vessel 'DSR America' on its way from Singapore via Colombo to Bremerhaven focused on two tanks. Figure 6a shows the concentration of phytoplankton cells in the aftpeak tank filled close to Singapore. After some oscillations during the first few days, there was a strong decrease resulting in an about 90 % reduction in cell number on the tenth day after departure. The bulk were diatoms of which 30 species were identified at the beginning, whereas dinoflagellates, represented by 13 species, started with a much lower concentration and disappeared on day 13.

On arrival in Bremerhaven after a 23 day cruise, only 4 species of diatoms had survived.

Zooplankton exhibited a similarly sharp decrease in the aftpeak tank as phytoplankton. Of 24 taxa recorded on the second day after filling, only 4 survived the cruise. These were a few specimens of the benthic harpacticoid copepod *Tisbe graciloides*, a turbellarian, a gastropod and a bivalve larva. Juvenile copepods constituted the predominant zooplankton component at the beginning. Their abundance decreased rapidly during the first 5 days (Figure 6b).

A similar decrease in diversity from 16 to 4 species was observed in the second tank filled after departure from Colombo on the way to Bremerhaven. Surprising in this case, however, was the observation that *Tisbe graciloides* had considerably increased in concentration after the 14 day cruise.

Figure 7 shows the temperature records for the 4 tanks with the sea surface temperature for comparison. Tank temperatures followed sea temperature with a delay of one to two days. It is interesting to note that apparently it was not the temperature drop that was responsible for the sharp fall in species number and concentration of phyto- and zooplankton observed in the aftpeak tank, as this occurred before temperature changed. Oxygen and pH showed comparatively little variation over the whole cruise. An over saturation of up to 126 % was recorded from the fourth to the seventh day, when the vessel was pitching and rolling due to an increased wind force of 6–7 Beaufort. Since the tank was not completely filled, the overlying air was mixed into the water, leading to the observed over saturation with oxygen. Although the rolling of the water in the tank could have had an adverse effect on delicate plankton organisms, the main concentration drop (Figure 6a, b) had already occurred before, so that this effect can also be ruled out. A third possible explanation could lie in the organisms having been damaged through the pumping system, causing a subsequent high mortality.

The transition from warm to cold temperature will generally harm ballast water organisms to a lesser extent than the other way round, since a temperature decrease is physiologically easier to tolerate than an increase. To show how strong the temperature increase is that ballast water organisms may be exposed to the seasonal change of sea surface temperature during a cruise from the west coast of North America to northern Europe and vice versa is shown in Figure 8. The year-round high tropical temperatures met in passing the Panama Canal will probably in most cases act as a barrier for the transport of boreal and temperate organisms from one area to the other.

Discussion

The investigation of ballast water tanks and hulls of ocean-going vessels for the presence of living organisms as proof of a possible transfer mechanism by which non-indigenous species are able to establish themselves in foreign ecosystems is the first step in assessing the ecological and also economical risks involved. Therefore after the pioneer work by Carlton (1985) on many organisms and that by Australian researchers on phytoplankton (Hallegraeff *et al.*, 1988, 1990; Hallegraeff and Bolch 1991, 1992), further studies in other countries were initiated, e.g. in Canada (Subba Rao *et al.*, 1994).

Investigation of ballast water proved, however, much more difficult than initially thought. The main problem is opening the manhole of a tank for adequate sampling. During our study, we only succeeded a few times in persuading a ship's crew to open a manhole. Since we had no official backing from local governmental or harbour authorities, we first had to politely approach shipping agencies and shipyards before being allowed to take samples at all. The two other sampling methods employed, handpumping through sounding pipes and tapping of the pump system, constitute a compromise which did not work satisfactorily in all cases.

More information on environmental conditions in ballast water tanks and on survival of organisms will help to evaluate the risks of transport (Rigby and Hallegraeff, 1994). Following the fate of the organisms from ballasting to deballasting through repeated checking of the conditions on board will yield interesting results. Our study showed a rapid decline of plankton concentration during the first days after filling the tanks. The reason, however, is not yet clear.

The second step in evaluating the ecological and economic risk involved in transporting non-indigenous species by ship traffic is to study their geographical distribution and range of tolerable environmental conditions, their trophic relationships and behaviour by means of a thorough literature review. If experimental conditions permit, it may in some cases be possible to successfully culture such organisms in the laboratory for conducting detailed studies on their ecological tolerance during their life cycle.

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We thank the Federal Environmental Agency, Berlin for funding this project and Dr. A. Kunitzer for her advice as well as all shipping companies, agencies, dockyards, port offices and ship crews who kindly supported this project. Technical help and information were given by Dr. M. Rolke (Bundesamt für Seeschiffahrt und Hydrographie), H. J. Golchert (Verband Deutscher

Reeder) and Germanischer Lloyd. This paper is partly based on a doctoral thesis by S. Gollasch, Fachbereich Biologic, Universitat Hamburg, Germany.

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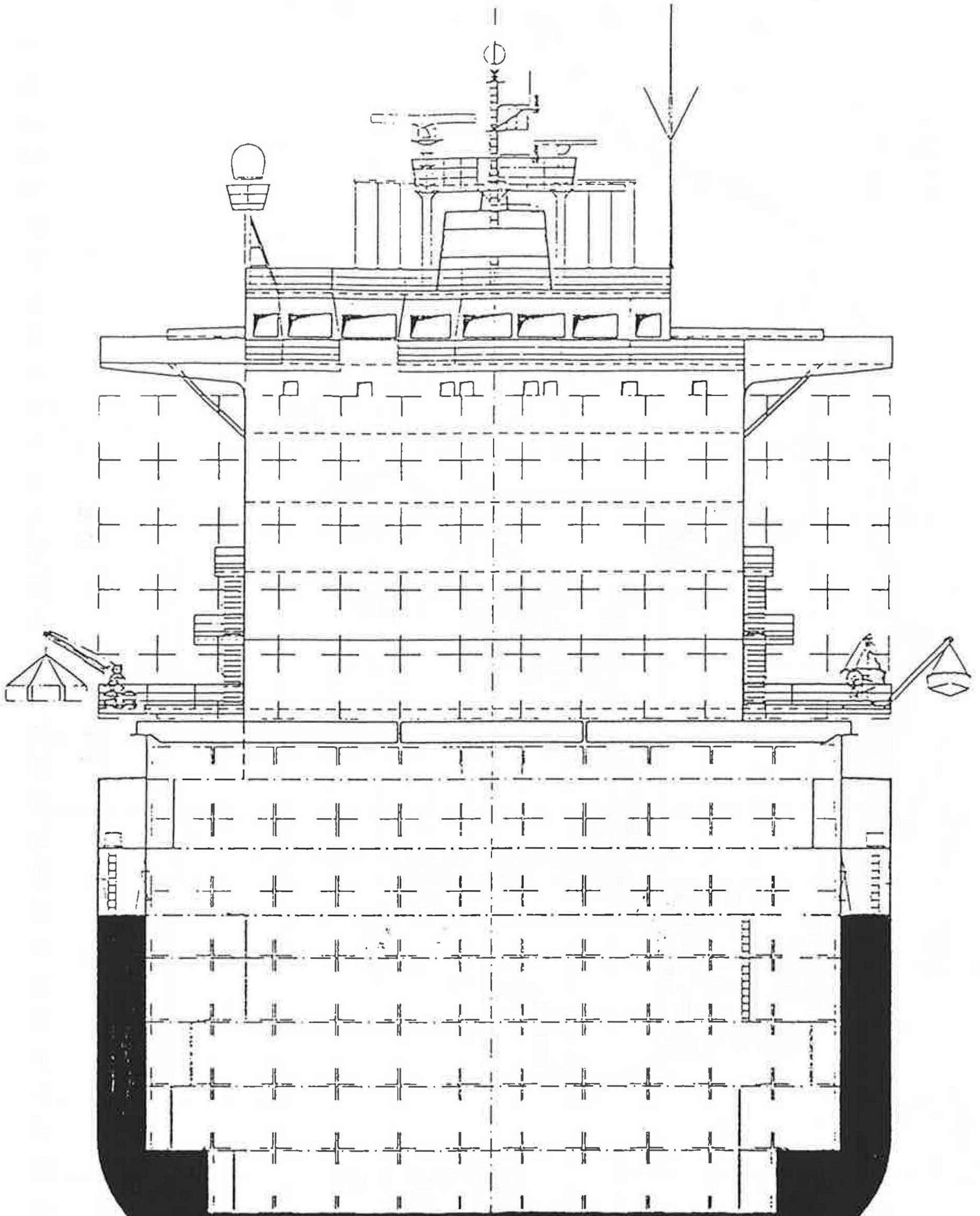

Figure 1 Schematic cross-section through a modern container vessel showing the position of the ballast water tanks (shaded).

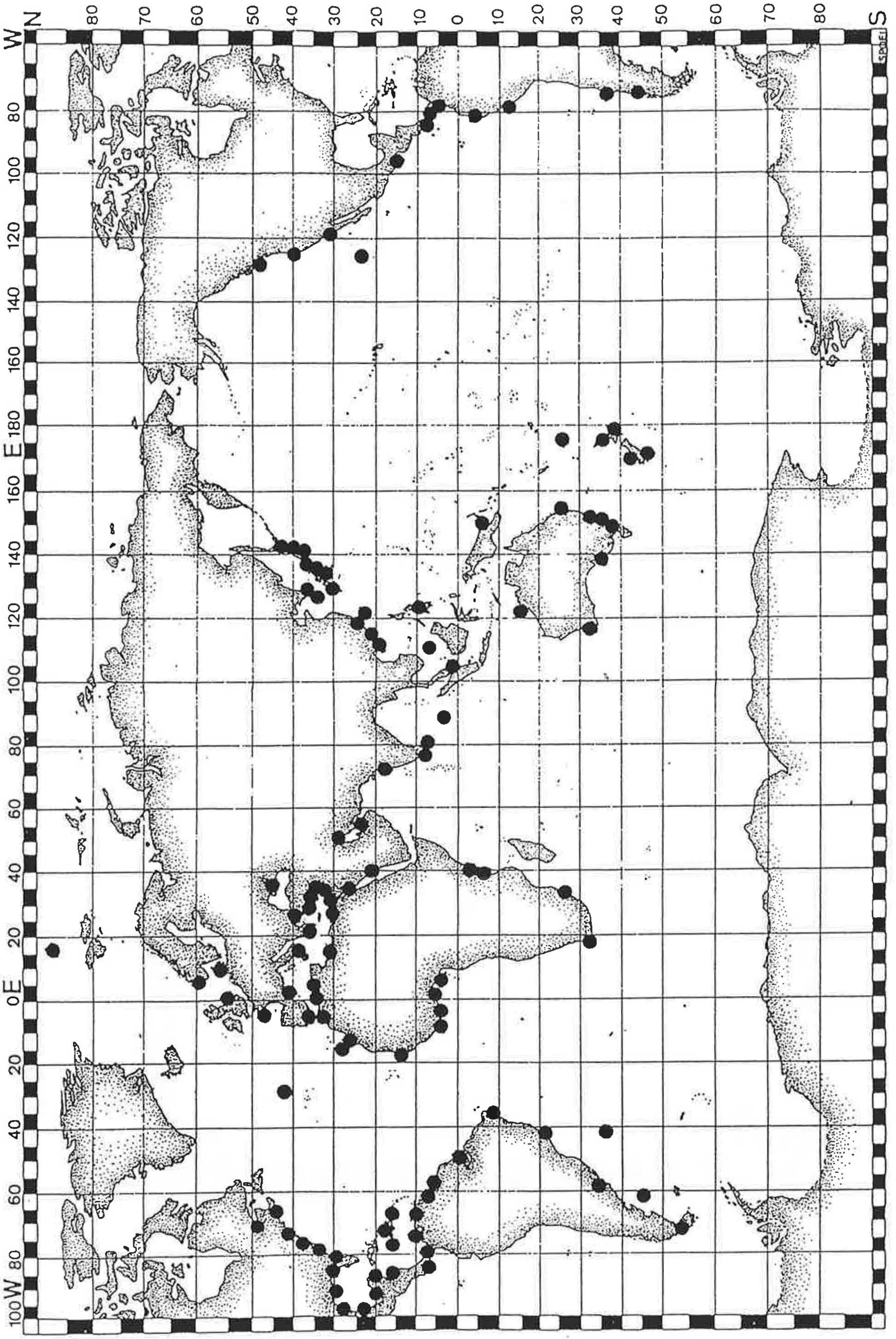

Figure 2 Geographical origin (departure ports) of vessels investigated.

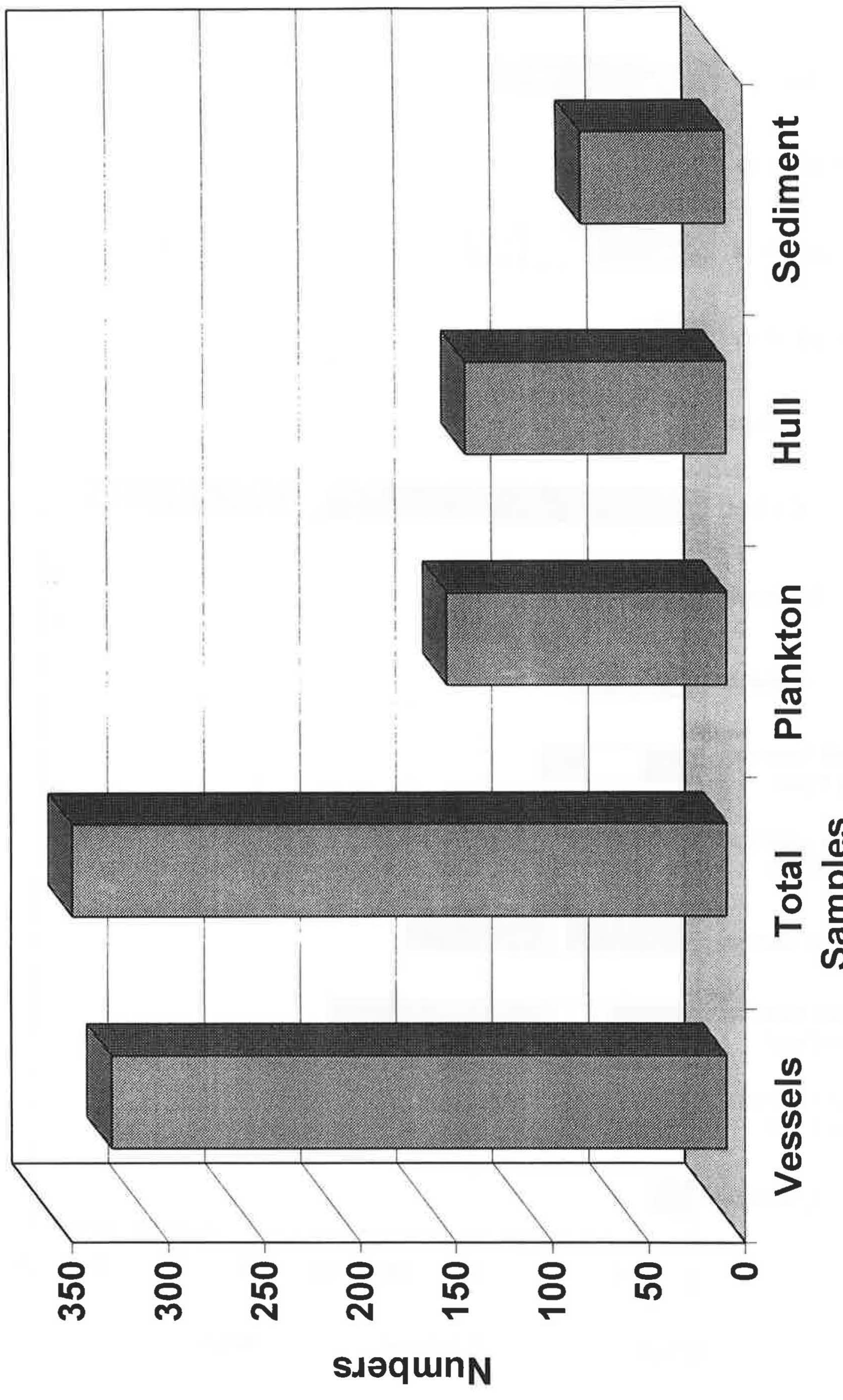

Figure 3 Number of vessels investigated, total number of samples and specification of samples (March 1992–July 1995).

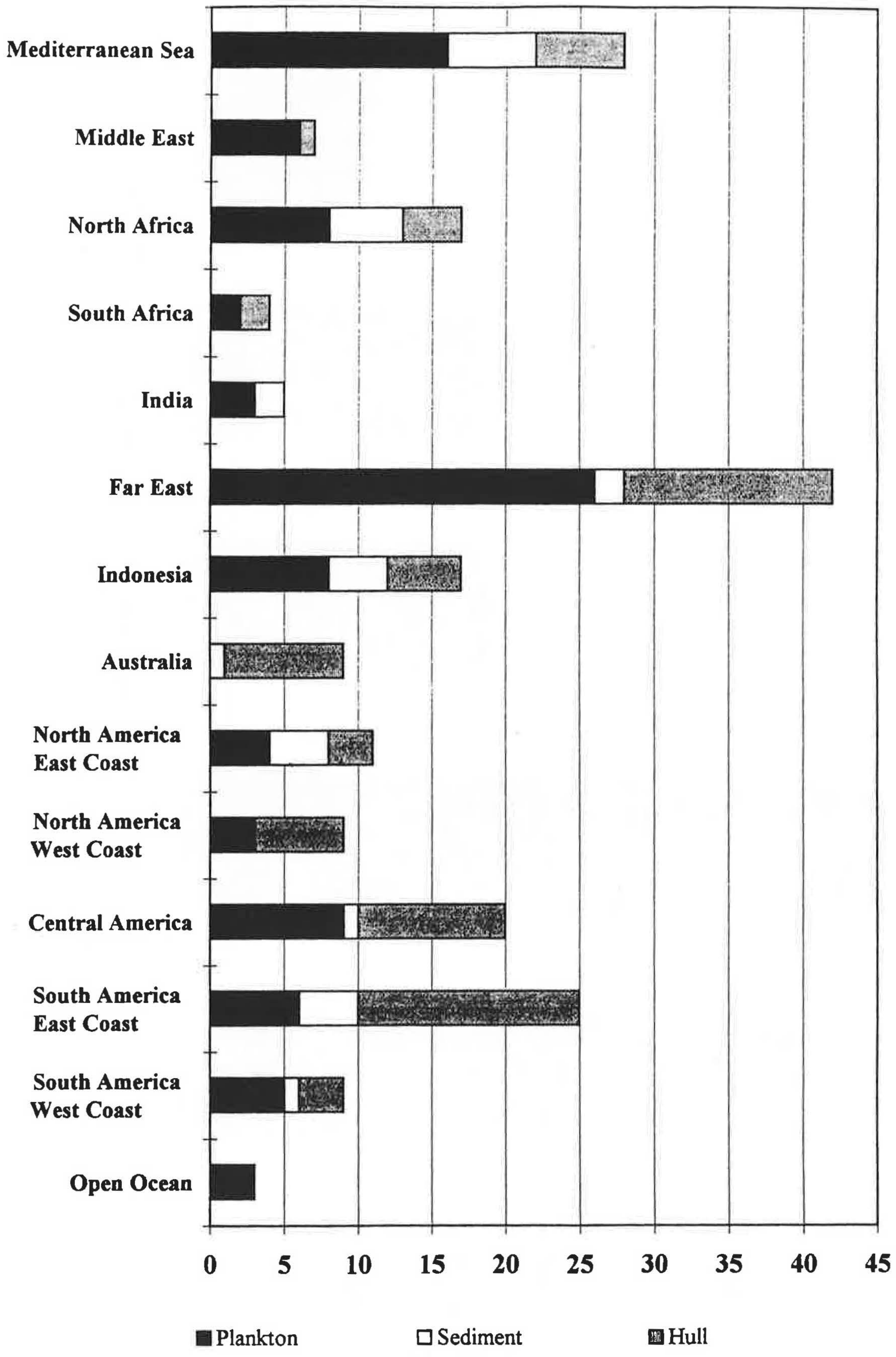

Figure 4 Number of plankton, sediment and hull samples according to their geographical origin.

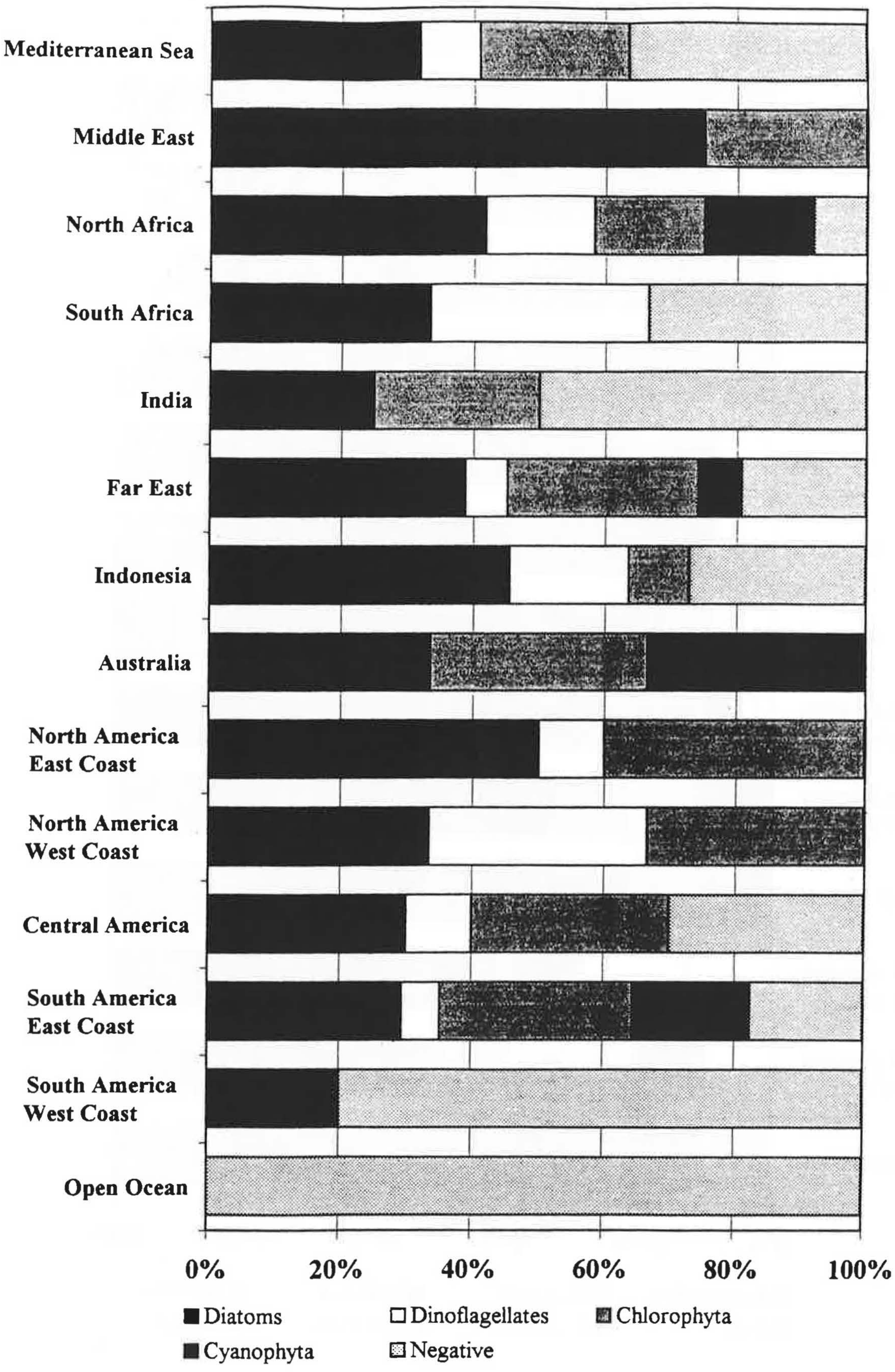

Figure 5a Unicellular algae present (%) in ballast water samples according to their geographical origin.

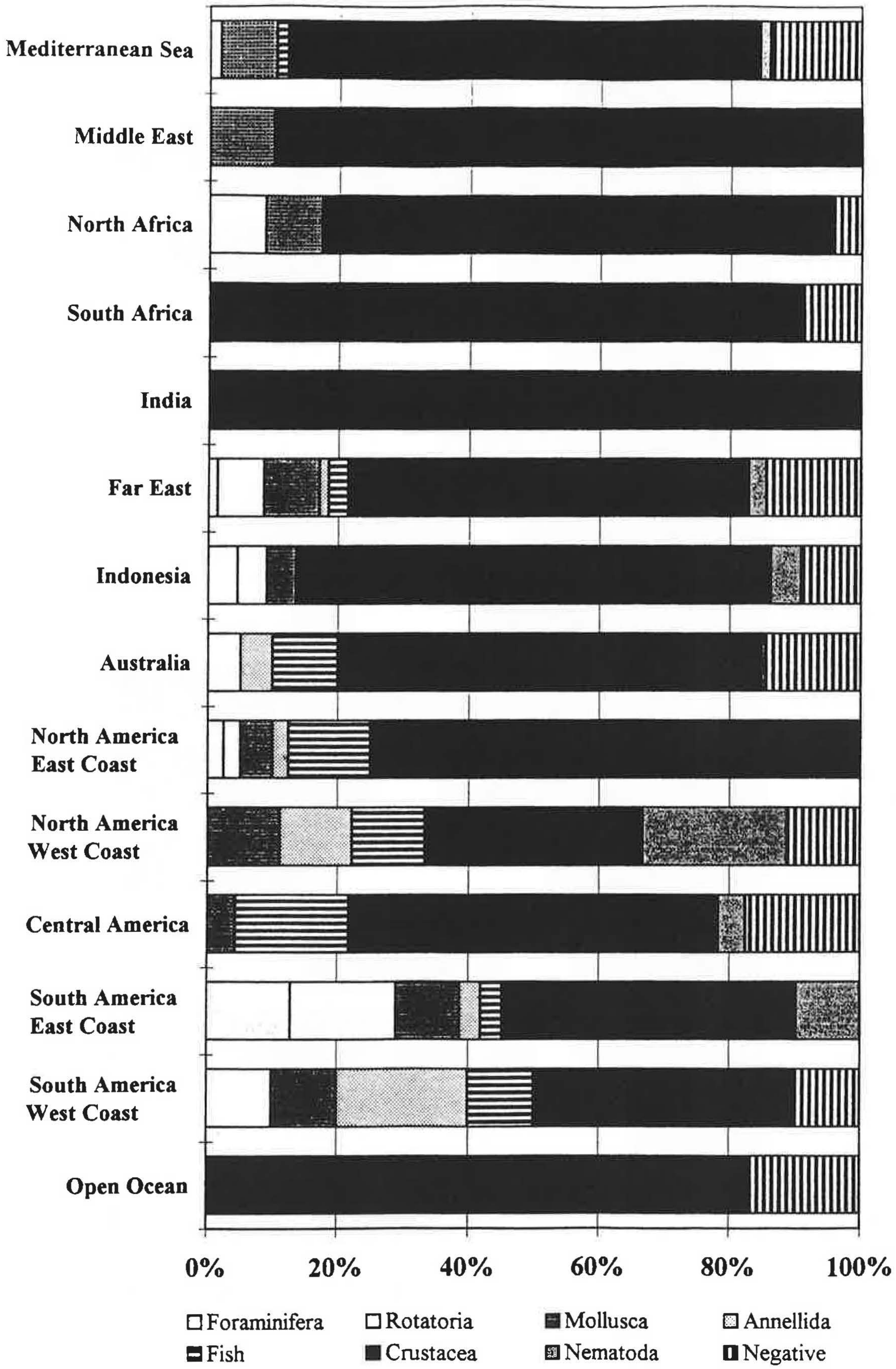

Figure 5b Organisms present (5) in ballast water samples according to their geographical origin.

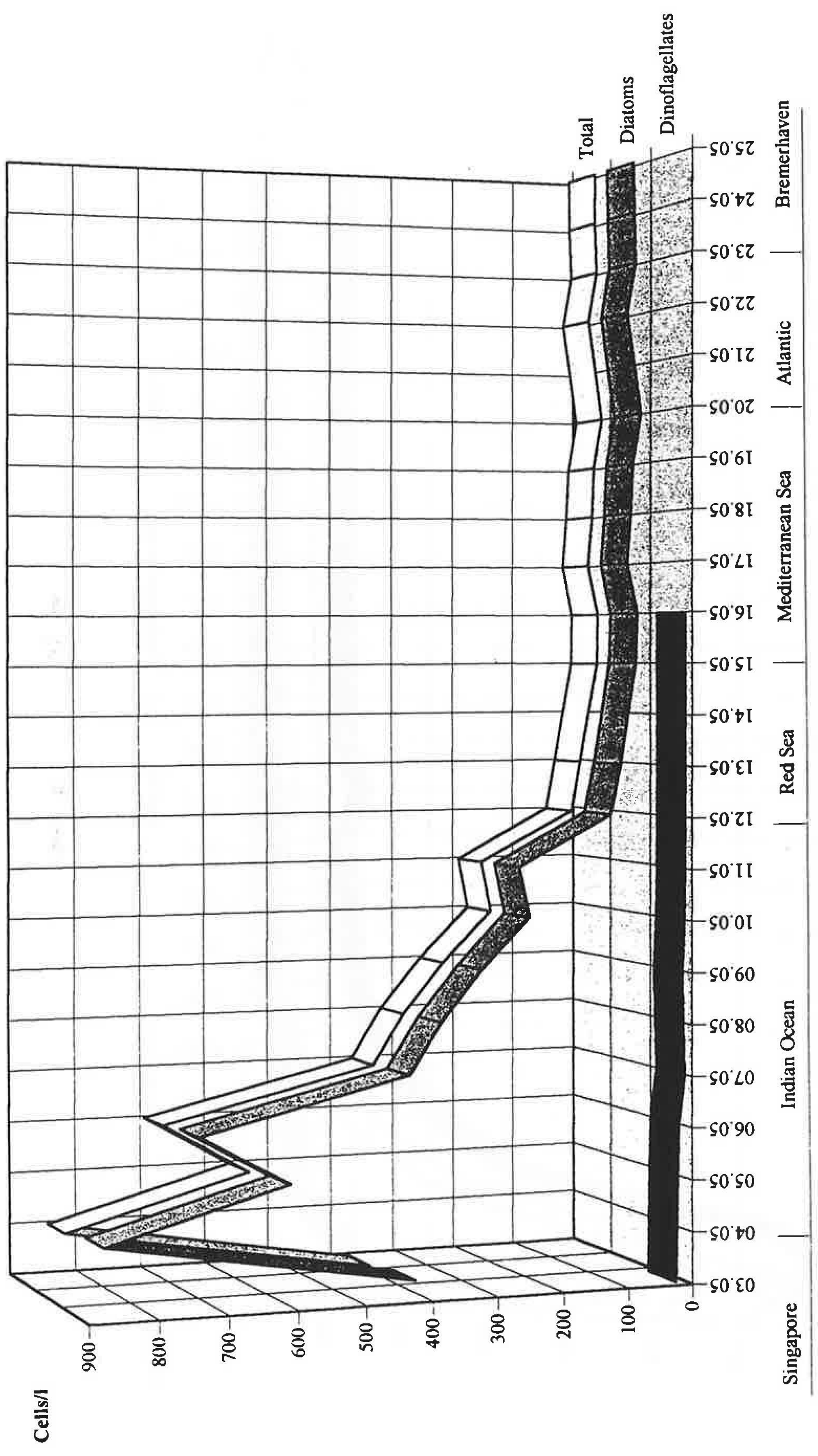

Figure 6a Concentration of phytoplankton cells in the aftpeak ballast water of 'DSR-America'.

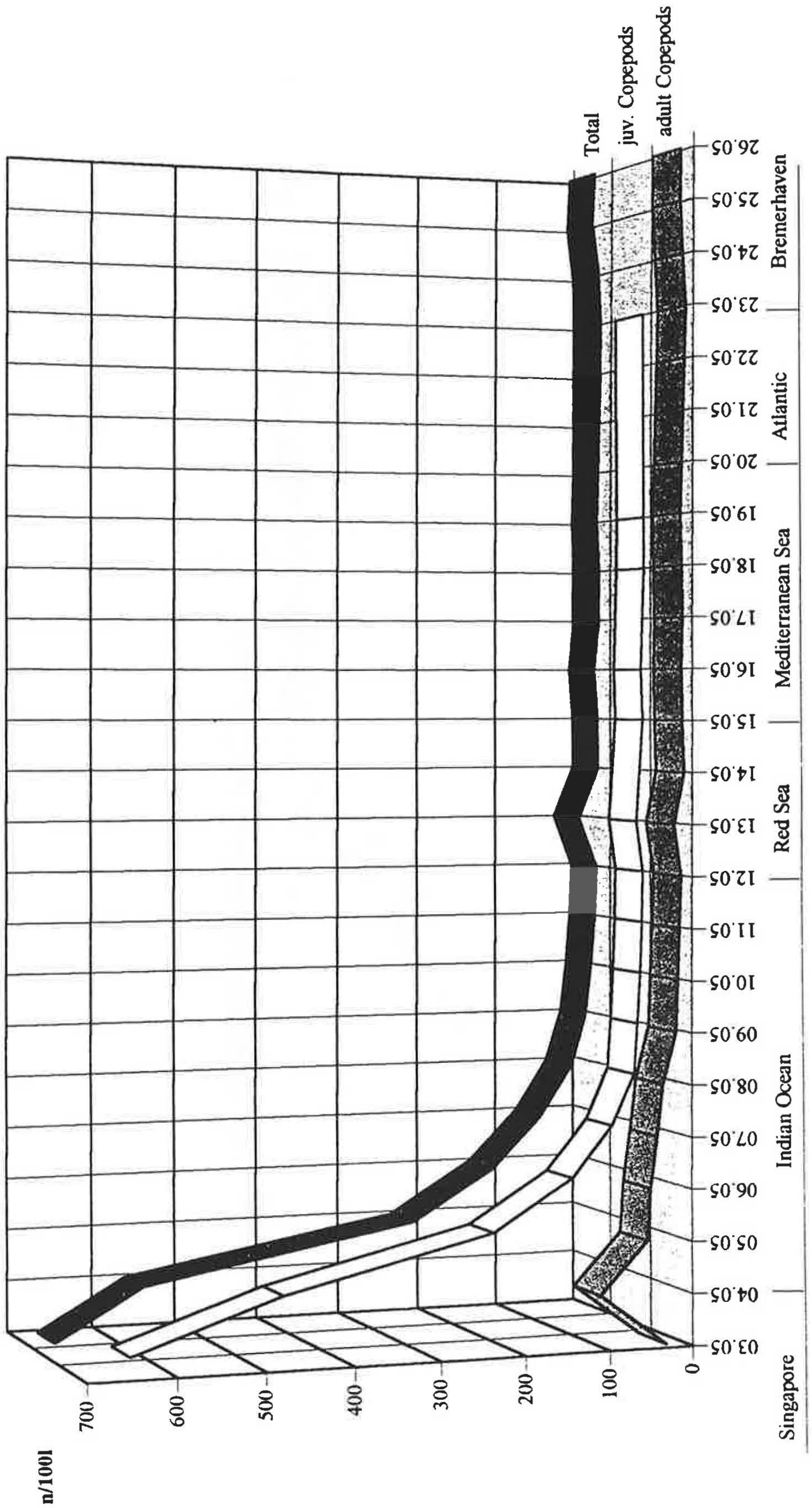

Figure 6b Concentration of zooplankton organisms in the aftpeak ballast water of 'DSR-America'.

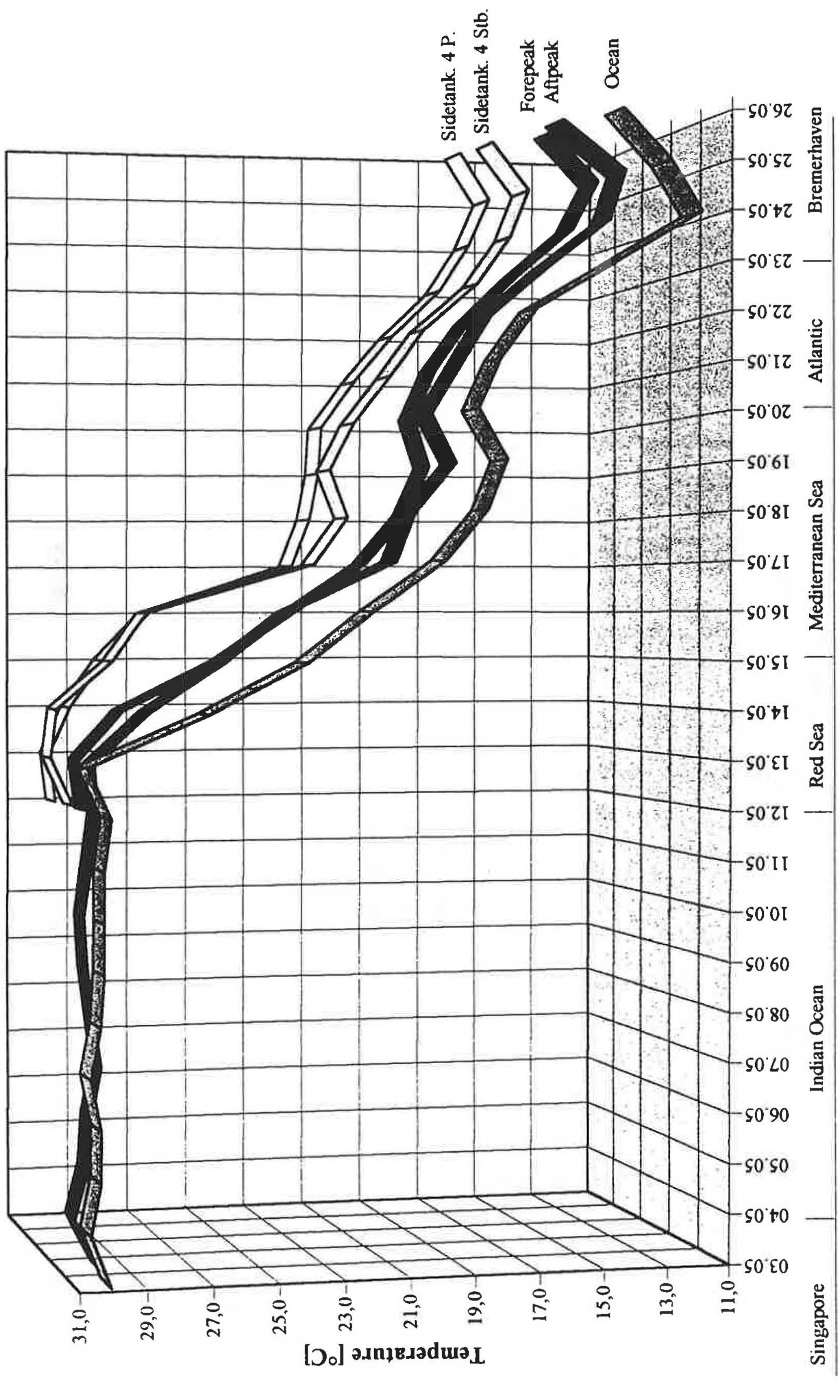

Figure 7 Temperature variation in different ballast tanks and the open ocean during the cruise from Singapore to Bremerhaven on board the 'DSR-America'.

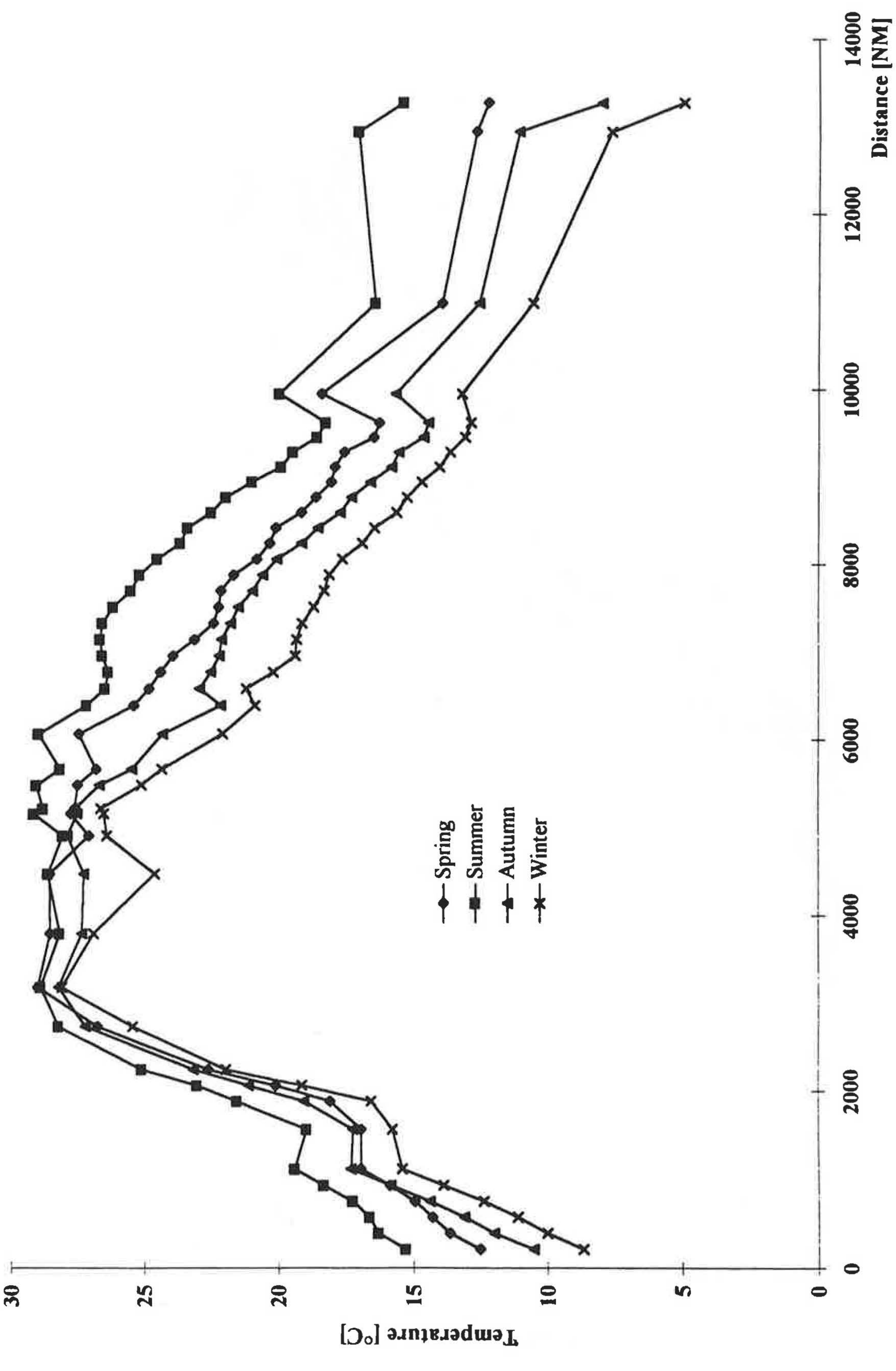

Figure 8 Seasonal mean ocean surface temperature along the shipping route from NW-America (Vancouver) to NW-Europe (Bremerhaven). Data from Climatological Atlas of the World Ocean, NOAA 1983.

A New Zealand perspective on ballast water

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The New Zealand economy is dominated by bulky exports of primary products such as meat, dairy and forestry products and, because large oceans separate New Zealand from all its trading partners, we are almost totally dependent on shipping to sustain our economy. We have thousands of kilometres of unpolluted coastline and maintenance of our high water quality and natural biodiversity are major concerns of all New Zealanders especially those involved in environmental organisations and the seafood and tourist industries. Therefore the unintentional introduction of exotic organisms as a result of ballast water discharges is regarded with concern. Voluntary Controls on Ballast Water Discharges have been operating in New Zealand since March 1992. These request vessels entering New Zealand waters to either exchange their ballast water in mid-ocean before discharge, to treat it before discharge or to refrain from discharging if at all possible. Eighty nine percent of vessels larger than 500 tonnes claim to comply with the controls. Although the controls are voluntary, New Zealand authorities have the ability under an Act of Parliament to ban the discharge of ballast water from a vessel if the ballast water is considered a risk to existing flora and fauna.

Introduction

The unintentional introduction of exotic organisms as a result of ballast water discharges is regarded with concern in New Zealand for several reasons. Large oceans separate New Zealand from all its trading partners and, because our main exports are bulky primary products such as meat, dairy and forestry products, we are almost totally dependent on shipping to sustain our economy. That reliance on primary industries makes us particularly vulnerable to exotic invasions, whether they be aquatic or terrestrial. Therefore we cannot afford to ignore the ballast water problem.

Secondly, New Zealand is a relatively small country -- similar in area to the United Kingdom but unlike the UK where there are approximately 600 people per square mile, New Zealand is sparsely populated with only 30 people per square mile. The low population density coupled with the absence of a significant heavy manufacturing sector means that New Zealand has thousands of kilometres of unpolluted coastline. Maintenance of that high water quality and natural biodiversity are major concerns of all New Zealanders especially those involved in environmental organisations and the seafood and tourist industries. New Zealand's image as a clean and green country is widely used, and therefore fiercely defended. In other words, New Zealand recognises that it has much to lose by ignoring the ballast water issue.

The New Zealand Ballast Water Working Group

A New Zealand Ballast Water Working Group (BWWG) was established in 1988 that comprised representatives from research institutes, regional councils, port companies, fishing and shipping industries, and government departments. The Group is chaired by the Ministry of Agriculture and Fisheries Regulatory Authority (MAF RA) which develops policy and standards related to the importation of plants and animals and their associated pests and diseases. MAF RA was seen as the most appropriate agency to develop guidelines to mitigate the risk of introduction of unwanted organisms in ballast water. This is because it is responsible for quarantine issues and because it already has inspectors who visited every international vessel at its first, and each subsequent, New Zealand port of call.

The New Zealand voluntary controls on ballast water discharges

Voluntary ballast water guidelines for vessels in New Zealand territorial waters were developed and introduced in 1992. These were based on the International Maritime Organization's (IMO) "Guidelines for Preventing the Introduction of Unwanted Aquatic Organisms and Pathogens from Ships' Ballast Water and Sediment Discharges" and the Australian Quarantine and Inspection Service's guidelines "Controls on the Discharge of Ballast Water and Sediment from Ships Entering Australia from

Overseas". Modifications were made to allow for data collection and to reflect the New Zealand situation. The main features of the New Zealand controls are:

1. If possible, ballast water should not be discharged within New Zealand.

2. If ballast water has to be discharged then it should be ballast which has been exchanged or loaded in the open ocean. Details of the exchange, and the original source of the ballast water, must be provided to an inspector. Ballast water, which has been loaded within the territorial waters of another country, cannot be discharged without reporting it to an inspector prior to discharge. An option is also available where the master can provide a certificate from the relevant overseas authority certifying that the ballast water is clean.

3. Ballast water may be discharged if there is documented evidence to show that the ballast has been disinfected. To date, no vessel has provided such evidence although an occasional vessel has provided evidence that it has taken on town supply water as ballast.

4. If none of the above three options can be fulfilled then the master has the option to discharge ballast in an approved area of New Zealand or to an onshore facility, to treat the ballast, or to have the ballast tested to show it is not a risk. Currently there are no specific areas approved as ballast dumping areas nor any onshore facilities and no vessel has used this option.

5. No sediment or mud from the cleaning of the holds or ballast tanks, or anchor or chain lockers can be landed in New Zealand waters without the permission of an inspector. This clause of the controls is mandatory because satisfactory alternatives to dumping sediment in the sea exist e.g. by disposal in a landfill not immediately adjacent to the sea.

6. It is recognised that compliance with these controls has to be consistent with the safety of the crew and the vessel, and that responsibility must lie with the Master of the vessel.

The Biosecurity Act 1993

Legislation and prosecution are only part of the process of minimising the risks associated with ballast water. NZ also has an Act of Parliament, the Biosecurity Act, 1993, which contains all the powers likely to be required in order to enforce any aspect of ballast water policy that the New Zealand government chooses to apply. In the Biosecurity Act, the term "risk good" is defined as any organism, organic material, or other thing that (by reason of its nature or origin) it is reasonable to suspect to constitute, contain, or otherwise pose a risk that its presence in New Zealand will result in:

a) Exposure of organisms in New Zealand to damage, disease, loss, or harm; or

b) Interference with the diagnosis, management, or treatment in New Zealand, of pests or unwanted organisms.

Therefore, if an inspector "reasonably suspects" that ballast water arriving into New Zealand poses a risk to the flora and fauna already in New Zealand, then the ballast water can be declared a "risk good" and the powers of the Biosecurity Act used. The inspector does not need to know if a particular unwanted organism is present. He or she only needs to suspect that the ballast water is a risk good according to the above definition.

Sections of The Biosecurity Act permit enforcement of ballast water policy in the following ways:

- The person in charge of a vessel going to New Zealand must give notice of the vessel's impending arrival time and location, and the vessel is compelled to go to that designated arrival place.

- The master must ensure that no risk goods leave the vessel without the permission of an inspector and can be required to pay a bond not exceeding $10,000 to ensure compliance.

- The master is legally compelled to obey any reasonable direction relating to the discharge of ballast water and movement of the vessel and must provide written information on the ballast status of the vessel.

- An inspector may board a vessel in New Zealand territory and require that the risk goods be dealt with in a particular manner, may require the vessel to leave New Zealand territory or may seize (in a legal sense) the risk goods.

- The penalties for non-compliance include imprisonment for up to five years and fines up to $200,000.

While there are adequate powers in the Biosecurity Act 1993 to deal with the ballast water issue, there is currently only limited use of it as an enforcement mechanism. That situation is unlikely to change markedly until there are more effective, safe, practicable, economically sound and environmentally acceptable options for dealing with ballast water. At present the Act is used only:

i) to ensure that masters of vessels provide correct written information about their ballasting operations,

ii) to prevent the discharge of sediment and tank cleaning residues in New Zealand waters, and

iii) to prevent the discharge of Tasmanian ballast water during the months when *Asterias amurensis* larvae may be in the water.

How do the voluntary controls and the biosecurity act work in practice?

When a vessel arrives in New Zealand, an inspector from the MAF Quarantine Services boards the vessel to carry out various quarantine functions including a check on the ballast water arrangements for the vessel. The master is required to complete a "Vessel Ballast Report Form" which includes details of compliance with the Voluntary Controls on Ballast Water Discharges. This form is generally completed at the first port of entry into New Zealand but is updated if necessary as the ship moves around the coast. At the final New Zealand port of call the report form is removed from the vessel and put on a database.

Since the introduction of the Voluntary Controls in March 1992, the mean number of vessel visits to New Zealand has been 1,860 per year (Figure 1). This figure may include some vessels which visited New Zealand more then once per year. The estimated average ballast capacity of these vessels was 8.7 million tonnes per year (shaded columns in Figure 1). This figure was estimated by multiplying the total dead weight tonnage (DWT) of each ship type by the average ballast capacity of each type of ship under normal (light) ballast condition (Kerr, 1993). Vessel types included in the calculation were bulk (including woodchip) carriers, tankers (oil and refined products, chemical and liquefied gas), car carriers, container, general cargo and roll-on-roll-off (RoRo) vessels. Vessels such as passenger ships and fishing vessels that carry minimal quantities of ballast water were not included in the calculation.

Based on the claims made by ships' masters on the VBR forms, less than half of the estimated volume of ballast water going to New Zealand is actually discharged there. On average, 4.7 million tonnes of ballast water are discharged in New Zealand annually (Figure 2). This figure is derived from the proportion of vessels which have not complied with the New Zealand's voluntary ballast water controls (MAF, 1992) and those that claim to have complied by exchanging their ballast water before discharge. The major portion of ballast water discharged has apparently been exchanged before discharge (striped sections in Figure 2).

Of the 1,860 vessel visits each year, an average of 89.5% of vessels claim to comply with the voluntary ballast water controls by either exchanging their ballast before discharge or by not discharging it at all (Figure 3). The percentage of vessels that exchanged their ballast prior to discharge has increased during the three years. During this time controls have been in place while the percentage able to withhold discharge has decreased. The percentage of vessels that admit to not complying with the controls has also decreased over the three years. These are interesting trends but without more detailed information, one can only guess at the possible causes.

Although some very large vessels have visited New Zealand in the last three years, the majority of vessels (97%) were smaller than 50,000 tonnes. Figure 4 shows the extent of compliance with the voluntary controls by different sizes of vessel. It has been reported in several publications that mid ocean exchange may be unsafe for vessels larger than 40,000 tonnes deadweight. The right hand portion of Figure 4 indicates that even though mid-ocean exchange is not always safe for very large vessels, many are managing to do it.

The solid bars in Figure 4 indicate the proportion of vessels that admit to not complying with the voluntary controls. It is interesting to note that it is not the very large vessels that are failing to comply with the controls. In fact the number not complying increases as vessel size decreases. The reasons for this need investigating. Are the companies that operate larger vessels more committed to developing alternatives to direct discharge? Is there a perception among smaller vessels that because they discharge less ballast they present less of a threat? Or is there a genuine technical reason e.g. are the smaller vessels more difficult to modify to allow exchange?

These data are based on the word of the ships' masters only so we do not know their accuracy. We also do not know how thoroughly the exchange or flushing process has been. We hope that the voluntary controls have significantly reduced the volume of contaminated ballast water being discharged into New Zealand ports but will not know that until a strategy for evaluating their effect has been developed.

Research needs

New Zealand has recognised the need for a national ballast water research strategy which is linked with, and driven by, policy and management requirements so that the research outcomes will provide the scientific basis for decision making (The Royal Society, 1995). Key priority areas for ballast water research were identified in a 1994 report (Hayden, 1994) which is likely to form the basis of New Zealand's research strategy. The report discusses research options aimed at minimising the risk to New Zealand in the short to medium term as well as research that will contribute to the international research effort to find totally effective long term solutions. The research requirements focus around two main questions:

1. What is the risk to New Zealand associated with ballast water?

2. Having identified the extent of the problem, what can be done about it?

Many countries, including our close neighbour Australia, have done a considerable amount of excellent research which is directly applicable to New Zealand and we have no intention of repeating relevant studies done elsewhere. Because of our proximity and similar latitude to Australia it is tempting to use their ballast water statistics as the basis for solving New Zealand's problem. However analysis of the VBR forms indicates a vastly different picture in New Zealand from that reported in Australia. Based on Kerr's (1993) estimates of the ballast water arriving in Australia in 1991, Australia receives approximately 2.6 times as many ship visits as does New Zealand but 14 times as much ballast water. The reason for the huge discrepancy is that in one year, Australia receives approximately 4000 visits from heavily ballasted bulk carriers. That is more than twice the total number of ship visits of all types per year to New Zealand. It is clear that our shipping patterns are very different from those in Australia. It is also clear that the volume of ballast water discharged in New Zealand is far less than in Australia and many other countries. This means that solutions are inappropriate in some countries because of the large volumes involved but may be viable options in some New Zealand ports. Thus we consider research to determine the nature and extent of the problem in New Zealand to be an essential first step towards finding solutions. All countries face this challenge if they are to develop solutions that are appropriate to their particular situation. However, the process is hampered by the urgent need for research into appropriate risk analysis techniques.

The second question, what can be done about the problem, can be addressed in two parts:

i) What can be done to improve management of the problem now? We consider it a priority to conduct research that evaluates the effectiveness of our current Voluntary Guidelines. They have been in operation in New Zealand for more than three years now but we have no idea how effective they are. Because they are based on the IMO guidelines, such an evaluation will be helpful at the international level as well.

ii) What can be done to develop more effective solutions for the future? There is ample evidence to show that there is rarely a cure for the effects of unwanted aquatic invaders - prevention is what must be strived for. This will be most effectively achieved by research into alternative ballasting systems for vessels and into technologies for treating the ballast which are safe, effective and economically viable. It is unlikely that a single generic solution will be possible. Rather a "tool box" of solutions is needed to suit the variety of vessel types and port conditions. International collaboration among scientists and shipping companies is essential for this type of research. Studies such as that conducted in Australia on the use of heat for treating ballast water (Bolch and Hallegraeff, 1993; Rigby and Hallegraeff, 1994) have shown that effective treatment options may be just over the horizon. Techniques for treating ballast water, either by themselves or in combination with other management practices, offer the best solution to the ballast water problem in the future. Such research should therefore be given highest priority.

Acknowledgements

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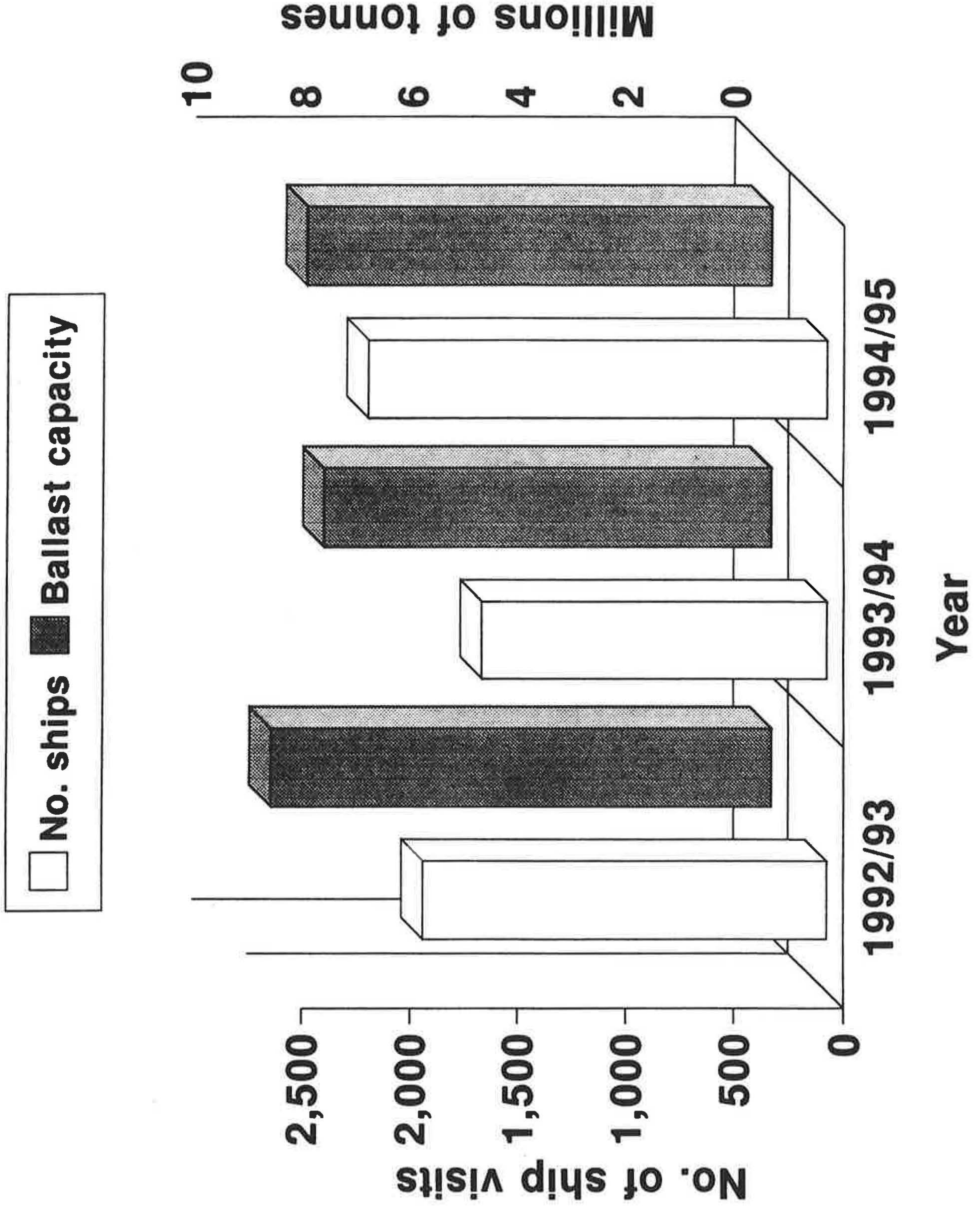

Figure 1 Annual number of vessel visits to New Zealand and their estimated ballast capacity.

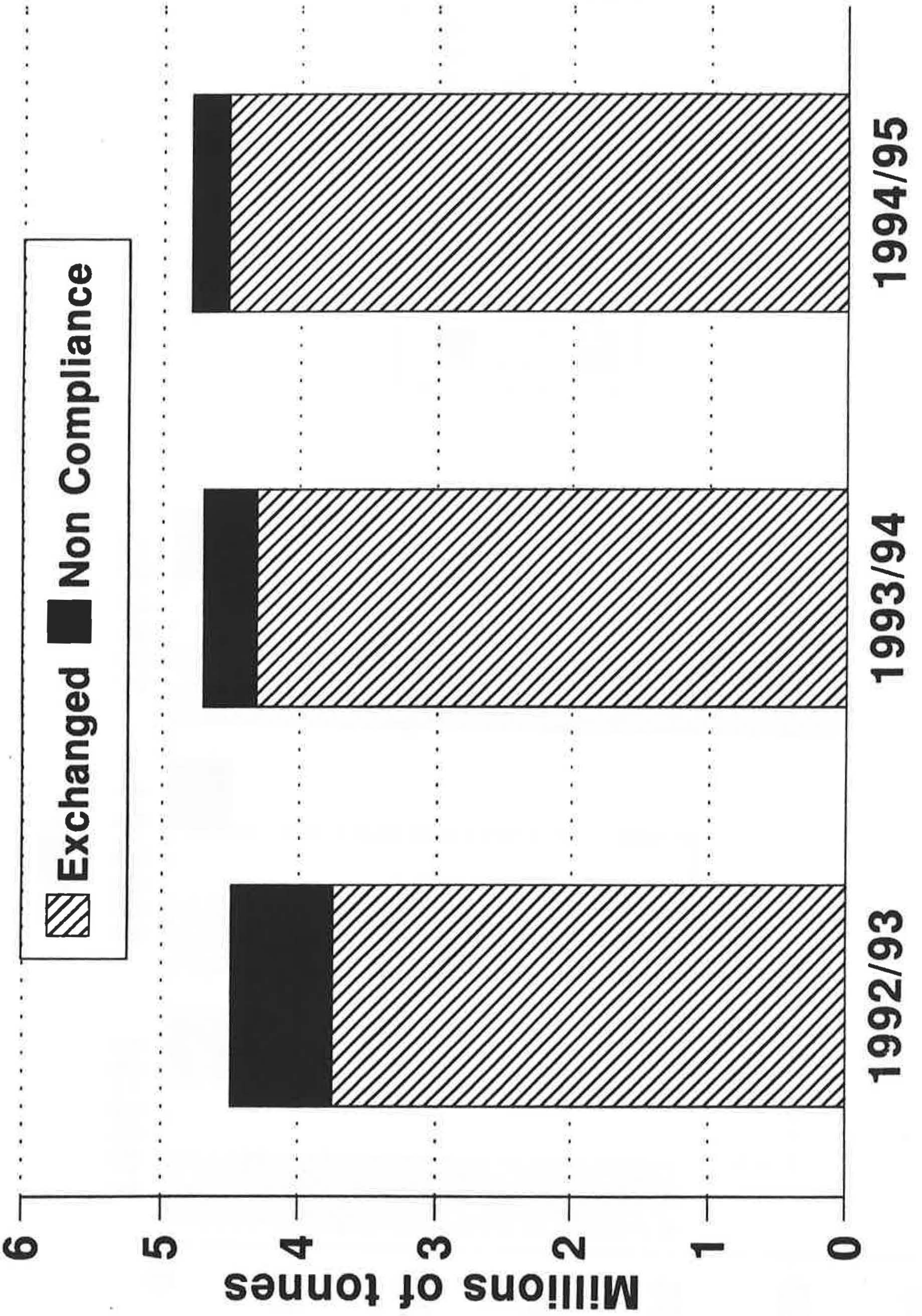

Figure 2 Estimated quantity of ballast water discharged in New Zealand.

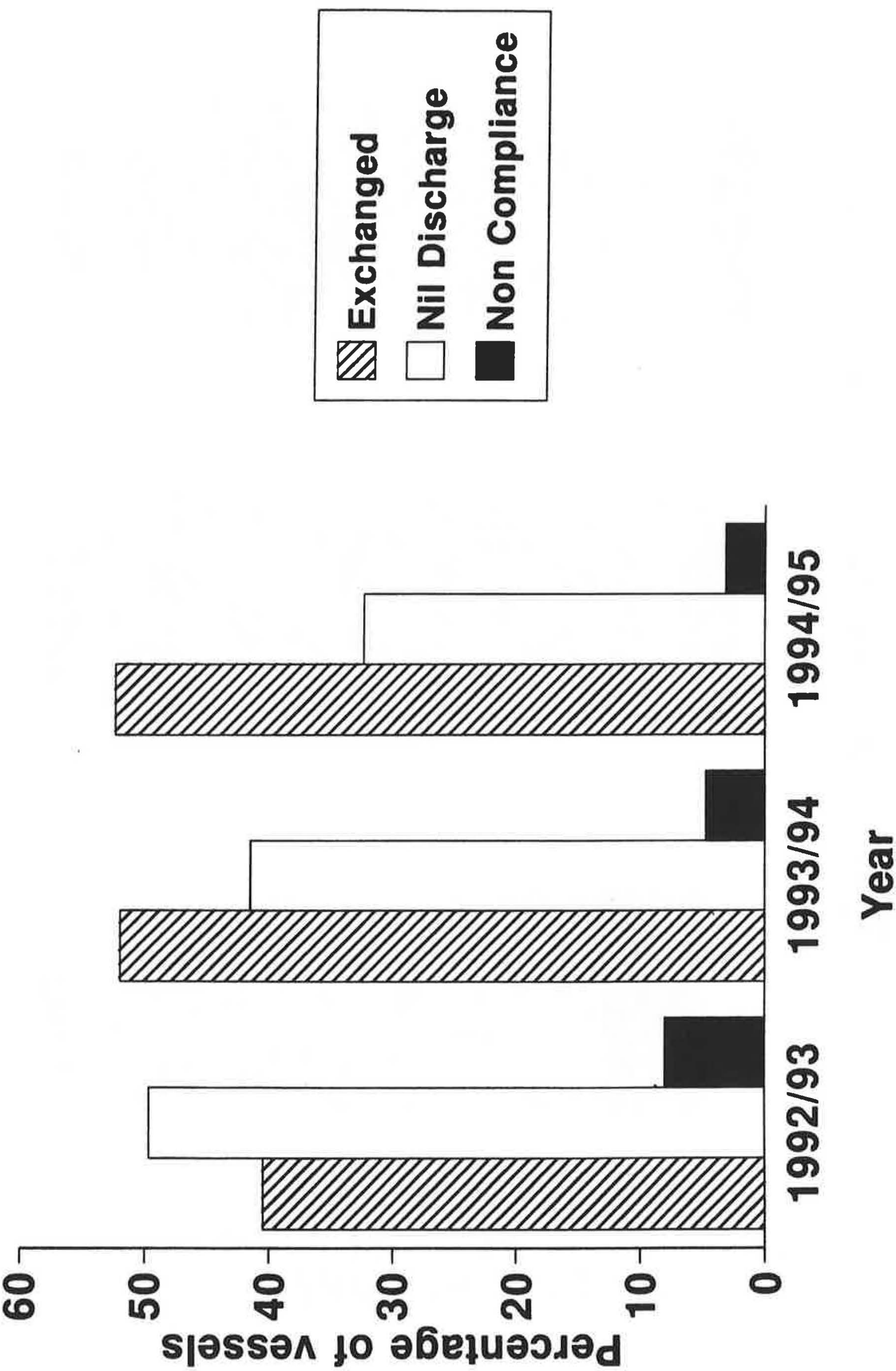

Figure 3 Percentage compliance with the Voluntary Controls on the Discharge of Ballast Water in New Zealand.

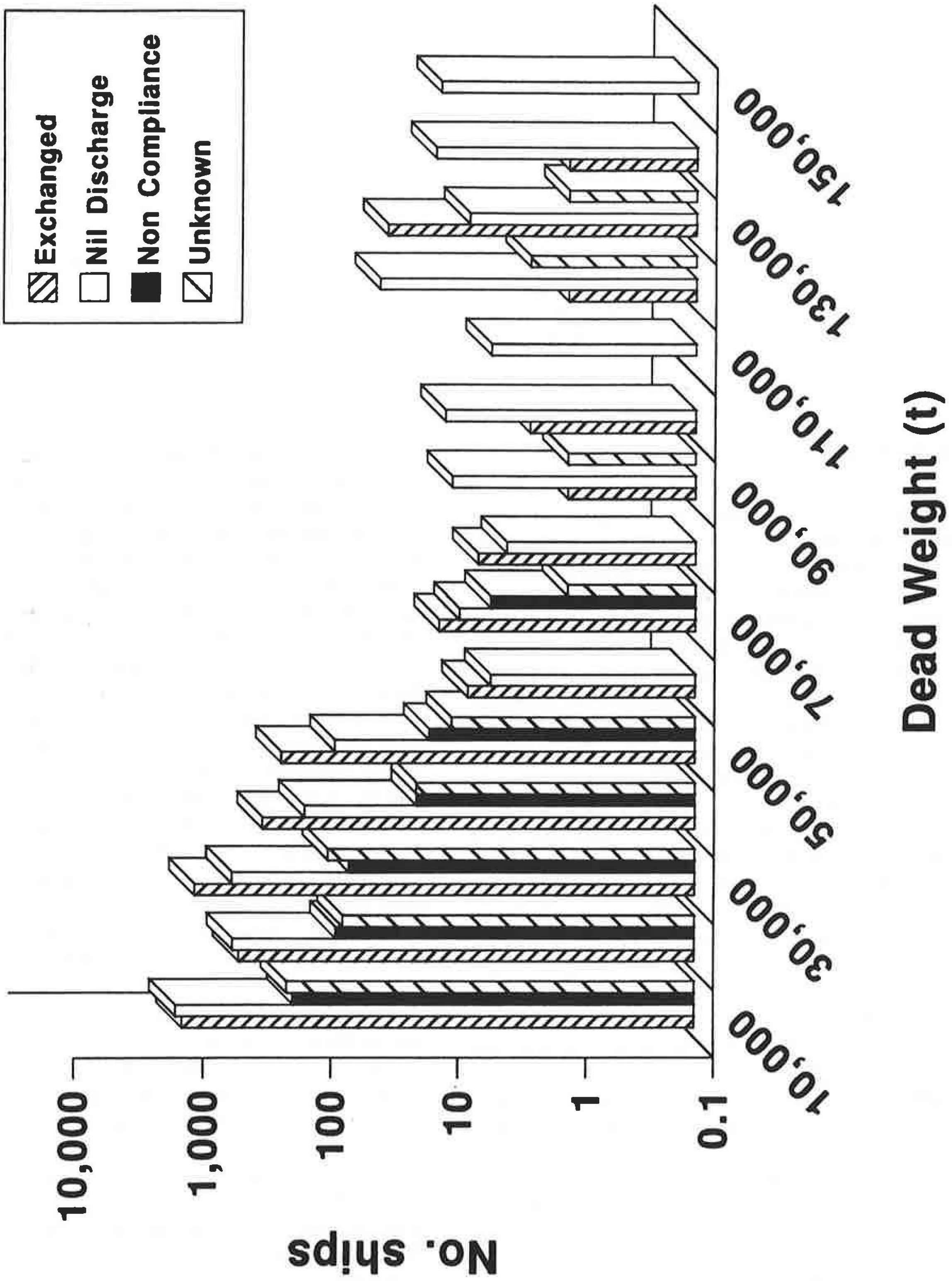

Figure 4 Comparison of vessel size and category of compliance with the Voluntary Controls on the Discharge of Ballast Water in New Zealand between March 1992 and February 1995.

Transport of toxic dinoflagellates via ships' ballast water: an interim review

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Toxic dinoflagellates are probably the best studied model organism to assess the bioeconomic risks of ballast water introduction of non-indigenous marine pests into Australian waters. A plausible scenario for their successful introduction and establishment includes: (1) ballast water intake during seasonal plankton blooms and to lesser extent via resuspended cysts in sediments from Japanese or Korean ports; (2) survival as resistant resting cysts during the ballasting process, the voyage in a dark ballast tank, and subsequent ballast water discharge (inoculation); (3) successful germination of cysts, sustained growth and reproduction of plankton cells in an Australian port; and (4) further spreading via coastal currents or domestic shipping, culminating under suitable environmental conditions in harmful algal blooms impacting on aquacultural operations (causative organisms of paralytic shellfish poisoning). Until we achieve international agreement and acceptance of a fully effective, safe, economically viable and environmentally friendly ballast water treatment option (heat treatment is actively being explored), an international warning network for algal blooms in ports appears to be an effective way to minimise risks. It is also recommended that aquaculture operations should be sited well clear from the ballast water influence of shipping ports.

The evidence

My interest in the problem of transport of toxic dinoflagellates in ship's ballast water was raised by alarming observations of an apparent global increase in the frequency, intensity and geographic distribution of paralytic shellfish poisoning (PSP) (Hallegraeff, 1993). This human illness (15% mortality) results from the consumption of shellfish products contaminated with alkaloid toxins from some 11 species of plankton dinoflagellates. While in a strict sense a completely natural phenomenon well known to native North American Indian tribes, until 1970 poisoning records were confined to temperate waters of Europe, North America and Japan. By 1990, PSP outbreaks were documented throughout the Southern Hemisphere, including South Africa, Australia, New Zealand, India, Thailand, Brunei, Sabah, the Philippines and Papua New Guinea (Figure 1). Similarly, in the Australian region PSP was unknown until the late 1980s when the first toxic dinoflagellate blooms appeared in the ports of Hobart (caused by *Gymnodinium catenatum*), Melbourne (*Alexandrium catenella*) and Adelaide (*Alexandrium minutum*) (Hallegraeff *et al.*, 1988). Explanations for this apparent global increase include increased scientific awareness caused by the developing aquaculture industry and stimulation of dinoflagellate blooms by increased coastal eutrophication. However, in a limited number of cases translocation of non-indigenous estuarine dinoflagellate species across oceanic boundaries (either via ship's ballast water or translocation of shellfish products) has to be invoked. Unambiguous evidence for the presence of viable toxic dinoflagellate cysts in ship's ballast water (up to 300 million cysts per ballast tank; both *Alexandrium* and *G. catenatum*; Hallegraeff and Bolch, 1992) as well as associated with shellfish stocks (Scarett *et al.*, 1993) is now available. However, to prove that a particular dinoflagellate population is non-indigenous is extremely difficult. For *Gymnodinium catenatum* in Tasmania such evidence has focused on an Australian -wide sediment survey for the distinct fossilisable resting cyst (Bolch and Hallegraeff, 1990; McMinn, 1991). Fossil cyst records of this species are absent from the whole Australian region. Recent cyst beds are confined to south-east Tasmania, and Pb210 -dated sediment cores from the Hobart region unambiguously demonstrate its sudden appearance around 1973 coinciding with the starting up of a new woodchip mill (Figure 2; McMinn and Hallegraeff, unpublished). The precise origin of the Tasmanian population is still unclear and is currently being traced by means of a global population study of toxin signatures (Oshima *et al.*, 1993), sexual mating compatibility (Blackburn *et al.*, 1989) and microsatellite molecular markers (Bolch and Hallegraeff, in progress).

Unfortunately, *Alexandrium* cysts lack resistant sporopollenin walls and hence do not leave a fossil record. In this case, the evidence has focused on elucidating population-specific small subunit RNA sequences which revealed a remarkable match between Japanese and Australian *A. catenella*, and between European and Australian *A. minutum* (Figure 3; Scholin *et al.*, 1995). The problem with such molecular evidence arises because of the slow rate of evolution of rDNA. Thus our current inability to date the "molecular clock", we cannot yet confidently distinguish whether matching molecular fingerprints are the results of thousands of years of natural dispersal along coastlines or anthropogenic translocations within the last 50 years.

In conclusion, while it may still be too early to take the Australian PSP evidence to the "International Court of Justice", the risk of ballast water introductions has been amply demonstrated and the "not doing anything" option is no longer acceptable. The Australian Government's position has been to attempt reducing quarantine risks rather than to aim for the near impossible task of complete elimination of the risks from introduced species. In this context, cyst-producing toxic dinoflagellates appeared to be useful model-organisms, based on the premise that any monitoring strategy or ballast water treatment technique capable of dealing with them most likely would also eliminate most of the other target species. The present review summarises the conclusions of 10 years of Australian research efforts on toxic dinoflagellate cysts in ballast water, supplemented by similar studies now underway in Europe, North America and Japan.

Scenario of successful ballast water introduction

There exist many hurdles for a toxic dinoflagellate to be successfully transported via ship's ballast water (Figure 4):

1) Ballast water intake during seasonal plankton blooms in a Japanese or Korean port.

In Australia, 85% of ballast water imports (a total 120 millions tonnes per year) derive from the Asian region, of which 54% originate in Japanese ports, with a further 34 million tonnes of ballast water transported in association with coastal shipping around Australia (Kerr, 1993). Toxic PSP dinoflagellates occur widespread in Japanese coastal waters: *Alexandrium tamarense* is found mainly in Northern Japan, *A.catenella* is found mainly in Southern Japan, while *Gymnodinium catenatum* occurs in the Seto Inland Sea and Yatsushiro Sea (Fukuyo, 1985; Matsuoka and Fukuyo, 1994). *A. tamarense* was first recognised in Korean waters in 1986 (Park, 1991), and our identification of *Gymnodinium catenatum* cysts in Korean ballast water samples represented a new record of this species for this region (Hallegraeff and Bolch, 1992), which was subsequently confirmed by cyst surveys in Chinhae Bay.

The probability of ballast water intake of toxic dinoflagellates is strongly dependent upon shipping patterns, seasonality of plankton blooms in overseas port waters and the presence of local sediment cyst beds. In both Japanese and Korean coastal waters, toxic dinoflagellate blooms tend to occur mainly in early spring to summer (March to June) and again in fall (September to November). However, bloom events vary considerably in magnitude from year to year, dependent upon water temperature and rainfall. In a survey of 343 cargo vessels, Hallegraeff and Bolch (1992) found that 65 % of ships contained ballast tank sediments . Of the sediment-containing samples, 50% contained dinoflagellate cysts and 5% contained toxic dinoflagellate cysts. The seasonality of ships arriving in Australian ports testing positive for toxic dinoflagellate cysts closely reflects the seasonality of overseas plankton blooms (Figure 5).

Cyst dormancy requirements confirmed that most ballast water cysts are derived from plankton blooms in the water column (estimated 90% of cases). Cysts often failed to germinate until about 6 months later, suggesting that they were newly formed cysts undergoing a mandatory dormancy period, rather than mature cysts resuspended from harbour sediments. Oshima *et al.*, (1992) traced a toxic dinoflagellate bloom from Muroran in Japan (40,000 cells L-1; July 1989) to Eden in Australia (300 million cysts in 25,000 t ballast water of a woodchip carrier), by matching up toxin fingerprints of Japanese dinoflagellate plankton, of ballast water cysts and of the germinated dinoflagellate cultures. In a limited number of cases, ships originating for example from Kure in Japan were found to carry toxic dinoflagellate cysts throughout the year which suggests that resuspended sediment cysts can be an additional source for contaminated ballast water (estimated 10% of cases).

2) Survival as resistant resting cysts during the ballasting process, the voyage in a dark ballast tank, and subsequent ballast water discharge.

Ballast water samples from ships arriving in 18 Australian ports (Hallegraeff and Bolch, 1992) as well as routine ballast water inspections made en -route during two voyages on the "Iron Whyalla" (Rigby and Hallegraeff, 1994) have been examined. These have shown that motile dinoflagellate cells usually do not survive long voyages in ballast tanks where they are exposed to darkness, high zooplankton grazing pressure and changing temperature and nutrient conditions. Such on-board or end-of-voyage phyto-plankton ballast tank observations are now available for ships travelling between Japan and Australia (Rigby and Hallegraeff, 1994; Yoshida *et al.*, 1995) and Japan and North America (Kelly, 1993), Japan and Canada (Rigby and Hallegraeff, 1994; Yoshida *et al.*, 1995) and voyages within Europe (Macdonald, this symposium). The major risk is posed by the resistant cyst stages (hypnozygotes) of dinoflagellates, such as *Alexandrium catenella*, *A. minutum*, *A. tamarense* and *Gymnodinium catenatum*. No cyst mortality can be expected to result from the ballasting process itself, and during the voyage grazing by zooplankton will not affect survival as the persistent cysts survive passage through the animals' guts and can be excreted in a viable form within their fecal pellets. Mortality would occur, however, if the cysts were to germinate and find themselves in the wrong environmental conditions. *Gymnodinium catenatum* cysts, formed in the plankton, will germinate within 2 weeks after formation (Blackburn *et al.*, 1989) and thus could suffer major mortality. In contrast, *Alexandrium* cysts, newly formed in the plankton, require a mandatory dormancy period of up to 6 months (Anderson, 1980) and hence are not exposed to this risk. Mature *Gymnodinium* or *Alexandrium* cysts, buried in harbour sediments where they are prevented from germination by anoxic conditions, would probably try to germinate when re-suspended during ship ballast water intake. Rapid burial within the anoxic ballast tank sediments would guarantee their further survival during the voyage.

3) Successful germination of cysts, sustained growth and reproduction of plankton cells in an Australian port.

For toxic dinoflagellates, which tend to occur in comparatively high concentrations, the volume of ballast water transported is not necessarily the best risk indicator. A viable inoculum could consist of approximately 1000 cells, and the frequency of ships' visits therefore more adequately reflects the risk of repeated ballast water discharges during different seasons. During 1991 the Australian Port Hedland received 407 visits, Hay Point 403, Newcastle 500, Sydney 171, and Hobart 26 (Kerr, 1993). Ballast water movements are most significant to the first three ports, but the climate match of ships entering Port Hedland (17%) and Hay Point (4%) is poor. In contrast, Newcastle (90% of ships coming from similar climates), Sydney (56%) and to lesser extent Hobart (85% match, but limited traffic) are exposed to more significant risks. Figure 6 summarises Australian ports where toxic dinoflagellates have been detected in ship ballast water samples. During and after the deballasting process in the Australian port, the cyst stages may be readily buried below the sediment surface from which they are gradually re-suspended into the water column. These cysts will attempt recurrent germination attempts over the next 10–20 years. When successful this will result in dinoflagellate blooms in the Australian port. Once it produces new cyst stages, it will have effectively colonised a new water body from which it cannot be eradicated. Accepting the sediment cyst evidence that indicates that *G. catenatum* was introduced into Tasmania around 1973 (soon after the opening of a new woodchip mill in 1971), it took another 8 years for the first bloom events to develop in its new environment in 1980.

4) Further spreading via coastal currents or domestic shipping, culminating under suitable environmental conditions in harmful algal blooms impacting on aquacultural operations.

Estuarine dinoflagellates are sensitive to water temperature, to lesser extent salinity, and often show associations with river plumes and rainfall events (contributing micronutrients and/or chelating humic substances; Hallegraeff *et al.*, 1995). The most meaningful approach to estimate the probability that introduced dinoflagellates can establish themselves in Australian ports, would be to look at dinoflagellate cyst assemblages in various Australian ports with particular attention to the presence of species which in other parts of the world are associated with *Alexandrium* or *Gymnodinium catenatum*. A further approach would be to compare seasonal temperature regimes in Australian and overseas ports. Of interest is the absence of toxic dinoflagellate populations in the Australian Ports of Hay Point and Port Hedland (Figure 7), despite the fact that cyst species of *G. catenatum* and *Alexandrium* have been repeatedly detected in ballast water samples discharged in these areas. In contrast, the port of Hobart which has insignificant shipping traffic has a disproportionally high number of introduced species (dinoflagellate *G.catenatum*, seaweed *Undaria pinnatifida*, starfish *Asterias amurensis* etc.). This illustrates the importance of matching port conditions in the successful establishment of introduced species. Domestic transport of viable *Alexandrium* and *Dinophysis* dinoflagellate populations has been documented by Gosselin *et al.* (1995) for short (<36 hr) voyages in the Gulf of St Lawrence region.

Ballast water management

Until we achieve international acceptance of a fully effective, safe, financially viable and environmentally friendly ballast water treatment option, prevention is better than to cure and a monitoring network warning about the possible contamination of ship's ballast water appears to be an effective way to minimise risks. Monitoring could be carried out:

1) at the overseas ballasting port, focusing on both the presence of toxic dinoflagellate cells and especially suspended cyst stages in port waters, at the precise depths from which ballast water intake occurs.

2) "en-route" during the 10–20 day voyage, focusing on toxic dinoflagellate cysts in ship's ballast tanks. Dependent upon cargo loading patterns, different tanks may contain water from different ports or mixtures from more than one port. The results of this on-board monitoring therefore have implications for the management of ballast water in situations where only one port may be contaminated. Various ballast water treatment options are best carried out at this stage. Options that have been successfully tried on toxic dinoflagellate cysts include reballasting at sea or continuous ballast water exchange (flushing) (Rigby and Hallegraeff, 1994), sterilisation with hydrogen peroxide (Ichikawa *et al.*, 1992; Bolch and Hallegraeff, 1993), heat treatment at 40-45°C (Bolch and Hallegraeff 1993; Yoshida *et al.*, 1995) and electric shock (Montani *et al.*, 1995) (Table 1).

3) Upon arrival at the receiving Australian port, and before commencement of deballasting. Unfortunately, the routine monitoring of toxic dinoflagellate cysts in ship's ballast water and sediments is at present severely hampered by the lack of a sensitive, rapid diagnostic test which can be used by untrained personnel. A significant recent breakthrough has been the development of a suitable fluorescent staining protocol (primuline) for *Alexandrium* dinoflagellate cysts (Yamaguchi *et al.*, 1995).The feasibility of a rapid diagnostic test, either based on immunological recognition of species-specific cell-surface proteins or using DNA probes to detect species-specific DNA / RNA sequences inside the target cells has been evaluated by Scholin *et al.* (1994). Until we achieve international agreement on a suitable ballast water treatment option, an international warning network for algal blooms in ports appears to be an effective way to minimise risks. It is also recommended that aquaculture operations and marine parks should be sited well clear from the ballast water influence of shipping ports. For too long, the shipping industry has had a virtually free ride on the world's oceans with grave environmental consequences for our precious coastal environments. Bulk cargo shipping therefore ought to be subject to strict "traffic" regulations, analogous to the strict limitations that apply to coastal or aquaculture developments.

Table 1. Treatment options for toxic dinoflagellate cysts

CHEMICAL	**Treatment**	**Species**	**Reference**
Chlorine	500 ppm, 24 hrs	*G.catenatum* cysts	Bolch & Hallegraeff 1993
Hydrogen peroxide	100 ppm, 96 hrs	*A.catenella* cysts	Ichikawa *et al.*, 1993
	150 ppm, 48 hrs	*Alexandrium* cysts	Montani *et al.*, 1995
	5000 ppm, 24 hrs	*G.catenatum* cysts	Bolch & Hallegraeff 1993
PHYSICAL			
Electric shock	100 V, 5 secs	*Alexandrium* cysts	Montani *et al.*, 1995
Heat	35°C, 30 min	*G.catenatum* motile cells	Marshall & Hallegraeff, unpublished
	35-37.5°C, 1-2 hrs	*G.catenatum* cysts	Marshall & Hallegraeff, unpublished
	40-45°C, 30-90 secs	*G.catenatum* cysts	Bolch & Hallegraeff 1993
	45°C, 3 mins flushing	*Alexandrium* cysts	Montani *et al.*, 1995
	42 hrs (90-95% exchange)	Natural Plankton	Rigby & Hallegraeff 1994
Reballasting	28 hrs (not 100% effective)	Natural Plankton	Hallegraeff & Bolch 1992

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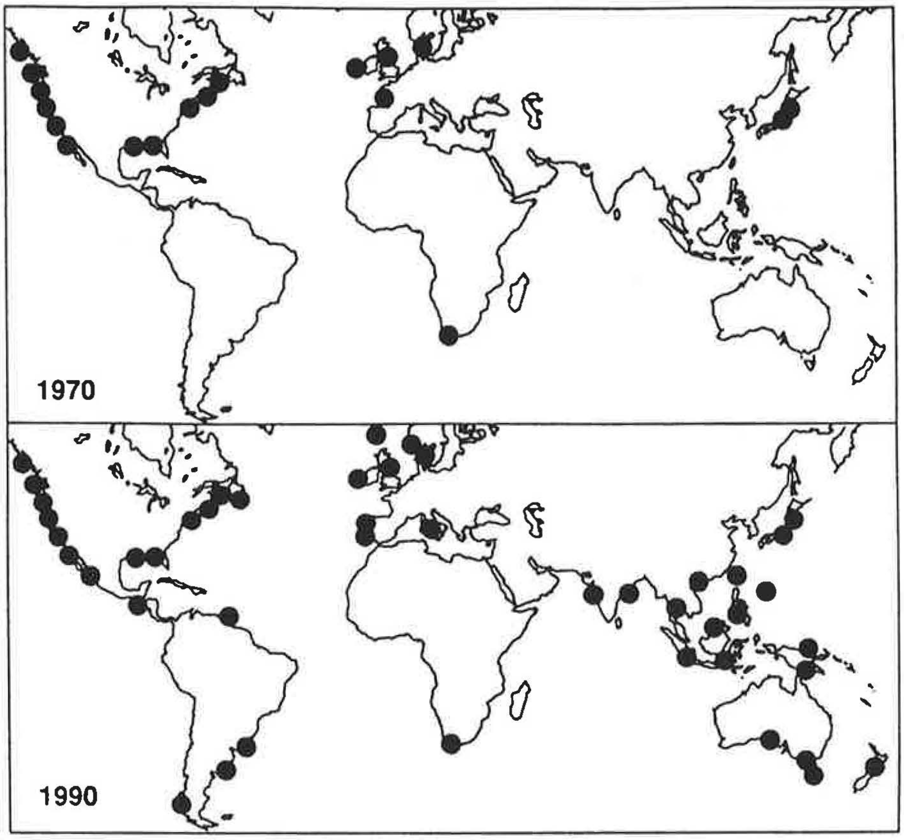

Figure 1 Known global distribution of paralytic shellfish poisoning (PS) in 1970 and 1990 (From Hallegraeff 1993).

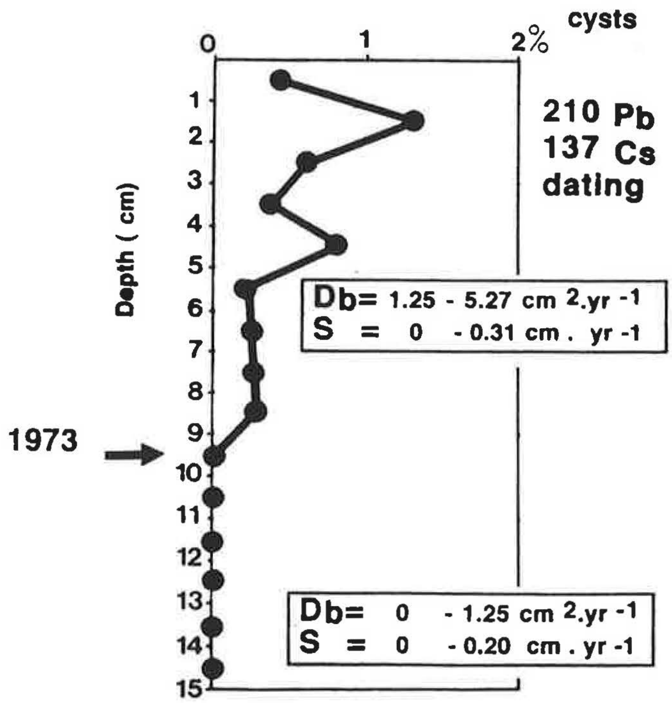

Figure 2 Depth distribution of *Gymmnodinium catenatum* cysts in an undisturbed 40 cm deep sediment corer from southern Tasmanian waters, showing absence of this species before 1973. Estimates of sediment dioturbation rates Db and sedimentation rates S are based on radionuclide dating using ^{210}Pb and ^{137}Cs (McMinn & Hallegraeff, unpublished data).

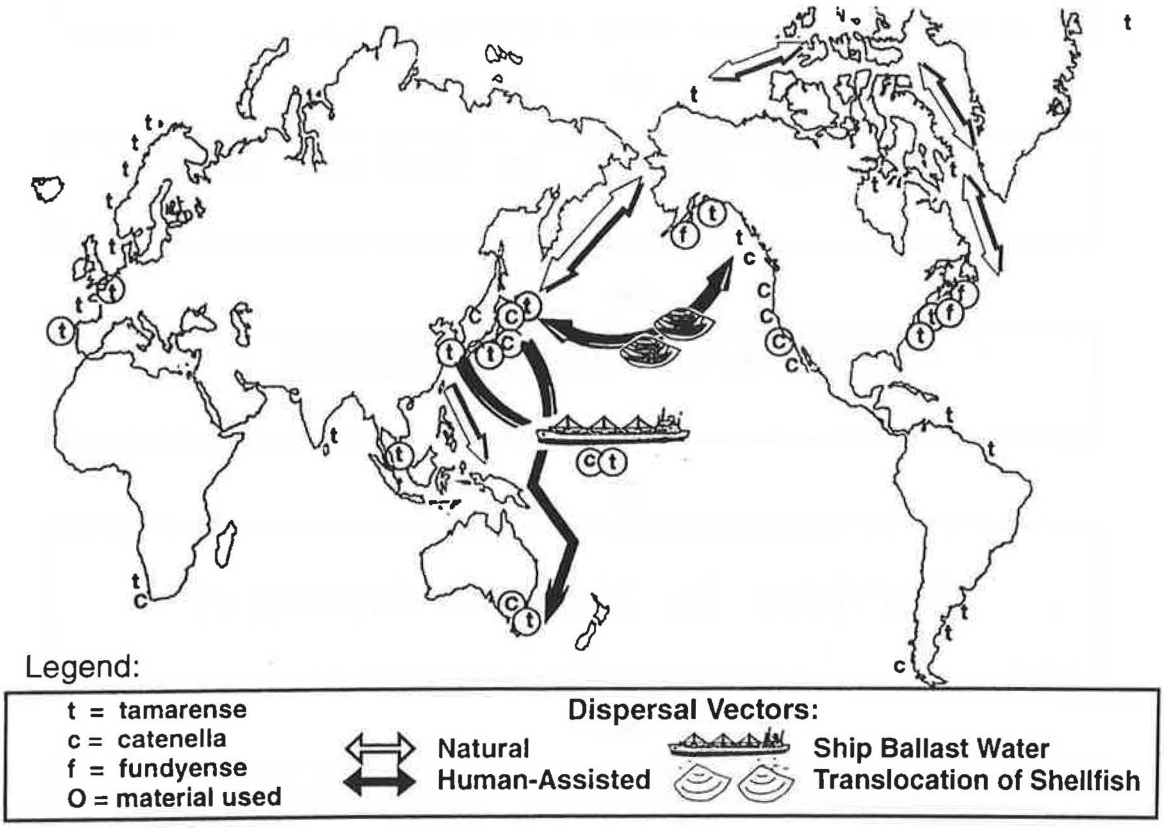

Figure 3 Global map summarising known distributions of the closely related toxic dinoflagellates *A. Tamarense* (t), *A. Catenella* and *A. Fundyense* (f). Using SSU rDNA sequences, evidence could be obtained that Japan has been on the receiving end of introductions from Europe, the east and west coast of North America, as well as possessing its own indigenous Asian populations. Some of these Japanese molecular fingerprints were caught in the act of being transported via ballast water to Australia, where they have now established reproducing populations (From Scholin *et al.*, 1995).

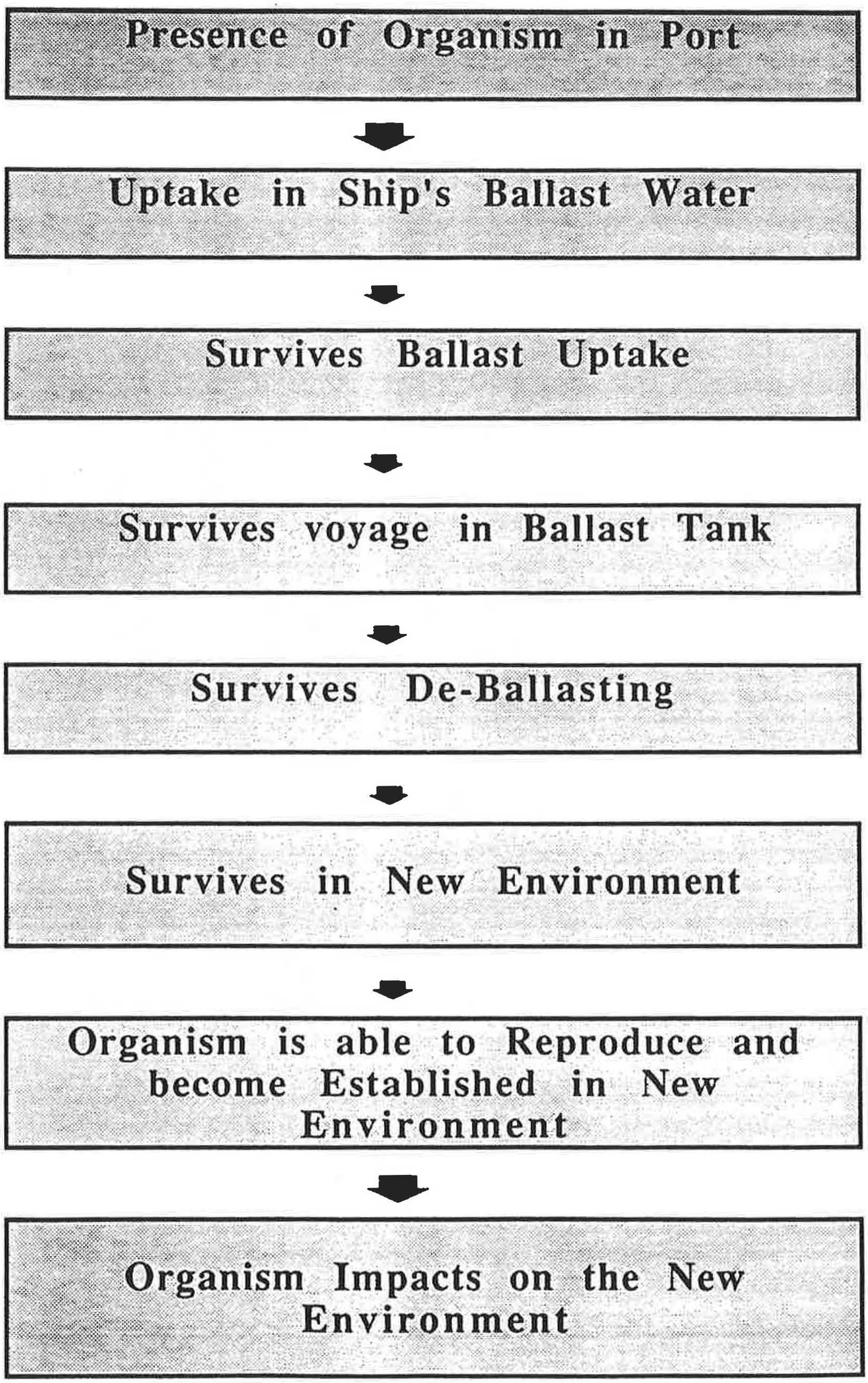

Figure 4 Flow chart summarising the steps necessary for the successful introduction of a marine organism via ship's ballast water. Monitoring of ballast water would be most effective if carried out at the overseas port, before or during ballast water uptake.

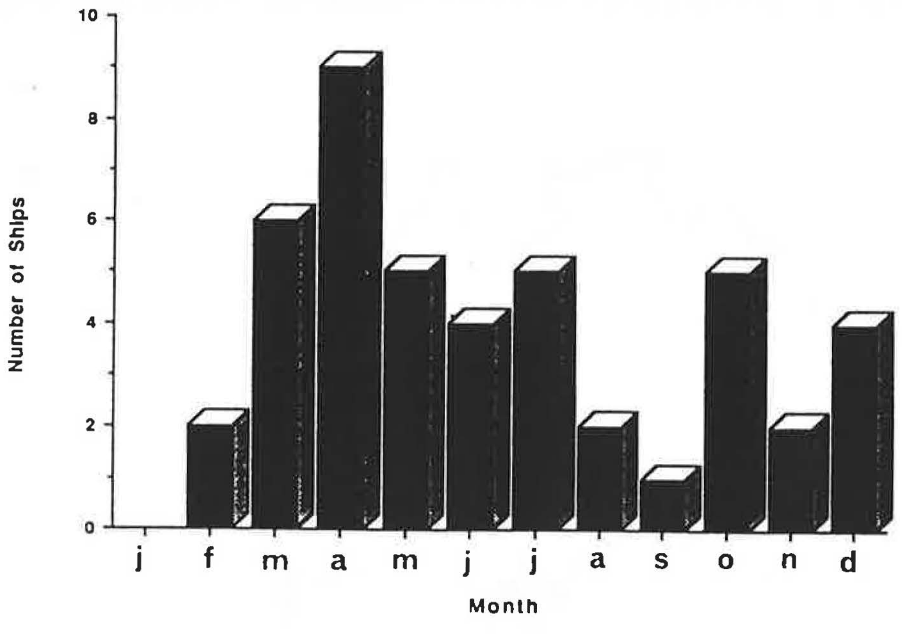

Figure 5 Seasonal occurrence of toxic dinoflagellate cysts in ship ballast water samples, intercepted at 18 different Australian ports during 1987 to 1995 (based on data from Hallegraeff & Bolch 1992 and Australian Government Analytical Laboratories (AGAL), unpublished data).

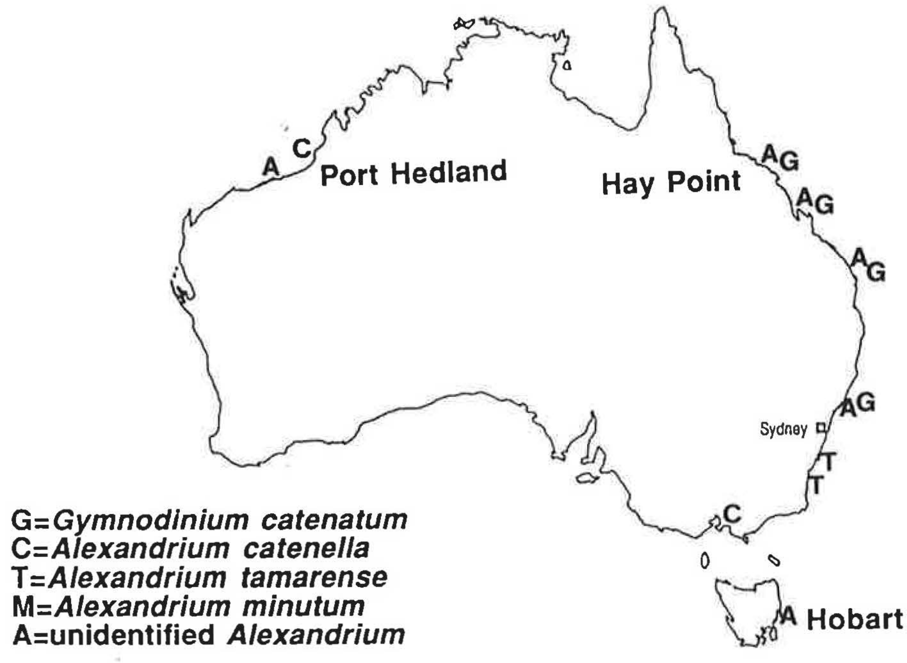

Figure 6 Toxic dinoflagellate cysts detected in ballast water from ships entering Australian ports during 1987 to 1995.

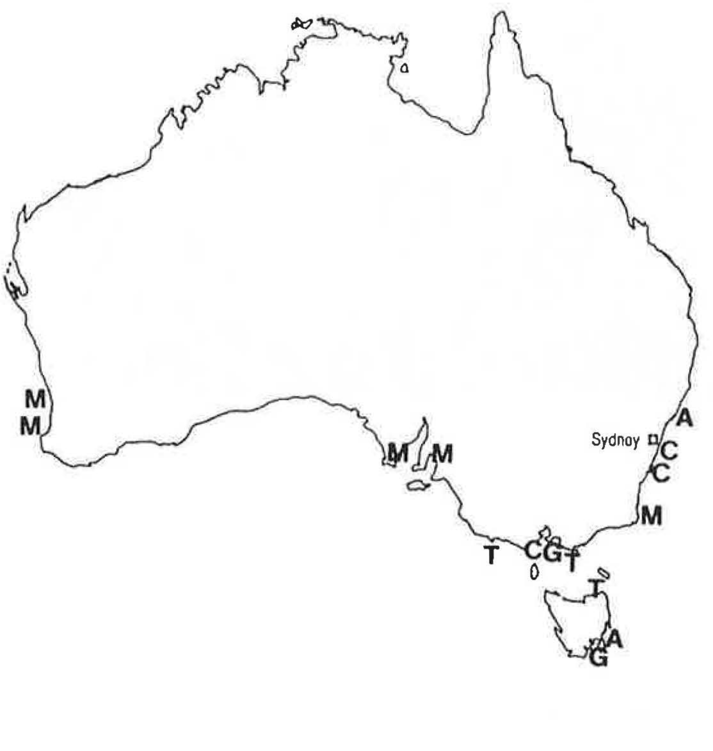

Figure 7 Australian ports where toxic dinoflagellate populations, both indigenous and introduced strains, have become established.

Reducing the impact of ship-borne marine introductions: focal objectives and development of Australia's new centre for research on introduced marine pests

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Preventing further introductions of exotic marine species and controlling those already in Australian waters requires research on the development of more effective barriers, on assessing which exotic species are already present and the risks they pose for human health, marine industries and the marine environment, and on developing an effective means of controlling, if not eradicating them. Australia has a long history and considerable success in applying research to meet these needs for introduced terrestrial pests, but efforts to limit the impacts of marine introductions have to date focused largely on barrier controls. The development of a co-ordinated, broadly-based research effort has also been hampered by the lack of any central body with clear responsibility and adequate funding to address the problem. Two recent initiatives by the Federal Government – the establishment of the Interim Australian Ballast Water Management Advisory Council and the provision of funds for a CSIRO Centre for Research on Introduced Marine Pests – are significant moves towards redressing this situation.

Introduction

As a result of Australia's geographical isolation, its dependence on shipping for import and export, and marine quarantine procedures that world-wide are poorly developed, Australia now hosts over 70 known exotic marine species. Around 20 of these are believed to have been introduced in ships' ballast water (Jones 1991) (Table 1). Although no detailed surveys have yet been done, overseas experience (Carlton, 1989) suggests that the actual number of introduced species in Australian ports is much higher. Supporting this, a preliminary assessment of a southern Australian port suggests that in some habitats, as much as a third of the fauna may be introduced.

In most cases the threat posed by these exotic species is not known. However, three introductions – the toxic dinoflagellate, *Gymnodinium catenatum*, the alga, *Undaria pinnatifida*, and the Northern Pacific seastar, *Asterias amurensis* – alone could cost the shipping, mariculture and fishing industries millions of dollars annually. Both *Undaria* and *Asterias* have the potential to cause major changes to the structure of temperate Australian coastal marine ecosystems. The potential impacts of other previously cryptic exotic species, such as the Mediterranean fan worm, *Sabella spallanzanii*, and the European shore crab, *Carcinus maenas*, are only now being assessed. Reflecting these concerns, the Australian Coastal Zone Inquiry (Resource Assessment Commission, 1993) highlighted the need for research directed at two areas: (i) preventing new introductions and (ii) assessing and minimising the impacts of existing introductions.

Preventing new introductions

Australia has taken a high profile internationally in an effort to minimise the risks of ballast water introductions. The Australian Quarantine and Inspection Service (AQIS), through its chairmanship of the Marine Environment Protection Committee of the International Maritime Organization, has been a strong advocate for international controls on the discharge of ballast water. As well, in 1994 AQIS convened a national Ballast Water Symposium in Australia, to highlight the importance of the issue and to progress action on it. The major outcome of the symposium was a Draft National Strategy on Ballast Water Management.

The draft strategy recommended the establishment of an Australian Ballast Water Management Advisory Council, supported by a Research Advisory Group and core funding for research. Pending national endorsement of this strategy, an interim council has been set up to progress urgent issues. The interim council consists of government departments with a stake in the ballast water issue (quarantine, transport, marine safety, environment), key industry groups (shipping,

Table 1 Known introduced marine species in Australian waters; their possible origin, likely mode of introduction, and current Australian status.

Taxon	Species	Possible origin	Mode of introduction	Australian status
ANIMALS				
Coelenterata				
Hydrozoa				
	Bougainvillia ramosa (hydroid)	N.Hemisphere	hull	?
Annelida				
Polychaeta				
	Hydroides norvegica (serpulid)	Europe	ballast; hull	?
	Mercierella enigmatica (serpulid)	India	ballast?; hull	?
	Boccardia proboscidea (spionid)	Japan/NE.Pacific	ballast; hull	abundant
	Polydora ciliata (spionid)	Europe	?	?
	Pseudopolydora paucibranchiata (spionid)	Japan/NE.Pacific /NZ ballast; hull		?
	Sabella spallanzanii (giant fan worm) [2]	Mediterranean	ballast	abundant; pest
Mollusca				
Gastropoda				
	Maoricolpus roseus (screw shell)	NZ	with oysters	abundant
	Zeacumantis subcarinatus (screw shell)	NZ	?	?
	Aeolidiella indica (sea slug)	widespread	ballast; hull	common
	Janolus hyalinus (sea slug)	Europe	hull	?
	Okenia plana (sea slug)	Japan	hull	?
	Polycera capensis (sea slug)	California	hull	?
	Godiva quadricolor (sea slug)	S. Africa	hull?	?
	Thecacera pennigera (sea slug)	?	hull	?
Bivalvia				
	Crassostrea gigas (Pacific oyster)	Japan	deliberate	commercial/pest?
	Neilo australis (clam)	NZ	with oysters	common
	Ostrea lutaria (NZ mud oyster)	N Z	deliberate	?
	Paphirus largellierti (clam)	N Z	with oysters	?
	Perna canaliculus (NZ green mussel)[1]	NZ	with oysters; hull?	
	Musculista senhousia (Asian mussel)	Pacific/Asia	hull; ballast	common
	Theora lubrica (semelid)	Pacific/Asia	ballast	?
Polyplacophora				
	Amaurochiton glaucus (chiton)	NZ	with oysters	?
Crustacea				
Mysidacea				
	Neomysis japonica (mysid shrimp)	Japan	ballast	?
Tanaidacea				
	Tanais dulongi (tanaid)	Europe	ballast	common
Isopoda				
	Cirolana harfordi (isopod)	USA	hull	?
	Eurylana arcuata(isopod)	NZ/Chile	hull; ballast	?
	Paracerceis sculpta (isopod)	USA/S. America	hull	?
	Paradella dianae (isopod)	USA/S. America	hull	?
	Sphaeroma serratum (isopod)	widespread	hull	?
	Sphaeroma walkeri (isopod)	Indian Ocean	hull	?
Cirripedia				
	Balanus improvisus (barnacle)	Atlantic	hull	?
	Megabalanus rosea (barnacle)	Japan	hull?	?
	Megabalanus tintinnabulum (barnacle)	cosmopolitan	hull	?
	Notomegabalanus algicola (barnacle)	S. Africa	hull	?
Decapoda				
	Cancer novaezelandiae (crab)[1]	NZ	with oysters	common
	Carcinus maenas (European shore crab) [2]	Europe	hull?; ballast?	common; pest

Table 1 Continued

Taxon	Species	Possible origin	Mode of introduction	Australian status
	Halicarcinus innominatus (crab)	NZ	with oysters; hull	?
	Pyromaia tuberculata (crab)	E. Pacific	ballast	?
	Palaemon macrodactylus (Japanese shrimp) N. Pacific	?		common?
Bryozoa				
	Anguinella palmata	Atlantic	hull	?
	Bugula flabellata	Atlantic/Medit	hull	?
	Conopeum tubigerum	Atlantic	hull	?
	Schizoporella unicornis	Japan	hull?	?
	Watersipora arcuata	Mexico	hull	?
Echinodermata				
Asteroidea				
	Asterias amurensis (northern Pacific seastar) [2]	Japan	ballast	abundant; pest
	Astrostole scabra (seastar)[1]	NZ	?	common
	Patiriella regularis(seastar)	NZ	with oysters	common
Chordata				
Ascidiacea				
	Molgula manhattensis (ascidian)	N. Atlantic	hull	?
	Styela clava (ascidian)	NW. Pacific/Europe	hull	?
	Styela plicata (ascidian)	widespread	hull	?
Pisces				
	Lateolabrax japonicus (Japanese sea bass)	Japan	ballast	established
	Triso dermopterus	W.-Equat. Pacific	ballast	established
	Sparidenrax hasta (Sobaity sea bream)	Arabian Gulf	ballast	?
	Tridentiger trigonocephalus (striped goby)	W. Equat. Pacific	ballast	established
	Acanthogobius flavimanus (yellowfin goby)	W.-Equat. Pacific	ballast	established
	Fosterygion varium (blenny)	NZ	?	common
	Oreochromis mossambicus (tilapia)	SE Asia	deliberate	common, pest?
	Salmo salar (Atlantic salmon)	N. America	deliberate	commercial
	Salmo trutta (brown trout)	UK	deliberate	common
	Oncorhynchus mykiss (rainbow trout)	NZ (California)	deliberate	commercial
PLANTS: Phycophyta				
Chlorophyceae				
	Caulerpa filiformis	S. Africa	hull?	abundant
	Caulerpa taxifolia[1]	Atlantic/Indo-Pac	hull?	abundant
Dinophyceae				
	Gymnodinium catenatum (dinoflagellate)[2]	Japan?	ballast	abundant; pest
	Alexandrium minutum (dinoflagellate)[1,2]	Mediterranean?	ballast?	abundant, pest
	Alexandrium catanella (dinoflagellate)[1,2]	Japan?	ballast?	abundant, pest
Rhodophyceae				
	Arthrocladia villosa	N. hemisphere	?	?
	Sperococcus compressus	N. hemisphere	?	?
	Antithamnionella spirographidis	N. hemisphere	?	?
	Polysiphonia brodiaei	N. hemisphere	?	?
	Polysiphonia pungens	N. hemisphere	?	?
Phaeophyceae				
	Undaria pinnatifida ("wakame")[2]	Japan	ballast; hull?	abundant; pest
	Discosporangium mesarthrocarpum	Mediterranean	?	?
	Spacella subtilissima	Mediterranean	?	?
	Zosterocarpus spp.	Mediterranean	?	?

Notes:
[1] Introduced status uncertain; possibly on Australian endemic. [2] IABWMAC target pest species

port authorities, fishing and mariculture industries) and a senior science representative (CSIRO). The Research Advisory Group consists primarily of industry representatives and a broader spectrum of relevant science agencies. The interim council has focused its attention on three objectives:

- allocation of responsibility for ballast water management;
- development of a secure funding base for long-term research; and
- development of a strategic research plan.

Responsibility for ballast water management

The question of who should, or in fact, who can take responsibility for developing and enforcing ballast water regulations or guidelines in Australia has yet to be resolved. Cogent arguments can be made for this role being either a federal or a state responsibility. The underlying problem is that the plethora of acts and regulations that are relevant to introduced marine pests and their transport vectors are administered by a number of different state and federal departments. All have some regulatory responsibilities in relation to the issue, but it is not clear where the authority to respond lies, or which agency can respond most effectively. A similar problem arises in relation to the role of port authorities, the potential implementers of any management strategy. These authorities differ in their responsibilities from state to state and it is unclear if any have the legislative authority to enforce ballasting controls. The interim council has invited comments on this issue from all relevant state departments and has established a sub-committee, chaired by a state representative, which will make recommendations to the Council and, through it, to the federal government for implementation.

Funding for long-term research

The Australian Government has a "user-pays" approach to the provision of government services and research. This means, in the case of marine introductions, that if international shipping or its clients are viewed as the main perpetrators of the problem, they should bear the brunt of the cost of remediation and control. Such an approach, however, presupposes a capacity to allocate responsibility for specific introductions, which requires unequivocal identification of transport vectors and a detailed knowledge of high risk vessels and shipping routes. An alternative approach, canvassed by the council, is a broadly based levy on the shipping industry. Opponents of the levy rightly point out that it imposes an additional cost on "good corporate citizens", who already take suitable precautions to minimise risks, while providing no incentive for those "less responsible citizens" to do likewise. The issue is complicated further by different levels of interest shown by relevant industries in funding baseline as opposed to barrier-related research, and meeting costs associated with inspection, verification, and barrier co-ordination.

Development of a strategic research plan

Virtually everyone involved in the issue sees research and technology as the keys to resolving the introduced pest problem. The research required falls into two broad categories: baseline and barrier development. The first relates to the state of the current problem: How many ports are infected, and by what? What is the major transport vector?, and What international routes and carriers pose the greatest risks? The second deals with prospects for risk minimisation through development of a decision support system for re-ballasting, and by examining management options at the port of up-take, during transport, and in the receiving port. This approach is broadly consistent with that taken elsewhere (Carlton, 1989).

The interim council plans to have these issues resolved, and a draft strategic plan in place, by the end of 1995.

Assessing and minimising the impacts of existing introductions

The evaluation and control of introduced marine pests requires a multi-disciplinary approach involving areas as diverse as taxonomy, environmental impact assessment, economics and engineering. In 1994, the Australian Government allocated funds to the CSIRO (Commonwealth Scientific and Industrial Research Organisation) to conduct this research on a national scale. To do so, a Centre for Research on Introduced Marine Pests (CRIMP) was set up within the CSIRO Division of Fisheries. The objectives of the Centre are:

(i) To develop and promote implementation of tools for earlier warning, better prediction, and more effective assessment of risks and costs of marine pest species introduced to Australia.

(ii) To develop new methods or improve existing measures to control the spread and minimise the impacts of introduced marine species.

Achievement of these objectives involves evaluating the environmental and economic threats posed by known introduced pest species; developing cost-effective monitoring programs for early detection of these species in high-risk areas; providing the ecological basis for assessing the effectiveness of existing and new control measures; and developing and promoting new control measures nationally and internationally.

CRIMP is taking a staged approach to the problem, focusing on key objectives and collaborating, wherever possible, with other research initiatives in order to maximise the value of the research dollar. Discussions with the centre's primary clients lead to a research plan that has three main thrusts: (i) an assessment of the scale of the problem in Australian waters; (ii) investigation into ways to minimise the risk of domestic translocation of exotic species; and (iii) the development of biological controls against pest species.

Assessing the scale of the introduced species problem

To assess the number, diversity and distribution of the introduced marine species in Australian waters, CRIMP is undertaking three interrelated studies, two of which will be jointly funded with other agencies:

(i) *Intensive port surveys.* These surveys will provide an indication of the magnitude of the problem in a small number of representative ports. The first port to be examined will be Port Phillip Bay, in south-eastern Australia. Port Phillip Bay was chosen because of the availability of good local taxonomic knowledge, access to support infrastructure, its role as a major port for both domestic and international shipping, and a historical database against which the current species assemblage can be compared. For logistical and taxonomic reasons, the survey will concentrate on a few major groups – primarily fish, selected macro-invertebrate groups and the macroalgae – and will be largely qualitative (mainly presence-absence). The Port Phillip Bay study will be completed by the end of 1996, after which the focus will shifted to a tropical port (most likely Darwin).

(ii) *National ports survey.* CRIMP and the Australian Association of Port Management Authorities are jointly funding a survey of all major shipping ports in Australia. The survey will be semi-quantitative, and have three objectives:

- to determine the geographical distribution of a set of identified "pest" and exotic species (Table 1);
- to obtain opportunistic information on other introduced species in the ports; and
- to make a preliminary risk assessment for each port on likelihood of translocation of existing pests and to recommend ways to reduce these risks.

The national port survey will start in 1995, will be completed by 1997, and may lead to an on-going monitoring program.

(iii) *Community-based coastal monitoring.* In 1995, the Australian Government provided funding for a national 'Coast Care' initiative, to facilitate community involvement in coastal management. As part of this program, CRIMP and the relevant commonwealth department are developing a national "early warning" network for introduced species. Fifty four regional coordinators are being appointed, who will develop links between CRIMP (and other scientific agencies) and local community groups, such as dive clubs, fishing groups and schools. CRIMP will provide technical expertise and identification material to support the efforts of volunteers to map the presence of known pests and keep an eye open for new ones. It is hoped that the broad geographical coverage of the network will make possible the rapid detection of any new introductions and provide opportunities to eradicate such species before they can establish and spread.

Minimising the domestic translocation of exotic species

CRIMP is progressing this issue in three ways. First, studies are underway to assess the relative importance of hull fouling and domestic ballast water exchange in the coastal transport of the main pest species. This study involves surveys of hulls for fouling organisms, particularly known pest species, and experiments to determine whether the larvae of these species survive in and remain viable in the ballast tanks of coastal vessels. Preliminary indications are that hull fouling is likely to be the main transport vector for several of the major pest species.

Second, discussions are underway with mariculture co-operatives to develop treatment protocols to minimise the risk of accidental transport of eggs, larvae or juveniles of pest species in the live fish or shellfish trade.

Third, we are initiating a long-term project to look at the impact of port management practices on the colonisation success of invading species. Theoretical and empirical considerations suggest that vacant habitat created by disturbance may be a major factor in facilitating colonisation exotic species. Field and experimental studies are being planned to examine this with a view to recommending changes in port practices that would lower the risk of invasion by introduced species.

Biological control

The CRIMP advisory committee recommended that in the medium to long-term, significant centre resources should be allocated to assess the feasibility of developing biological control techniques for established pest species. CRIMP is currently recruiting specialist staff to develop this program, which is expected to draw heavily of the extensive experience of other CSIRO Divisions that work on the integrated pest management of terrestrial pests. Initial efforts will focus on natural parasites and pathogens, with the intent of moving to transgenic technology only if necessary. Work on transgenic technology is underway in several CSIRO Divisions, but the ethical problems associated with this approach (Goodman, 1993) and the practical difficulties involved in adapting the technology to marine organisms warrant a detailed search for natural parasites first.

While awaiting appointment of key staff, CRIMP has commenced several information gathering projects. Field teams have been commissioned to examine native populations of the northern Pacific seastar, *Asterias amurensis*, in Russia and Japan to identify potential biological control agents. At this stage, the most likely candidates are eulimid gastropods and ascothoracidan barnacles, both parasitic castrators. A small project to assess the feasibility of mass rearing marine parasites for release has also been commissioned, as part of a collaborative study with Armand Kuris's laboratory at the University of California on the potential for biological control of the European shore crab, *Carcinus maenas*. We will also be having discussions with specialist parasitologists working on several, possibly relevant groups, with a view to funding projects relevant to the biological control initiative. In Australia, monitoring programmes are being put in place for the two species that are likely first targets for attempted biological control (*Carcinus* and *Asterias*). From these adequate baseline information is available on the population dynamics of these species against which the impacts of the biological control agent can be assessed.

It is difficult to predict the time course of the biological control project, given vast uncertainties in everything from the availability of parasites to the likelihood that they can be reared in captivity. Optimistically, CRIMP hopes to undertake trial releases of parasites in 3–4 years, with full scale release 1–2 years later, following detailed impact assessments.

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A synopsis of the Canadian situation regarding ship-transported ballast water

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With the longest navigable coastline in the world, bordering on the Atlantic, Arctic and Pacific Oceans, Canada is a country where shipping plays an important role in national and international trade. This synopsis describes the situation in Canada with regards to vessel traffic, regulations, management activities and scientific studies concerning the introduction in Canadian waters of unwanted species by ship-transported ballast water.

Many nuisance species have been introduced into Canadian ports and coastal waters, which annually receive at least 52 million tonnes of discharged ballast waters. Canadian waters are unprotected from this threat because there are presently no specific ballast water regulations or national policies. However, there are two sets of voluntary guidelines for mid-ocean ballast water exchange, of questionable effectiveness and which are geographically limited to the Great Lakes and the Îles-de-la-Madeleine. Canadian management activities are segmented by region and not integrated between official authorities. Recent scientific studies focus mostly on the ecology of invading species while few address the transport mechanism of organisms by way of ballast waters. Thus, there is a need for a national action plan, developed in consultation with shipping, fishing and aquaculture industries, which could lead to policies, regulations and an integrated research program regarding ship-transported ballast water.

Introduction

Worldwide introductions of plants, animals and pathogens to new habitats as a result of human activities are having dramatic impacts on terrestrial and aquatic ecosystems (Biodiversity Science Assessment Team, 1994). Ballast water, taken on for vessel stability in one port of call and released in another, has been identified as a likely vector for the introduction of numerous species in coastal waterways in Canada and around the world (Leach *et al.*, 1995; Locke *et al.*, 1993; Mills *et al.*, 1993a, b). Shipping routes traverse sections of Canada's coastline along the Atlantic, Pacific and Arctic Oceans, and Gulf of St. Lawrence, into the interior Great Lakes via the St. Lawrence Seaway (Figure 1). The St. Lawrence Seaway is initially under Canadian jurisdiction at Montreal and then American at Massena, New York, prior to entering the Great Lakes. This series of locks allows the navigation of vessels to the head of Lake Superior, a distance of 3,769 km from the Atlantic Ocean. With the problem gaining increasing environmental and economic recognition, the purpose of this report is to overview vessel traffic, regulations, management activities and scientific studies concerning the introduction of non-native species by ship-transported ballast water in Canadian waters.

Vessel traffic

For the Canadian Atlantic coast, the Eastern Canada Region Vessel Traffic Services (ECAREG–VTS) database reported 1,377 foreign vessel entries in 1991 of which 1012 originated from a last-port-of-call (LPOC) that was outside the Northwest Atlantic zone, as defined by the FAO "waters of the world" (Table 1). These vessels originated from ports bordering the Northeast Atlantic, Northwest Atlantic and West Central Atlantic in respective proportions of 40%, 24% and 11%, although their ballast waters may have been taken on during the voyage. Of these 1012 vessels, respectively 68%, 30% and 2% entered the ports of Halifax in Nova Scotia, St. John in New Brunswick and St. John's in Newfoundland, discharging 2.1, 2.6 and 0.02 million tonnes of ballast water for an estimated total of 4.7 million tonnes (D. M. Reid, personal communication).

Based on the ECAREG–VTS database, a total of 762 vessels of which 612 foreign vessels entered the major ports of the Estuary and Gulf of St. Lawrence in 1993 (DFO, unpublished). Of these, 526 originated from a LPOC that was outside the Northwest Atlantic zone, some 47%, 26% and 18% originating respectively from Northeast Atlantic (excluding Mediterranean), the United States and Mediterranean. These ships entered the ports of Port-Cartier, Sept-Îles and Baie-Comeau in proportions of 23%, 21% and 14 %, respectively. Based on estimates of discharges of ballast water in ports from Montreal to Québec City and taking into account the proportions of vessels arriving "in ballast" or "in cargo" (D. M. Reid, personal communication), it is estimated that about 6.1 million tonnes of ballast water were discharged in the Estuary and Gulf of St Lawrence during 1993 (Table 1) of which 1.7, 1.6 and 0.7 million tonnes were discharged respectively in the ports of Port-Cartier, Sept-Îles and Baie-Comeau (DFO, unpublished).

For the Great Lakes – St. Lawrence River system, the ECAREG–VTS database reported 755 vessel entries in 1991 of which 735 originated from a last-port-of-call (LPOC) that was outside the Northwest Atlantic zone. Of these 735 vessels, 56% and 16% originated respectively from Northeast Atlantic (excluding Mediterranean) and Mediterranean (D. M. Reid, personal communication). Of these 735 vessels, 56.6% and 43.4% entered respectively the ports upstream of Montreal and those from Québec City to Montreal. Since ships entering the Great Lakes typically contained about 7,500 m^3 of ballast water (Sprules *et al.*, 1990), it is estimated that respectively 1.4 and 1.1 million tonnes of ballast water were discharged in the Great Lakes – St. Lawrence River system in 1991 (D. M. Reid, personal communication).

For the Pacific coast, the Vancouver and Prince-Rupert port authorities reported respectively 3117 and 398 foreign vessel entries in 1991, of which 3023 and 386 originated from a last-port-of-call (LPOC) that was outside the Northeast Pacific. Respectively 78%, 13% and 3% of these vessels originated from ports bordering the Northwest Pacific, West Central Pacific – Indonesia – and Northeast Pacific. These vessels discharged respectively an estimated 33.5 and 5.4 million tonnes of ballast water in the ports of Vancouver and Prince-Rupert, for a total of about 38.9 million tonnes (Table 1) (D. M. Reid, personal communication).

Table 1 Vessel traffic and estimated discharges of ballast water from foreign FAO Regions.

Ports	Year	Vessels	Discharges (10^6 t)
Atlantic: Halifax (N.S.), St. John (N.B.) St. John's (Nfld.)	1991	1,012[1]	4.7[3]
Estuary and Gulf of St. Lawrence: Sept-Îles, Port-Cartier, Baie-Comeau, Gaspe and Cacouna (Que.), Dalhousie and Belledune (N.B.), and Summerside (P.E.I.)	1993	520[1]	6.1[4]
Great Lakes: Canadian and US ports, Montreal and Quebec (Que.)	1991	744[1]	2.5[3]
Pacific: Vancouver and Prince Rupert (B.C.)	1991	3409[2]	38.9[3]

[1]FAO zones other than Northwest Atlantic – mostly Northeast Atlantic and the Mediterranean
[2]FAO zones other than Northeast Pacific – mostly Northwest Pacific, West central Pacific (Indonesia) and Northeast Pacific
[3]D. M. Reid, personal communication
[4]Department of Fisheries and Oceans, unpublished data

Regulatory aspects and management activities

By prohibiting the release of a pollutant into harbour or coastal waters, the Oil Pollution Prevention Regulation, Part XV under the Canada Shipping Act, is currently the only regulation related to ballast water that applies to all vessels entering Canadian ports. Typically, this refers to various types of oil products. However, according to the definition of pollutant under Part XV, this also encompasses "any substance or water containing a chemically altered substance that, if added to any waters, would degrade or alter or form part of a process of degradation or alteration of the quality of those waters to an extent that it is detrimental to their use by man or by any animal, fish or plant that is useful to man". Based on this definition, ballast waters are considered to be clean and can be released in, or taken on from any Canadian harbour or coastal waters, with a few exceptions, as discussed below.

Aside from regional activities described below, Canada participated in the 34^{th} to 37^{th} meetings held from 1993 to 1995 by the Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO). This Committee requested the Ballast Water Working Group to develop a possible new Annex to MARPOL 73/78 regarding ballast water management. S. Gosselin and D. Gauthier of DFO's Maurice Lamontagne Institute in Mont-Joli, Québec, successively represented Canada.

Lower Estuary and Gulf of St. Lawrence

The threat of introductions of toxic phytoplankton to local mussel farming industries prompted the Canadian Coast Guard in 1982 to issue the Notice to Mariners #995. This yearly renewed notice prohibits ships bound for the Mines Seleine's pier, situated in the Grande-Entree Lagoon of the Îles-de-la-Madeleine, Gulf of St. Lawrence (Figure 1), from discharging their ballast waters within 10 nautical miles of the Islands unless these waters had been taken on in a well-defined area off Canada's east coast, at a distance of 5 miles or greater from the shoreline.

Great Lakes – St. Lawrence River and Estuary

Jurisdictional management of the Great Lakes – St. Lawrence River system is complex as two federal, two provincial and eight state governments, and numerous environmental groups and transport associations are concerned. Policies and management perspectives are now provided by the International Joint Commission and the Great Lakes Fishery Commission in accordance with binational treaties and agreements (Leach *et al.*, 1995). The latter Commission was created in 1955 by the Governments of Canada and the United States, to address the problem of the devastation wreaked on the Great Lakes commercial fisheries by the invading sea lamprey (*Petromyzon marinus*) in the early 1940s and 1950s. Its primary mandate is to advise governments on measures and issues affecting fish stocks of common concern to Great Lakes fisheries, including the introduction of exotic species via ballast water discharges (Dochoda, 1991).

In May 1989, the Canadian Coast Guard, after consultation with the US Coast Guard, the Great Lakes Fishery Commission, the Department of Fisheries and Oceans, the Department of Environment, as well as representatives from the shipping industry, promulgated the Voluntary Guidelines for the Control of Ballast Water Discharges from Ships. These guidelines apply to all vessels carrying ballast water entering the St. Lawrence Seaway from outside the Exclusive Economic Zone (EEZ) – beyond 200 nautical miles from shore – bound for the St. Lawrence Seaway and Great Lakes ports west of 63°W longitude (modified to 64°W in 1995). Vessels are requested to exchange their ballast water on the high seas where depths are greater than 2000 m before entering the Gulf of St. Lawrence. The guidelines are based upon the rationale that most freshwater organisms do not survive in salinities above 8 ‰, and as open ocean salinities are typically around 35 ‰, any organisms present during ballast water exchange would be subject to lethal osmotic stresses.

Control of compliance with these guidelines begins with information supplied to the ECAREG–VTS operators from vessels entering Canadian waters. If a ship is proceeding up the seaway and into the Great Lakes, it will be requested to exchange its ballast water in open ocean at depths greater than 2000m. If this is not technically feasible, ships are permitted to conduct an exchange in a "backup exchange zone" within the Laurentian Channel of the lower St. Lawrence Estuary, to the southeast of 64° W longitude in water depths greater than 300m. Once contact with ECAREG–VTS operators has been established, foreign vessels typically pick up a pilot at Les Escoumins within the St. Lawrence Estuary There they are given a "Ballast Water Exchange Form" to be completed prior to their arrival in Montreal. Upon arrival at the St. Lambert locks in Montreal, the ballast water information provided on the form is verbally verified with respect to ballast water exchange. Vessels are considered to be in compliance with these guidelines if they carry:- no ballast water only residual ballast water that could not be completely expelled; permanent ballast water; ballast water that is not intended to be discharged in the Great Lakes; or only ballast water that has been exchanged offshore or in the Laurentian Channel (Hall-Armstrong, 1994). In regards to ballast water, a fine of up to $50,000 may be imposed for providing false information to a Pollution Prevention Officer of the Canadian Coast Guard, where such information is requested for the promotion of environmental protection (Hall-Armstrong, 1994).

In general, for tankers and carriers of greater than 50,000 dry weight tonnage, the number of such vessels exchanging their ballast waters is low Generally this is because of safety issues, such as structural integrity of the vessel, demonstrated loss of stability and propeller exposure during the exchange process and associated time delays to complete the procedure (Prior, 1995). Laker carriers or "lakers" are not subject to these guidelines as they do not operate outside the EEZ (D. M. Reid, personal communication). Although these guidelines apply to all vessels bound for the St. Lawrence River and Great Lakes ports west of 64° W longitude, compliance is not as easily monitored or enforceable for vessel traffic frequenting ports within the Lower St. Lawrence Estuary such as Sept-Îles and Port-Cartier on the Québec north shore (C. Wiley, personal communication).

Section 207 of the United States Public Law 101-225, the Great Lakes Exotic Species Prevention Act of 1989, directed the US Coast Guard to report to Congress on methods for preventing the introductions of non-native species into US waters by ballast discharge, with mid-ocean exchange considered the most feasible method (Kelly, 1992). In March 1991, the Canadian and US Coast Guards jointly issued guidelines based on those established in Canada, which were in effect until 10 May 1993. Subsequently, US Public Law 101–646 concerning mandatory ballast water exchange for ships entering American waters came into effect under the Non-indigenous Aquatic Nuisance Prevention and Control Act of 1990. In addition to specific regulations, this Act called for a number of federal agencies to administer a "National Ballast Water Control Program", which included a Biological Study, a Ballast Exchange Study and a Shipping Study (Carlton *et al.*, 1995). Under this law, the US Coast Guard issued regulations that apply to vessels from outside of the EEZ and passing through the Snell Lock at Massena, New York (Figure 1) and bound for any Canadian or American port within the Great Lakes (Prior, 1995).

Essentially, the law requires that all vessels exchange ballast water, if possible, on the high seas – in depths greater than 2,000 m – such that the salinity of the ballast water is at least 30 parts per thousand. Vessels travelling "in ballast" through the Snell Lock are checked for sufficient salinity to indicate that the required exchange has occurred. Vessels will be allowed to proceed if: 1) problem ballast tanks are sealed for the duration of the voyage into the Great Lakes; 2) the vessel returns to sea or the "backup exchange zone" to conduct a proper exchange and subsequently passes inspection at the US lock; or 3) conducts a mutually agreeable procedure to remove the possibility of non-indigenous species being introduced into the Great Lakes via their ballast water discharge. Under the regulations, those vessels that opt to have their ballast tanks sealed are reboarded on their way out of the Great Lakes for verification of seals, water levels and salinity (Hall-Armstrong, 1994).

Lakewide Management Plans (LaMPs) have been required since 1987 under the Great Lakes Water Quality Agreement, which was signed by the governments of Canada and the United States. Article VI and Annexes 4 to 9 of that Agreement all address " Pollution from Shipping Activities" and assign specific coordinating, enforcement and reporting function to the US and Canadian Coast Guards (Dochoda *et al.*, 1990). Administered by two federal governments, four states, one province and several native governments, LaMPs are currently ongoing for both Lake Erie and Lake Superior, tending to focus primarily on the ecological effects of introduced species such as the sea lamprey and zebra mussel (*Dreissena polymorpha*), rather than their mode of entry via ballast water discharges (O. Johannsson, personal communication).

Within the context of the American Non-indigenous Aquatic Nuisance Prevention and Control Act of 1990, there is only one set of guidelines in place which attempts to curb the spread of the ruffe (*Gymnocephalus cernuus*), a small percid fish introduced into the Great Lakes via ballast water discharges. Joint American and Canadian government and industry initiatives led to these guidelines, implemented in 1995, which request that ships that have to take on ballast water from ruffe-inhabited ports, exchange ballast waters in the open waters of Lake Superior, west of a line drawn between the US/Canada boundary and the Ontagon River, Michigan, USA If ballast cannot be exchanged in that zone, it must be undertaken in other locations with water depths exceeding 75 m and at least 28 km from shore. Both the US and Canadian Coast Guards have access to ballasting records from the shipping companies to monitor compliance with the plan (Busiahn and McClain, 1995). In spite of these measures, the ruffe has recently invaded Lake Huron (J. T. Carlton, personal communication).

Pacific region

There are no regulations or voluntary guidelines for the exchange of ballast water along the Pacific coast. However, the 1992 Environmental Cooperation Agreement between Washington State and British Columbia called for an increase in the sharing of information and the initiation of joint monitoring and research, resulting in formation of the British Columbia/Washington State Joint Environmental Council. The Council produced a Marine Science Panel Report entitled "Task Force Recommendations for Action to Protect Shared Waters", including a section entitled "Minimize Introduction of Exotic Species", which served as the basis for its mandate.

Under the auspices of the B.C./Washington State Joint Environmental Council and as an initiative of the Puget Sound/Georgia Basin International Task Force, the B.C. Working Group on Minimizing the Introduction of Exotic Species held its first meeting at the University of British Columbia on June 13, 1995. Participants included representatives from the B.C. departments of Agriculture, Fisheries and Food, Fisheries and Oceans Canada, and the Department of Oceanography at the University of British Columbia. Their mandate is: 1) to review the current status and management actions concerning exotic species already introduced in inland waters of B.C.; 2) to examine the routes and risks of new introductions; 3) to assess the practicality of control measures against potential new introductions; 4) to hold a symposium / workshop to seek solutions; and 5) to develop a cooperative strategy for dealing with exotic species and their long-term management in jointly shared waters. A parallel working group has been established in Washington under the leadership of the United States Environmental Protection Agency in Seattle, and participants are from state, local and tribal governments, aquaculture industries and the US Coast Guard. The final output of both working groups should be a set of complementary policy recommendations to the B.C. Ministry of the Environment and to the Washington Department of Ecology.

Table 2 Examples of suspected ballast-water mediated introductions.

First Sighting	Species	Invaded areas
1974	European flounder (*Platichthys flesus*)	Lake Erie
1980s	European or spiny water flea (*Bythotrephes cederstroemi*)	Great Lakes
	Eurasian zebra mussel (*Dreissena polymorpha*)	Great Lakes, tributaries,
	European ruffe (*Gymnocephalus cemuus*)	Lake Superior
1989 to 1994	Eurasian quagga mussel (*D. bugensis*)	Lake Erie
	Black Sea goby or tubenose goby (*Proterorhinus marmoratus*)	St. Clair River, Great Lakes
	Mediterranean or round goby (*Neogobious melanostomus*)	St. Clair River, Great Lakes
	Chinese mitten crab (*Eriocheir sinensis*)	Various locations in the Great Lakes

(Source: modified from Chesapeake Bay Commission 1995)

Scientific knowledge and activities

Species

For the Great Lakes basin, Mills *et al.* (1993b) have estimated that 139 non-indigenous species have become established since 1810; of these, 40% became established after 1950, and approximately 10% have had significant impacts, such as the sea lamprey (*Petromyzon marinus*) and the zebra mussel (*Dreissena polymorpha*) (Table 2) (Leach *et al.*, 1995).

Native to the Atlantic Ocean, the sea lamprey invaded the upper Great Lakes in the 1930s, possibly via migration through the shipping route of the Welland Canal, and quickly parasitized and devastated local commercial fish stocks. This event is of note because it was one of the first biologically and economically significant appearances by a non-native species as a result of shipping activities. Furthermore, this resulted in the formation of the Great Lakes Fishery Commission designated to monitor subsequent species invasions and their impact on local fisheries. Despite expenditures by the Great Lakes Fishery Commission on research, chemical control and habitat modification – $168 millions in 1993, an estimated 575,000 adult sea lampreys presently live in the five Great Lakes (Leach, 1995).

The Eurasian zebra mussel has become successfully established in all five of the Great Lakes and connecting waterways, including the lower Hudson and Mississippi Rivers, mainly as a result of this species' high fecundity, free-swimming larval stage and tenacious "holdfast" in adult mussels. A second non-native and related species of mussel, the quagga mussel (*Dreissena bugensis*), has also been found in two locations in Lake Erie (Kelly, 1992; Mills *et al.*, 1994), and it is not unlikely that both species could progress downstream towards the St. Lawrence Estuary. Their predicted combined ecological impacts on resident biota is extensive and calculated costs associated with the population control and cleaning of fouled surfaces and intake waterpipes has been estimated to be up to 5 billion dollars by the year 2000 (Fifth International Zebra Mussel Conference, 1995).

The ruffe, a fish native to fresh and brackish European and Asian lakes and rivers, is an ecological and economic threat to the native yellow perch (*Perca flavescens*) and other fisheries of the Great Lakes (Pratt *et al.*, 1992). This species was first discovered in Duluth Harbour on Lake Superior in 1986 and speculated as being due to discharge of ballast water from an ocean-going freighter in the early 1980s. It has rapidly spread to several estuaries along the south shore of Lake Superior and in 1991, seven ruffe were collected in Thunder Bay, Ontario, 300 km to the northeast of its initial sighting, probably transported there in ballast water from the St. Louis River, the westernmost tributary of Lake Superior (Busiahn and McClain, 1995).

Other introductions of species into the Great Lakes via ballast water since the 1980's include the European or spiny water flea (*Bythotrephes cederstroemi*) (Sprules *et al.*, 1990) and several fish species such as the Black Sea or tubenose goby (*Proterorhinus marmoratus*) and Mediterranean or round goby (*Neogobious melanostomus*), which have all become successfully established with observable ecological and economic consequences (Mills *et al.*, 1993b; Leach 1995).

A few miscellaneous captures of species have also been recorded, and based on their country of origin, are most likely a result of ballast water discharges. Once again, in 1994, juvenile specimens of Chinese mitten crabs (*Eriocheir sinensis*) and European flounder (*Platichthys flesus*), previously caught in 1974 and 1976 in Lake Erie

(Emery and Teleki, 1978), were reported in the Great Lakes (Leach *et al.*, 1995).

These findings are not surprising as it has been shown that certain zooplankton taxa which live in brackish and salt water can survive, and apparently adapt to freshwater environments such as the Great Lakes (Locke *et al.*, 1993).

To date, phytoplankton sampling in Atlantic Canada has shown that the frequency of toxic algal blooms in and around Nova Scotia during summer months has tripled over the past 15 years, but a definitive connection with ballast water releases has yet to be established (Smith and Kerr, 1992). Concern over the import of toxic algae carried by ships bound for the Îles-de-la-Madeleine was subsequently investigated by Gosselin *et al.* (1993), who determined that 60% of ballast waters from ships whose last ports of call were all in Canadian waters contained small concentrations of four potentially toxic dinoflagellate species of *Alexandrium spp.* and *Dinophysis spp.*

In British Columbia, unintentional introductions that have induced significant ecosystem or economic effects include the parasitic copepod *Mytilicola orientalis*, several species of oyster drills, marine wood borers (including the isopod *Limnoria tripunctata* and the shipworm *Teredo navalis*), the brown alga *Sargassum muticum*, the soft-shell clam *Mya arenaria* and the seagrass *Z. japonica.* In the latter case, different tidal habitat preferences has resulted in an overall increased area of coastal seagrasses which has had a beneficial impact on resident invertebrates, fish and birds (Harrison and Tarbotton, 1995).

Several other organisms are recent introductions, such as the varnish clam (*Nuttallia obscurata*), or are considered likely candidates as a result of recent establishment in adjacent US coastal waters, such as the Asian calanoid copepod (*Pseudodiaptomus inopinus*)and the Asian brackish-water clam (*Potamocorbula amurensis*) (R. C. Wilson and R. Forbes, personal communication). The European green crab (*Carcinus maenas*) has recently become successfully established in San Francisco Bay (Cohen *et al.*, 1995; Grosholz and Ruiz, 1995). Considering the extensive ballast water-carrying vessel traffic along the B.C. coast between the Puget Sound/Strait of Georgia complex and this Bay, this crustacean is another species likely to be introduced into Pacific Canadian waters in the near future. Ecological and economic implications are potentially significant as this would be the first large predator species to be introduced into Canadian west coast waters (G. Jamieson, personal communication).

Scientific studies

The earliest study on ballast water in Canadian waters was commissioned in 1980 by Environment Canada and conducted by Bio-Environmental Services Ltd. (1981). Sampling of ballast water in 55 ships from 10 worldwide locations entering the Great Lakes – St. Lawrence system revealed that all contained viable aquatic organisms and even raw sewage in one instance. However, most notably, this study predicted that the zebra mussel could be introduced to the Great Lakes as a result of ballast water discharges (Bio-Environmental Services Ltd., 1981).

At a workshop entitled "The Risk to Canada's Marine Resources of Species Carried in Ship's Ballast Waters" sponsored by DFO in 1991 at the Bedford Institute of Oceanography in Halifax, one of the recommendations was to identify exotic organisms and their potential risk of introduction into Atlantic Canada's coastal waters (Smith and Kerr, 1992).

In 1991, the Great Lakes Fishery Commission convened a workshop entitled "What's Next? The Prediction and Management of Exotic Species in the Great Lakes", the results of which were published by Mills *et al.* (1993a). Through literature reviews, Mills *et al.* (1993b, 1994) developed and published an extensive list of documented introductions of non-indigenous aquatic flora and fauna into the Great Lakes basin since the early 1800s.

A review and evaluation of ballast water management and treatment options to reduce the potential for the introduction of non-native species to the Great Lakes was prepared for the Ship Safety Branch of the Canadian Coast Guard in Sarnia, Ontario, by Pollutech Environment Limited (1992). Phase I reviewed control, management and treatment options, and provided supporting documentation of the abiotic and biotic characteristics of ballast water. Phase II examined and ranked each treatment option in regards to cost, effectiveness, safety concerns and environmental acceptability, the results of which favoured physical measures such as mid-ocean exchange or discharges to a shore-based treatment facility over chemical treatments. Two of the more significant conclusions of this report were that a comprehensive characterisation of ballast waters and sediments was not yet available and secondly, that based upon the variety of organisms and life stages, e.g. larvae and resting cysts, the most effective control measure may never achieve 100% effectiveness in eliminating the risk of exotic species introduction (Pollutech Environment Limited, 1992).

From May to December 1990 and March to May 1991, Locke *et al.* (1991, 1993) examined the extent of compliance with the voluntary ballast water exchange guidelines by 455 ocean-going foreign vessels entering the St. Lawrence Seaway. Based on information from the 90% of vessels who submitted Ballast Water Exchange Reports to the Canadian Coast Guard and St. Lawrence Seaway Authority, 89% of vessels carrying ballast water conducted exchange procedures as per the voluntary guidelines. In a subsequent paper, Locke *et al.* (1993) calculated the effectiveness of ballast water exchange by examining the living zooplankton in the ballast water carried by 24 vessels originating in fresh or brackish ports, having reported saltwater ballast exchange and proceeding up the Seaway. Locke *et al.* (1993) calculated that ballast water exchange was 67% effective – 16 of 24 vessels – in eliminating all living freshwater-tolerant zooplankton. They concluded that the effectiveness of ballast water exchange is also limited by the possible resuspension of organisms carried in residual water or bottom sediments, thus becoming potentially available for discharge in subsequent ports of call (Locke *et al.*, 1993).

From May to September 1992, 62% of 60 ballast water samples taken from ships docked at Îles-de-la-Madeleine carried small concentrations of four potentially toxic dinoflagellates, *Alexandrium* spp. and three *Dinophysis* spp. (Gosselin *et al.*, 1993). Eight of nine sediment samples collected from the ballast tanks of three ships contained resting cysts of *Alexandrium* spp. (Roy, 1994).

Subba Rao *et al.* (1994) examined ballast water samples from 86 ocean-going foreign vessels – originally collected by Locke *et al.* (1991), to inventory type and abundance of potentially toxic phytoplankton species. A variety of organisms were found, including 69 diatom and 30 dinoflagellate species, several for the first time in Canadian waters. Of these, *Pseudonitzschia pungens* and *Dinophysis acuminata* are toxigenic and have occurred in bloom proportions on Canada's east coast. The hypothesis of whether or not such blooms occur more frequently in coastal sites that receive ballast water discharges has yet to be tested (Subba Rao *et al.*, 1994) and the level of risk of introduction also remains unquantified (Forbes, 1994).

The 1995 meeting of the ICES Working Group on Introductions and Transfers of Marine Organisms was held in Kiel, Germany, from April 10 to 13, and D. Kieser, of the Pacific Biological Station in Nanaimo, B.C., was the Canadian representative. Although the main focus was the control of planned species introductions, several papers were presented on ballast water issues, including the survival of the life stages of various plankton and fish species and research by Lloyd's of London to investigate the possibilities of ballast water treatment during passage (D. Kieser, pers. comm.).

In June 1995, the American Association for the Advancement of Science – Pacific Division met at the University of British Columbia to discuss "Shipping-Associated Introductions of Exotic Marine Organisms into the Pacific Northwest: How Serious is the Problem?". Presentation topics included marine exotics and the shellfish industry of British Columbia, the introduction of seaweeds, the Asian calanoid copepod *Pseudodiaptomus inopinus* and harmful marine phytoplankton species by ballast water, interactions of an introduced seagrass and the native eelgrass and a risk assessment of the introduction of non-native organisms to Pacific northwest ports. From a review of the presented papers, there is active concern that B.C. fisheries and aquaculture will be threatened by the introduction of exotic organisms in ballast water of ships. While the impact of algal introductions along the west coast appears to have been minimal, more detailed distributions of marine phytoplankton and benthic microalgae are required in combination with regional population genetics, in order to fully evaluate the potential effects of viable phytoplankton spores from ballast waters.

Ongoing and proposed research

Phase I of an ongoing project being conducted by the Canadian Coast Guard (Prior, 1995) aims at validating and quantifying the concerns regarding the safety aspects of mid-ocean ballast water exchange such as hull stresses and loss of stability, and possible alternatives for ships unable to comply. The results of a study on two bulk carriers transiting the Laurentian Channel, showed that due to structural limitations, both would be physically unable to comply with the mid-ocean Voluntary Ballast Water Exchange Guidelines. Although all relevant stability criteria were met during the ballast exchange operation, changes in forward and aft drafts produced several instances of propeller emergence as well as increased risk of forward slamming. Subsequent phases of this study will involve investigating different initial base ballast conditions (Prior, 1995).

In 1994, Aquatic Sciences Inc. initiated a study for the Canadian Coast Guard (CCG), Ship Safety – Central Region, designed to further investigate the work of Locke *et al.* (1991) on the effectiveness of ballast water exchanges. To obtain data on salinity stratification, unpumpable ballast and sediment and the potential of basin to basin transfer of organisms, preliminary sampling protocol and prototype equipment were developed for double bottom ballast tanks (Aquatic Sciences Inc., 1995).

Initiated in 1993 at DFO's Maurice Lamontagne Institute in Mont-Joli, Québec, an ongoing study has to date, identified nine species of organisms which may be considered to be high risk potential invaders of the St. Lawrence Gulf and Estuary and 31 additional species representing lesser risk of introduction, or more likely to be introduced by methods other than in ballast water (Reid and Gauthier, unpublished). Maritime traffic patterns and current ballast water management practices are also being investigated and sampling of 100 vessels entering ports of the Gulf of St. Lawrence was initiated in July 1995.

On the Pacific coast, the B.C. and Washington Working Groups on Minimizing the Introduction of Exotic Species, hope to produce by June 1996, a report describing introduced species in the inland waters of Washington State and British Columbia, with policy recommendations on minimizing the risk of potential future introductions and responses to already introduced exotic organisms.

Conclusions

- There are presently no ballast water exchange regulations in Canada. Two sets of voluntary guidelines for ballast water exchange apply only to vessels entering the Great Lakes inland waterways through the St. Lawrence Seaway or those bound for Îles-de-la-Madeleine in the Gulf of St. Lawrence.
- Management activities are segmented by region and not integrated between official authorities.
- The Voluntary Ballast Water Management Plan for the control of ruffe in Lake Superior ports is currently the only action to limit potential inter-basin transport of non-indigenous organisms in ballast water.
- Regulations enforced by the US Coast Guard, under the *1990 Non-indigenous Aquatic Nuisance Prevention and Control Act*, are presently the only ones that protect the Great Lakes.
- Overall effectiveness is questionable because of the following factors:
  - The existing voluntary guidelines have a limited geographic coverage;
  - Due to current ship design and safety considerations, ballast water exchange is limited to certain vessel types;
  - Tanks with exchanged ballast water or those with unpumpable ballast water and sediments may still contain live organisms.
- To address the risks to Canada's aquatic habitats and resources, there is a need for a national action plan, in consultation with shipping, fishing and aquaculture industries, which could lead to policies, regulations and an integrated research program regarding ship-transported ballast water.

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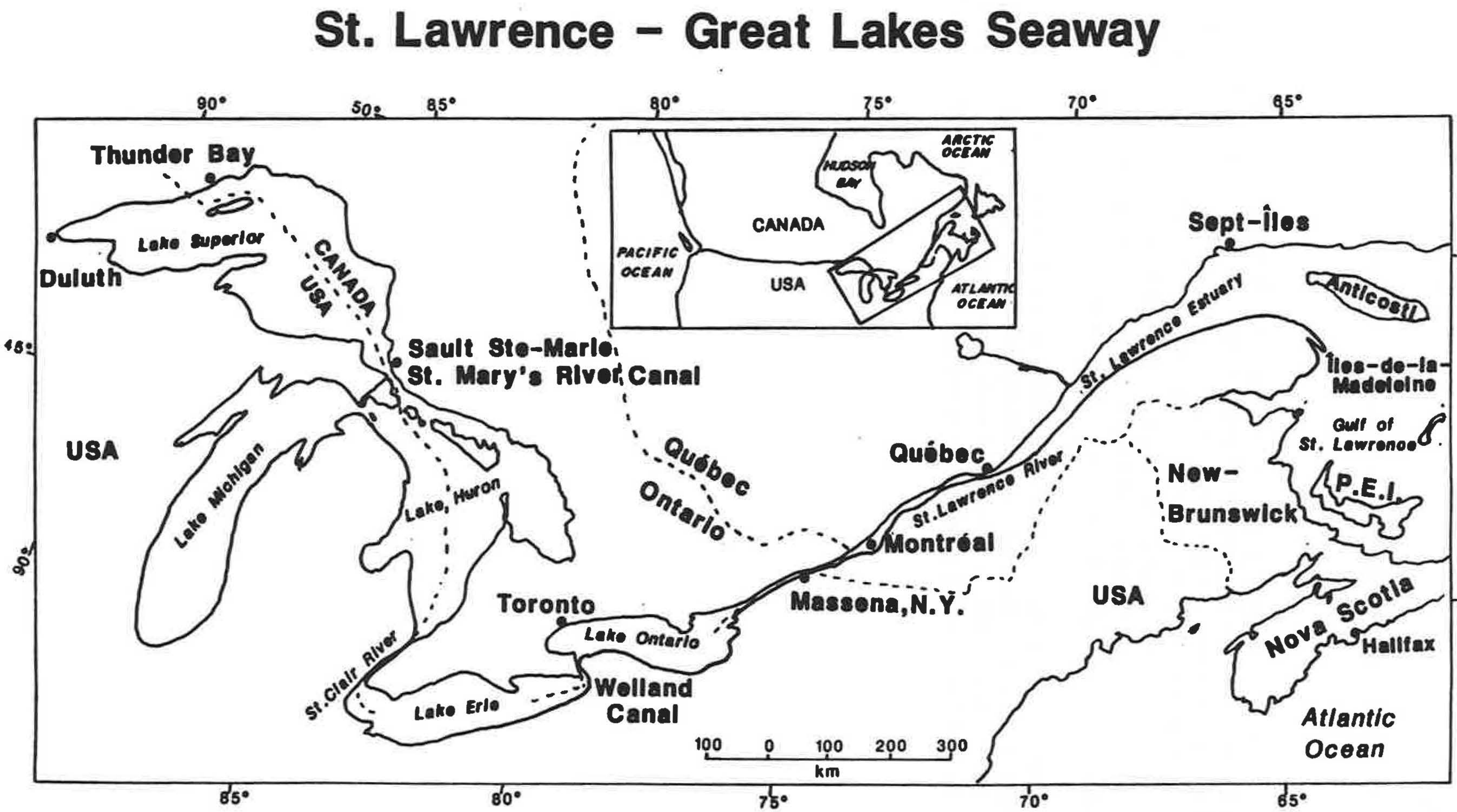

Figure 1 The St. Lawrence-Great Lakes Seaway.

Ballast water and mariculture in coastal areas: growing concerns about potential conflicts

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Mariculture activities in coastal waters are increasing world-wide. Much of the development takes place close to available infrastructure (for example, harbours, shipping routes, settlements with supplies and services). With increasing ballast water transfers by bulk carriers and by other types of ships, the risk of transferring locally, regionally, and intercontinentally, numerous organisms which may affect various aquaculture operations is of increasing concern. Although proof is difficult to obtain, circumstantial evidence suggests that, for example, algal blooms may have been inoculated by ballast water releases near shellfish farms and disease agents affecting fish culture systems are found in large quantities in the same ballast waters.

Mariculture operations are under strict control as to the transfer of new species and established culture candidates in order to minimise risk of disease transfers an ecosystem disruption. It is difficult to discipline the industry when other users of the coastal resource system are allowed to transfer water masses unrestricted, thereby being capable of introducing disease agents into waters near mariculture operations. The need for appropriate actions is emphasised.

Ballast water: its impacts can be managed

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The linking of ballast water and sediment discharges with the establishment of a range of non-indigenous marine organisms in various ports around the world, has focused recent attention on the identification and development of strategies to avoid further establishment of unwanted organisms. Several countries have introduced either voluntary, or mandatory regulations which seek to minimise the risks associated with discharge of water from overseas ports. A draft Australian strategy, for use with domestic ballast water is also currently under review. At the International level, the International Maritime Organization is developing a set of draft regulations as a basis for a new Annex to the existing International Convention on Marine Pollution (MARPOL 73/78).

Introduction

Although it is possible to develop an overall generalised strategy for international and national use, specific requirements may vary for different countries. These requirements will depend on many factors, including local port conditions, target organisms of interest, shipping patterns and quantities of ballast, seasonal effects, transit times, organism behaviour in ballast tanks and a host of other factors. In addition to basic management options (both proactive and reactive), based on an understanding of the factors involved, a range of physical, chemical, mechanical or biological treatment options continue to be investigated for their suitability as safe, cost effective, practical, technically effective and environmentally acceptable options. These may be used as part of the overall management "tool kit" of options to obtain the appropriate level of protection against the introduction of an organism, or group of organisms. Based on the "target" organism approach, coupled with an understanding of the conditions existing during ballasting, and in the discharge port, it is possible that only a relatively small number of ships may need to undertake ballast treatment before discharge, in some areas. This paper reviews the concept of an overall strategy, and briefly summarises some of the management and treatment aspects which have been investigated, as part of the Australian and related work, over the last 5 years.

Consequences of ballast water discharges and introductions

Clear evidence now exists that ships' ballast water has been a vector for the translocation around the world of marine organisms, including several toxic dinoflagellate species. In Australia, Jones (1991) has attributed some 16 organisms (including one toxic dinoflagellate, *Gymnodinium catenatum*) to ballast water or sediment discharge, although hull fouling has been proposed as another vector for introduction of some marine invertebrate species. The recently observed proliferation of the Northern Pacific Starfish (*Asterias amurensis*) in the Derwent River in Tasmania, Australia, is of major concern, although there is not yet clear evidence that ballast water has been the vector for this introduction. At the international level, Carlton and Geller (1993) have suggested that some 40 recent invasions have probably been mediated by ballast water.

Ballast water accounts for the movement of some 10 billion tonnes of water around the world annually (Rigby, 1994; Edwards, 1994). This water comes from a variety of ports and locations, each having its own set of environmental characteristics. A range of conditions, such as temperature, salinity, nutrient levels and tidal conditions will determine the characteristics of the particular communities present in the ballasting ports.

The economical and environmental consequences of introduced species have been very clearly demonstrated by the proliferation of the zebra mussel (*Dreissena polymorpha*) in the waterways of the USA (Edwards, 1994).

Regulatory measures

As a result of the establishment of foreign marine organisms in shipping ports, a range of measures have been put into place in various countries around the world in an attempt to minimise the likelihood of further spreading of these species and the establishment of new species (Rigby, 1994). Australia, Canada, USA, and New Zealand currently have applied the basic voluntary guidelines recommended by the International Maritime Organization (IMO).

The IMO guidelines were issued in 1993 at the 34th Maritime Environmental Protection Committee (MEPC) session, following agreement that ballast water is now regarded as an international pollutant of major consequence. An MEPC 36 working group was formed, and is continuing to draft proposed regulations for the new annex to MARPOL 73/78 for ultimate acceptance and implementation by all IMO contracting nations. The basic guidelines seek to put in place a range of management and treatment options that are safe, effective, environmentally acceptable, and cost effective. In Australia, a National Ballast Water Strategy recently announced by the Federal Government will ensure that the Australian impetus developed by AQIS, the shipping industry and other organisations will continue in the future. In New Zealand, steps are being taken at present, to initiate the development of a National Strategy.

An overall strategy

An overall management strategy (Figure 1) has been suggested as a basis for the minimisation of new introductions and establishment, arising from ballast water discharges (Rigby, 1994). This strategy (which has not yet been adopted) involves an assessment of conditions existing in the ballasting and deballasting ports, and the implementation of various management and treatment options in transit.

Ballasting port conditions

An essential part of the strategy is an understanding of the conditions existing in the port, and more importantly, whether the water being ballasted contains harmful or unwanted organisms. In Australia it is recognised that, at present, it will be unrealistic to eliminate all marine organisms, and a "target" organism approach has been adapted as part of the strategy. The selection of "target" organisms is based on such factors as likelihood of presence in the water during ballasting, survival in ballast tanks, establishment (once discharged) in deballasting port, and consequences once established. This understanding may require an effective and manageable monitoring/analysis program. Attention to ballasting practises can also assist in minimising the amount of water, or quantity of organisms involved.

If it can be demonstrated that the water is free of the defined organisms, the ship can then proceed to the discharging port and deballast in accordance with normal procedures involving monitoring, radio pratique and other quarantine formalities. This step avoids the need to undertake any ballast water treatment en-route. If the water is found to contain any of the "target" species, then management or treatment, involving one of the various options would need to be followed in accordance with established guidelines.

Whilst this approach may be practical for international ships bound for Australia, it may require some modification in other parts of the world. For example, for ships entering North America, treatment of all ballast water (to increase salinity levels to prescribed levels, for the control of zebra mussels) is mandatory.

Treatment/management options during transit

A range of treatment or management options have been suggested to destroy unwanted organisms (Carlton, 1990; Smith and Kerr, 1992; Rigby *et al.*, 1993; Ichikawa *et al.*, 1993). The Australian research associated with the various options has concentrated on toxic dinoflagellates, since this was the main area of initial concern, and it was considered that techniques that could manage these organisms could also be applicable to many other organisms of potential concern. An added complication has been that the toxic dinoflagellates of concern can produce resistant sexual cysts which can survive for long periods of time and subsequently germinate into the vegetative form under favourable conditions. Recent work by Rigby and Hallegraeff (1994) has shown that the vegetative forms of many of these dinoflagellates do not survive for many days in the closed ballast tank environment, and the sexual resting cysts are not likely to form in the ballast tanks. Concerns about the toxic dinoflagellates (especially *Gymnodinium catenatum* and *Alexandrium* species) have therefore been essentially isolated to the resistant sexual cysts, since the motile cells do not generally survive in the ballast tanks beyond 3 days (Rigby and Hallegraeff, 1994).

Mid-ocean exchange of ballast water is at present the most widely used approach to an appropriate level of protection against organism transfer. It is included as an option in all management guidelines in use throughout the world. In this option, water from the deep ocean (which is considered to be free of the organisms of concern) is used to exchange the original water taken on during ballasting. The near-surface dwelling (top 10-15 metres of the water column) organisms of the deep ocean, form a group quite distinct from those living in coastal waters, where ballast is generally first taken on. This exchanged water will generally contain organisms that are not likely to survive in coastal deballasting ports. In addition to exchanging all or part of the original water and organisms, ocean exchange can also be effective as a natural biocide by increasing salinity levels to a point where some fresh water species (such as the zebra mussel) are not able to survive. The effectiveness of ballast exchange in eliminating organisms will depend on the efficiency of ballast exchange, together with the degree of exchange necessary to have the desired effect. For example, an increase in salinity to a level sufficient to kill zebra mussels does not require complete exchange of the original water, whereas the elimination of all organisms would require total replacement of the original water.

Three basic options exist for ocean exchange of water. These are illustrated in Figure 2 and include (Rigby and Taylor, 1994):

- emptying of tanks followed by refilling (***reballasting***)
- continuous flushing or flow-through (***ballast exchange***)
- a combination of the above.

Reballasting can provide an effective way of replacing the original water with clean ocean water. The efficiency of replacement will depend on the design of the ship's ballast tanks and pumping system, but will typically be as high as 99.5 to 99.9% (Rigby and Taylor, 1994). Ship safety is a key consideration in utilising this technique to ensure that safe bending moments and shear stresses acting upon the hull of the ship are not exceeded. A set of guidelines based on the various options available for ocean exchange have been prepared as a basis for future use of this control option (Rigby and Taylor, 1994). The Marine Safety Committee (MSC) of IMO, through a Correspondence Group (chaired by Australia) is currently reviewing the safety aspects of ballast water exchange.

Ballast exchange avoids the problem of exceeding safe bending moments or stresses, since the tanks remain full at all times. The efficiency of exchange of this option depends on the number of tank volumes exchanged (Figure 3). Typically an exchange of three tank volumes will result in a replacement of approximately 95% of the original water and an even higher proportion of organisms. Reballasting compared to ballast exchange is generally more cost effective and can achieve a higher level of original ballast replacement in a shorter time. However safety aspects may dictate use of the ballast exchange option. Not all ships have provision for safe overflow of the flushing water and therefore are not able to use the ballast exchange option.

A combination of both reballasting and ballast exchange may be appropriate for some ships, especially where ship stresses are of concern when emptying some specific tanks. One example of a slight modification of the reballasting option, currently being practised by one shipping company (and of potential interest for future ship designs), is illustrated in Figure 4. During ballasting of this 120,000 dwt bulk carrier, ballast water (35,000 tonnes) is taken on in 2,3,5,7, forepeak and afterpeak tanks. Once at sea, in an appropriate area, tanks 1,4 and 6 are filled whilst the original tanks are emptied on a sequential basis. The overall result is that none of the original water is discharged in the receiving port, thus giving a 100% solution to possible organism translocation.

Initial work by Bolch and Hallegraeff (1993), and Rigby and Hallegraeff (1993), involving various chemical treatment options (for dinoflagellate cysts), using hydrogen peroxide, chlorine, copper sulphate and various other microbiocides, concluded that these are likely to be impractical, too expensive for general use, and in some cases, themselves environmentally unacceptable. As an example, the use of 500ppm free chlorine (required to treat dinoflagellates cysts on the BHP owned "Iron Whyalla"; 50,000 tonnes ballast water), would cost approximately $100,000. Treatment of motile dinoflagellates would require lower chemical dosages. However, even at 50ppm free chlorine, the cost of $10,000 would still be totally unacceptable for routine use. Recent work by Montani *et al.* (1995), also showed that sodium azide was likely to be too costly and ineffective against some dinoflagellate cysts. Physical treatment options, such as filtration, are able to minimise the majority of unwanted organisms but the cost for large ships (either as a ship based or shore based option) is likely to be prohibitive (Rigby, 1994). The cost of some of these treatments for ships involving very much smaller quantities of ballast water, may be acceptable under some circumstances.

Options involving the use of ultraviolet radiation, ozonisation and other techniques commercially used for industrial and potable water treatment are likely to be impractical (at the scale of operation required for large ships), far too costly, or ineffective against dinoflagellate cysts. Montani *et al.* (1995) have shown that germination of cysts of *Alexandrium, Gymnodinium, Proto-peridinium, Scrippsiella and Gyrodinium,* at levels equivalent to at least 40% of the controls, occurred after exposure to UV radiation for 2 hours. They also showed that inactivation of dinoflagellate cysts was readily achieved by use of an electric shock (100V for 5 seconds). Utilisation of this principal may be possible in some cases, and is presently under further evaluation.

The potential of inactivating toxic dinoflagellates cysts (and for killing other marine organisms) by heating ballast water has attracted recent interest as an environmentally friendly, and cost effective solution (Bolch and Hallegraeff, 1993; Rigby and Hallegraeff, 1994). Initial laboratory work by Bolch and Hallegraeff (1993) indicated that heating *Gymnodinium catenatum* cysts to temperatures of 40 to 45°C, for very short periods of time (30 to 90 seconds) resulted in inactivation. Heat treatment is also used as one of the basic control measures for zebra mussels in the temperature range of 33°C to 36°C, for exposure times varying from several minutes up to 2 hours (Jenner and Janssen-Mommen, 1994).

Waste heat from the main ship's engine can potentially provide a cost effective source of heat. However if this option is to be used, then heating needs to take place during the sea voyage, as the ship's engine is not generally in operation during ballasting or deballasting. An analysis of available waste heat from the "Iron Whyalla" has indicated that the most appropriate means of utilising this heat would be to flush the rejected hot water (available at a temperature of 45°C) through the ballast tanks in sequence, allowing the excess water to overflow from the ballast tanks (Rigby and Taylor, 1993). There is, however, insufficient heat available to reach a temperature of 40°C. The final temperature reached in the ballast tanks in the case of the "Iron Whyalla" (where the flow rate of hot water varies with the ocean water temperature in order to maintain a constant inlet temperature to the engine cooling circuit), will depend on the ocean temperature. For ocean temperatures between 25°C and 30°C, equilibrium ballast tank water temperatures in the vicinity of 35°C to 38°C may be possible (after approximately 48 hours flushing of each tank).

On the basis of these data, a series of further laboratory tests by Marshall and Hallegraeff (1995) and Rigby and Hallegraeff (1995) have been undertaken to examine the effects of lower temperatures for extended periods of time. This work has shown that most phytoplankton algae tested (including the diatom *Skeletonema costatum,* dinoflagellates *Amphidinium carterae,* and *Gymnodinium catenatum,* and the golden brown flagellate *Heterosigma carterae*) could, in the vegetative plankton stage, be readily killed at temperatures as low as 35°C and treatment times in the range of 30 minutes to 5 hours. Further studies using *Gymnodinium catenatum* cysts have indicated that significant mortality can also be achieved using longer incubation times (several hours) at temperatures as low as 35°C to 37.5°C. This work needs to be repeated with *Alexandrium* cysts.

These findings, together with the likely temperature profiles that could be expected in tanks on the "Iron Whyalla", suggest that this mode of treatment could provide a cost effective and environmentally attractive treatment option for a range of phytoplankton species, including toxic dinoflagellate cysts. Studies are in progress to quantify the ballast water temperature profiles and to examine the feasibility of ocean trials, to assess some of the practical issues involved and to further evaluate this technique.

Receiving port conditions

One of the key issues in the overall scenario outlined in Figure 1 is the likelihood of a particular organism becoming established in the deballasting port. Several recent studies have now allowed some early conclusions to be drawn on this aspect. The likelihood of an introduced species becoming established, and creating a reproducing population, depends on many factors. These primarily include the ecological characteristics of the species and the environmental conditions into which it is inoculated. These characteristics determine whether the species will survive the voyage in the closed ballast tanks, and also whether it will establish viable populations within the deballasting port.

Species most likely to become established in a new environment are those which come from a similar hydrological environment (for example, species from temperate environments are more likely to survive in temperate estuaries than in tropical ones). Another important aspect is that of the receiving environment. Estuarine or shallow bay areas are more likely to provide conditions suitable for establishment of compatible species, whereas the strong ocean currents and high water velocities (coupled with inhospitable ocean bed conditions) existing in open offshore ports, will disperse the organisms much more widely than in the shallow estuarine areas, and provide conditions unsuitable for toxic dinoflagellate growth. Two recent case studies in the ports of Hay Point in Queensland, and Hobart in Tasmania (Australia) have highlighted some of these aspects (Rigby and Hallegraeff, 1995). The port of Hay Point, located some 30 km south of Mackay in Queensland, is essentially a sub-tropical to tropical port with ocean temperatures varying between approximately 22°C and 27°C. The port has two coal export terminals (Hay Point and Dalrymple Bay) having a total export capacity in the vicinity of 50 Mtpa. The shipping berths are located 2 km offshore. Annual ballast water discharges from the bulk coal carriers are approximately 15 Mtpa. Tidal variations range from approximately 4m to 7m, and the ocean bottom, in and around the loading berths is essentially sandy to sandy/clay. Only minor amounts of mud (which would be conducive to retaining dinoflagellate cysts) exists in the port proper, although mud banks and other muddy areas exist to the north and to the south.

By contrast, the port of Hobart in Southern Tasmania, is essentially a temperate port with ocean temperatures varying from about 10°C to 18°C (Hallegraeff *et al.*, 1989). The shipping trade is essentially based on wood chips (Triabunna, since 1971), wood pulp (Port Huon, 1962-1982), fruit (Port Huon, 1950-1960), minerals (zinc) and general cargo (Hobart). Annual ballast water discharges amount to approximately 1Mtpa. Tidal variations range from 0.5 to 1.5m, and water movements (except during flooding) are relatively low (typically $50m^3s^{-1}$) compared to those which occur in the Port of Hay Point. Bottom conditions within the various bays and estuaries include predominantly fine mud conducive to retaining dinoflagellate cysts which may be discharged in ballast water and settle in the area.

A recent survey of the port of Hay Point unambiguously indicated the occurrence of a truly tropical plankton community with no evidence of the presence of toxic dinoflagellate species (such as *G. catenatum* and *Alexandrium*), both of which have been repeatedly detected in samples of ballast water discharged into this port (Hallegraeff and Bolch, 1991, 1992; Rigby and Hallegraeff, 1995). The only dinoflagellate cysts detected (*Protoperidinium, Gonyaulax, Scrippsiella*) were of non toxic species, all of which are widespread through Australian waters.

However by comparison, in the Port of Hobart, the toxic dinoflagellate *Gymnodinium catenatum* is prolific, while both *G. catenatum* and *Alexandrium* cysts have also been detected in the neighbouring port of Triabunna.

These two case study examples clearly illustrate the significance of matching port conditions in relation to the establishment of toxic dinoflagellates. In the case of Hobart, the water temperatures (10°C to 18°C) are consistent with those in the majority of temperate Japanese ports, where the majority of ballast water originates (14°C to 21°C), whereas the temperatures in Hay Point (22°C to 27°C) are too high for establishment of the Japanese toxic dinoflagellates. Hallegraeff *et al.* have shown that *Gymnodinium catenatum* blooms in Tasmania tend to proliferate at water temperatures in the range of 12°C to 18°C (Hallegraeff *et al.*, 1995). In addition to the temperature match between Hobart and the Japanese ports, the local environmental conditions (relatively low water movement and abundance of muddy bottom areas) also provide a desirable substrate for retention, and subsequent establishment of dinoflagellate cysts.

The initial Australian focus on toxic dinoflagellates, has allowed significant progress to be made in developing an overall strategy, and assessing a range of treatment/management options which may ultimately become part of the "tool kit" for implementation during the voyage.

The range of "target" organisms is currently under review by the Australian Ballast Water Advisory Council and the Research Advisory Committee. Further research projects aimed at establishing the extent of organism invasion, developing a risk management system and investigation of further treatment options for the "target" species" are also being developed.

A range of other management options, incorporating selective port ballasting, containment of contaminated water, utilisation of alternative sources of water, and ship design changes to allow more widespread and safe use of many of the potential options, are possible for future long term consideration and implementation.

Ongoing collaboration, at the international level is considered to be essential, to minimise duplication of efforts and to exchange the results of observation and research investigations.

Conclusion

It can be seen that by developing international and national management strategies involving an understanding of ballasting and receiving port conditions, and the behaviour of organisms in ballast tanks, coupled with a range of en-route management and treatment options, the impact of ballast water discharges can be effectively managed.

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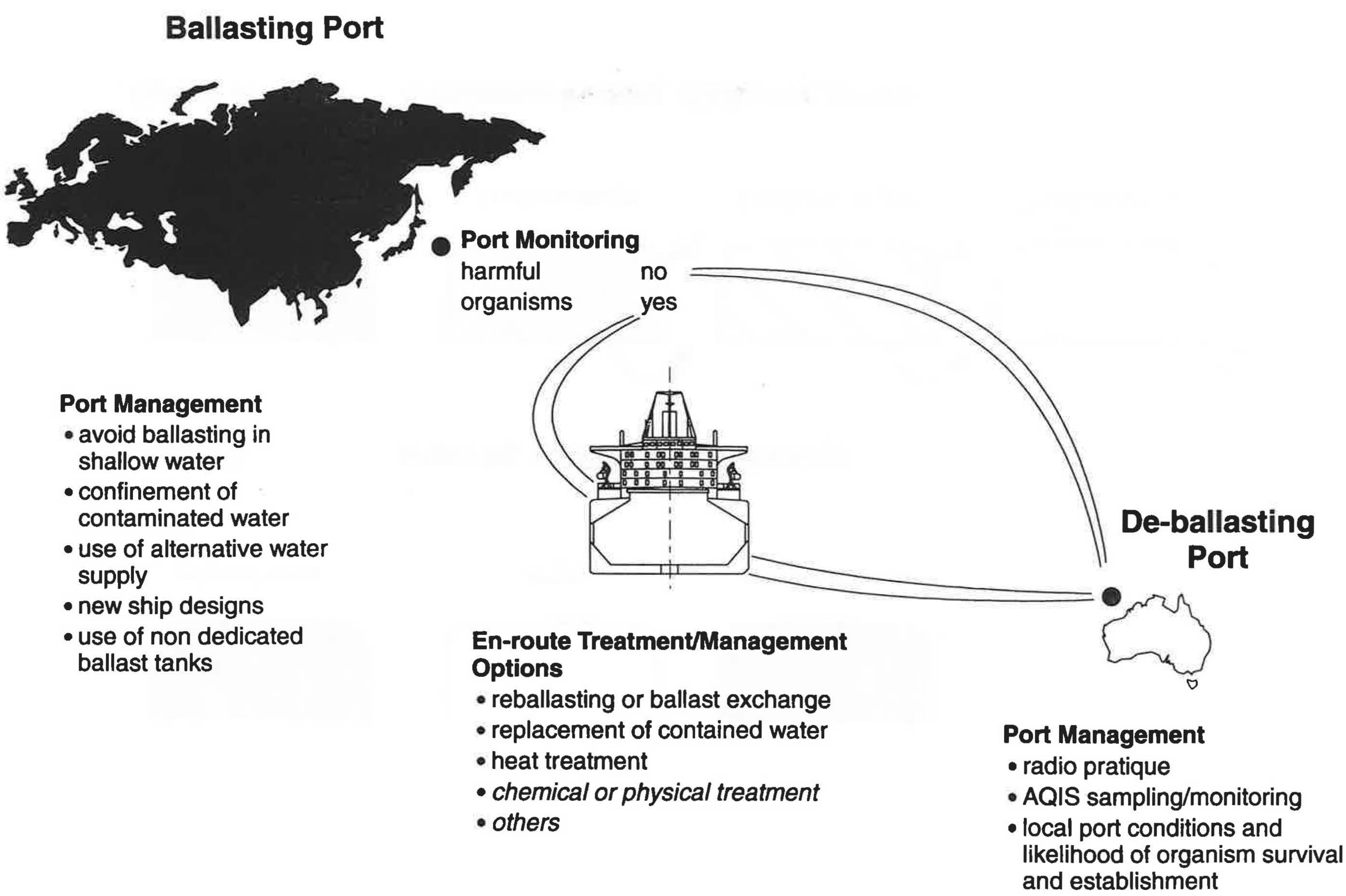

Figure 1 Overall Strategy for Ballast Water Management (from Rigby, 1994).

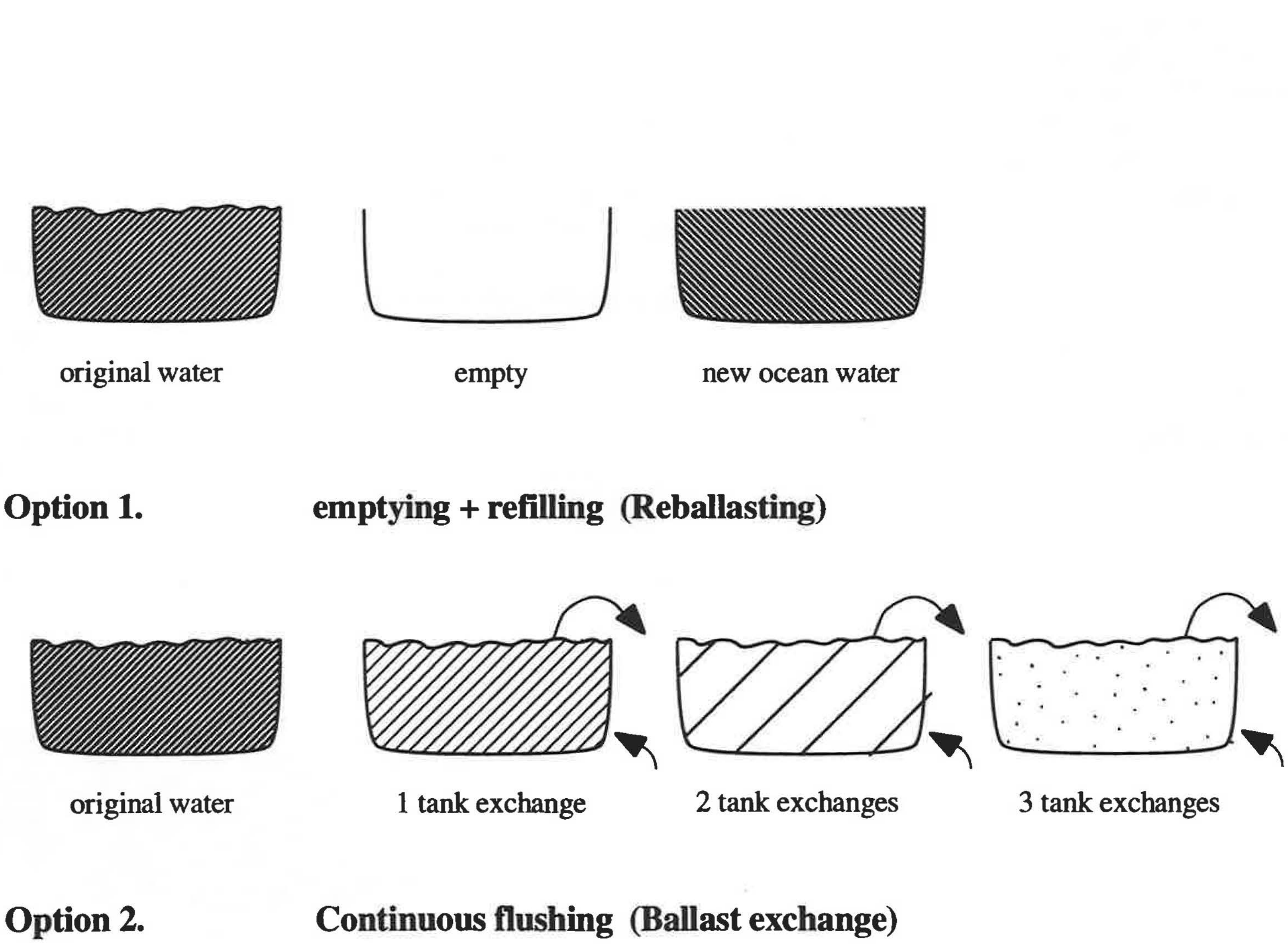

Figure 2 Options for Ocean Exchange of Ballast Water.

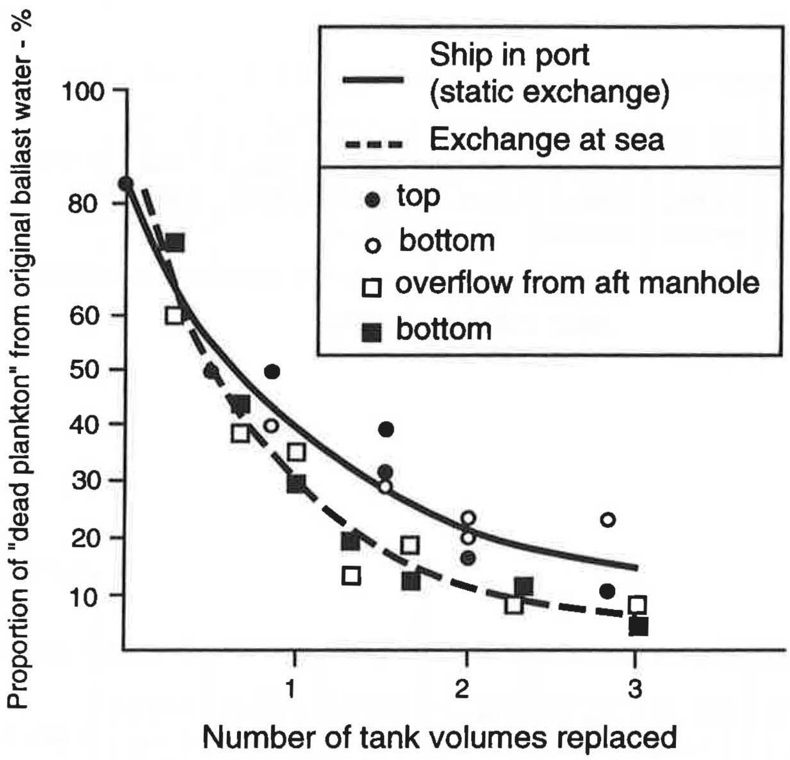

Figure 3 Efficiency of Replacement of Organisms on the "Iron Whyalla" using the Ballast Exchange option (Rigby and Hallegraeff, 1994).

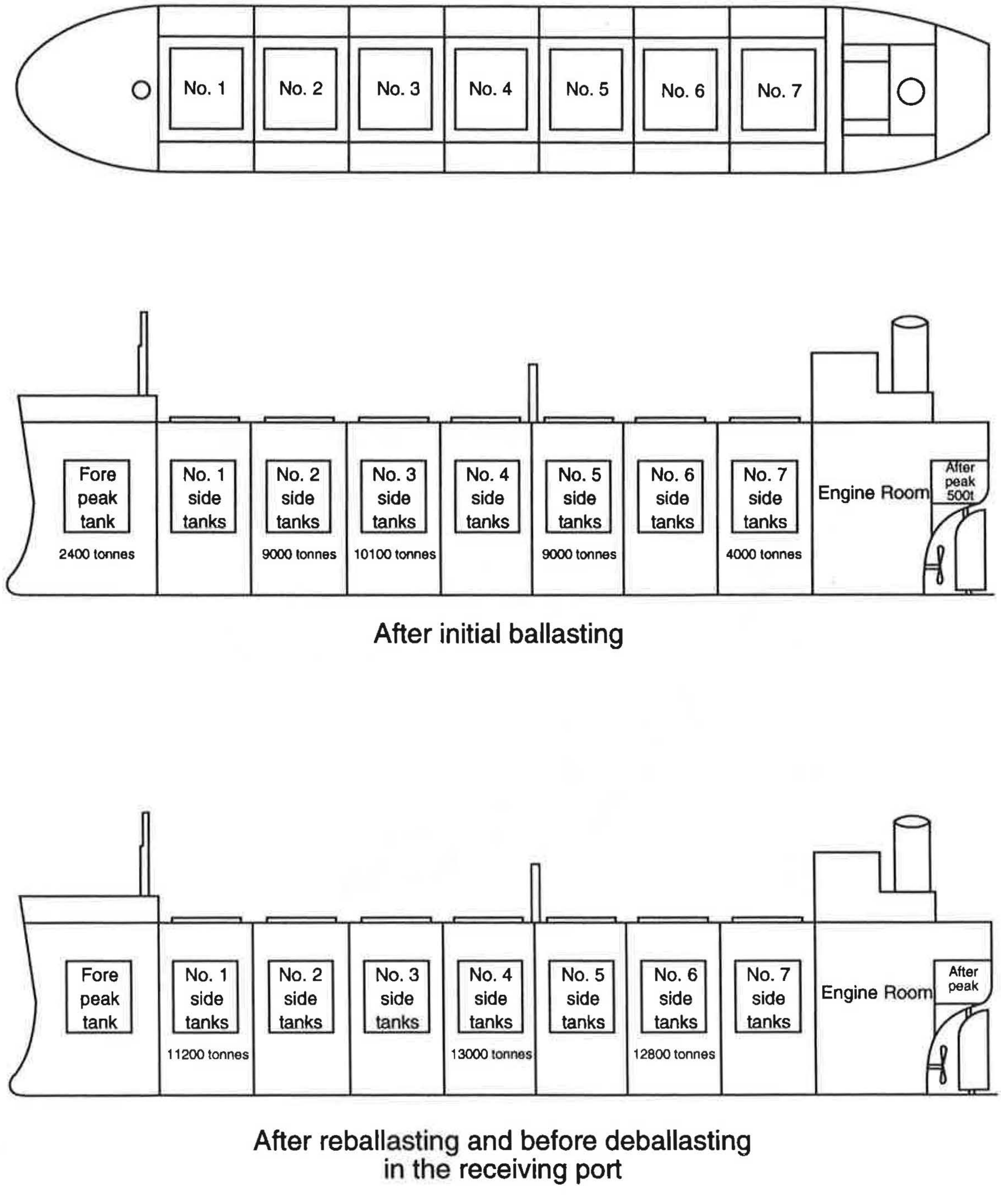

Figure 4 Two Step Reballasting, Deballasting and Reballasting Management Strategy.

Provisions for the control and management of ballast water to minimize the transfer of harmful aquatic organisms and pathogens

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Introduction

The International Maritime Organization (IMO) is a specialized agency of the United Nations dealing with maritime affairs, i.e. to improve safety of life at sea and to prevent marine pollution from shipping. In 1973, during preparation of the Convention of Pollution from Ships (MARPOL), the International Conference on Marine Pollution requested the World Health Organization, by resolution, to initiate studies and research concerning the effects of discharge of ballast water containing bacteria of epidemic diseases, on the basis of any evidence that may be submitted by any Government. In those days concern focused primarily on the transfer of pathogens through ballast water. It might be of interest to note that until very recently no Government has found it worthwhile to actually ask WHO to carry out such research. It has now been included in the work programme of WHO.

The role of ballast water discharges for the introduction and establishment of non-indigenous aquatic organisms was already known early in this century. From single data published in the mid 1970s, the list of organisms that have survived ballast water transfer today contains several hundred species, including bacteria, e.g., *Clostridium botulinum* and *Vibrio cholerae*.

It seems that the number of cases that have been reported in regard to the survival of organisms transported with ballast water and associated sediments have increased considerably since the mid 1970s. This could be due to increasing research activities on the one side, and, and on the other side, due to larger ships and faster voyages.

A number of the introduced non-native species have caused severe effects upon the ecology of their new habitats. From the many examples that are known to have caused catastrophic effects, I should mention those four cases that did convince a number of IMO Member States that action was needed to reduce opportunities for the transfer of aquatic organisms through ballast water. These are:

- the European zebra mussel *Dreissena polymorpha* in the North American Great Lakes, causing severe damage to underwater constructions and pipes;
- the American comb jelly *Mnemiopsis leidyi*, causing near extinction of anchovy and spray fisheries in the Black and Azov Seas;
- the South-east Asian brown kelp *Undaria pinnatifida*, having detrimental impact on the Tasmanian abalone industry; and
- the South-east Asian dinoflagellate of the *Gymnodinium* and *Alexandrium* species into Australian waters contaminating shellfish and producing toxins that are harmful to humans.

The countries that had been particularly affected by these events or feel threatened by the introduction of alien organisms in their waters have been in the forefront of IMO Member States requesting that action should be taken by IMO. These were Australia, Canada, New Zealand and the United States. They are currently supported by States bordering the Baltic Sea, after realizing that about fifty species had been introduced from elsewhere, and noting the catastrophe caused in the Black Sea by *Mnemiopsis*. These countries realized that this was an issue that could not be solved solely on the basis of national or regional regulations, but needed international action, which could then be complemented by domestic provisions.

Ballast water

Water is used as ballast in ships to ensure that the propeller and bow are submerged to an acceptable depth. Large ships, particularly bulk carriers, tend to spend 40 to 50 per cent of their sea time in ballast. Total water ballast tonnage can range from a few hundred up to about 80,000 tonnes.

Ballast water guidelines developed by IMO's Marine Environment Protection Committee (MEPC)

After several years of preparation, the Marine Environment Protection Committee (MEPC) of IMO in 1991 adopted Guidelines for Preventing the Introduction of Unwanted Aquatic Organisms and Pathogens from Ships' Ballast Waters and Sediment Discharge. These Guidelines contained advice to IMO Member States on how they might introduce relatively simple basic ballast water management controls. They were based on national control measures taken at that time by Australia, Canada and the United States. The MEP Committee emphasised that the adoption of these voluntary guidelines should be a first step in addressing the problem. In the longer term the Committee would have to evaluate whether legally binding provisions, either as amendments to MARPOL 73/78 or as a new annex to the MARPOL Convention might be appropriate. The attention of IMO Member States was also drawn to the fact that efficient treatment processes for ballast water on board ships still need to be developed.

Then in 1992, the United Nations Conference on Environment and Development (UNCED) included in its Agenda 21, Chapter 17 on the Protection of the Oceans and All Kinds of Seas......, a request for IMO to consider "the adoption of appropriate rules on ballast water discharge to prevent the spread of non-indigenous organisms" (paragraph 17.30(a)(vi)).

The development of legally binding rules on ballast water management is, from the technical point of view, not as easy as it may seem. There is at this stage still a lack of efficient ballast water treatment techniques. The basic advice provided in the Guidelines that ships should exchange ballast water during voyages in deep-sea areas is not without problems in relation to safety and stability aspects of the ships concerned. Simlarly, the advice that Port Authorities may set up port reception facilities for ballast water, and facilities for treating sediments from ballast tanks is not without problems.

The Marine Environment Protection Committee in 1993, when considering action to be taken in response to UNCED's request, therefore agreed that at this stage the Ballast Water Guidelines should remain voluntary due to the lack of any major advance in ballast water management and treatment processes. However, in light of the apparent lack of IMO Member States implementing or observing the Guidelines, MEPC requested the IMO Assembly to adopt by Resolution these Guidelines for Preventing the Introduction of Unwanted Aquatic Organisms and Pathogens from Ships' Ballast Waters and Sediment Discharge. Through this measure members of the MEPC expected that more weight would be given to the recommendations set out in these Guidelines.

In its submission of the Guidelines to the IMO Assembly, MEPC proposed that the Assembly should request IMO's Maritime Safety Committee to consider the safety aspects, particularly with regard to stability and structural integrity of ships exchanging ballast water at high seas. The Assembly further requested IMO bodies to liaise with other relevant organizations such as WHO, UNEP, IOC, ICES and the International Association of Ports and Harbors with a view to seeking their participation in resolving the issue of harmful aquatic organisms in ballast water.

Finally, in 1993 the IMO Assembly confirmed that the Marine Environment Protection Committee should keep the ballast water issue and the application of the IMO Guidelines under review with a view to developing legally binding provisions for inclusion in MARPOL 73/78.

Since 1994 a Ballast Water Working Group established by the MEPC has been considering form and contents of possible regulations for the "Control and Management of Ships' Ballast Water to Minimize the Transfer of Harmful Aquatic Organisms and Pathogens". These might be presented through a set of a number of legally binding provisions, accompanied by implementation guidelines. Such guidelines would only have the status of recommendations and as such could be easily reviewed, updated and amended in light of experience gained with them and of new research and technical developments. The combination of small sets of legally binding rules with more detailed guidance for their interpretation and effective implementation has been a very successful mechanism used by IMO, particularly if complemented by technical co-operation and assistance programmes for less developed countries.

The guidelines

The Guidelines in an introduction emphasize the purpose of their development and application, namely, "to provide Administrations and Port State Authorities with guidance on procedures that will minimize the risk from the introduction of unwanted aquatic organisms and pathogens from ships' ballast water and sediment. The selection of an appropriate procedure will depend upon several factors, including the type or types of organisms being targeted, the level of risks involved, its environmental acceptability, and the economic and ecological costs involved".

In this connection it should be noted that throughout the Guidelines mention is made of their aim to minimize the risk of introducing non-native organisms. This is somewhat more modest but also more realistic that their title referring to "preventing the introduction of unwanted organisms".

Under a section "General principles", it is pointed out that the ability of aquatic organisms and pathogens to survive, after transportation in ballast water, can be reduced if significant differences in ambient conditions prevail, e.g., salinity, temperature, nutrients and light intensity. The probability of organisms survival under different conditions of salinity are considered in a matrix comparing fresh water, brackish water and fully saline waters of ballast water uptake areas with those of the receiving waters.

PROBABILITY OF ORGANISMS' SURVIVAL AND REPRODUCTION

	Discharged Ballast		
	Fresh water	Brackish water	Fully saline water
Receiving Waters			
Fresh water	HIGH	MEDIUM	LOW
Brackish water	MEDIUM	HIGH	HIGH
Fully saline water	LOW	HIGH	HIGH

Under "Strategies", the Guidelines introduce seven different options that may be effective in minimizing the incidence and introduction of unwanted aquatic organisms and pathogens, as follows:

- the non-release of ballast water;
- ballast water exchange and sediment removal at sea, or in areas designated as acceptable for this purpose by the Port State Authority;
- ballast water management practices aimed at preventing or minimizing the uptake of contaminated water or sediment during ballasting operations;
- ballast water management practices aimed at preventing or minimizing the discharge of contaminated water or sediment during deballasting operations;
- discharge of ballast water into shore-based facilities for treatment or controlled disposal;
- ballast water and sediment treatment processes acceptable to Port State Authorities; and
- testing and certification, acceptable to the receiving Port State Authority, that ballast water and sediment from the ballasting port are free of unwanted aquatic organisms and pathogens.

Ballast water exchange and sediment removal

The Guidelines recommend that, in the absence of more scientifically based and technically approved efficient means of ballast water treatment and control, an exchange of ballast water in deep ocean areas or open seas offers a good possibility of limiting the transfer of fresh water species or coastal species with ballast water.

The probability of transferring unwanted organisms, through ballast water discharges, can indeed be greatly reduced by ocean or open sea ballast exchanges, preferably in recommended water depths of 2,000 m or more. This is currently the option most often used to minimize the risk of transfer and introduction of non-indigenous organisms. In those cases where ships do not encounter water depths of at least 2,000 m, the Guidelines recommend that an exchange of ballast water should occur well clear of coastal and estuarine influences. There is evidence to suggest that, despite contact with water of high salinity, the cysts of some organisms can survive for protracted periods in the sediment within ballast tanks and elsewhere on a ship. Hence, where ballast water exchange is being used as a control measure, care should be taken to slush out ballast tanks, chain lockers and other locations where sediments may accumulate, to dislodge and remove such accumulations, wherever practicable.

Pursuant to recognized maritime practices, the responsibility for deciding on ballast water exchange in open seas must rest with the Master of the vessel, taking account of the following safety requirements:

- stability has to be maintained at all times to values not less than those recommended by the Organization (or required by the national Administrations);
- longitudinal stress values shall not exceed those permitted by the ship's classification society with regard to prevailing sea conditions; and
- exchange of ballast in tanks or holds where significant structural loads may be generated by sloshing action in the partially filled tank or hold shall be carried out in favourable sea and swell

conditions only such that the risk of structural damage is minimized.

Where a Master, due to weather, sea conditions or operational impracticability, is unable to comply with the management option of "at sea" exchange of ballast water which may be required by a Port State, the Master should report this fact to the Port State as early as possible prior to entering port. This is to allow for appropriate alternative action to be arranged.

Port State Authorities may take and analyse ballast water and sediment samples. Where ballast water or sediment sampling for compliance or effectiveness monitoring is being undertaken, Port State Authorities should ensure that there is no undue delay to ships when taking such samples.

Ship operational and safer aspects of ballast water exchange at sea

Three typical commercial ships – a dry-bulk carrier, a tanker, and a container ship – were investigated by the University of Michigan (United States, 1994) to determine the level of potential hazards when exchanging ballast water at high seas. The at-sea investigations for hull bending moment, shear, and rate of slamming for these ships have shown that for a 10-foot significant wave height, the bending movement and shear values were far below the design values required by current (1991) American Bureau of Shipping rules, and slamming was very infrequent. For 20-foot significant wave height, and a ship moving at its design speed, the bending movement and shear magnitudes are greater, but still well below allowed values. However, groups of peak waves occurring approximately one-in-300 among the 20-footers produce shear and movement values near or above the allowed values. Rate of slamming, even at the significant height, reaches what may be an intolerable level at the higher ship speeds.

Somewhere between the 10- and 20-foot significant wave heights must lie a threshold sea state below which it is safe for any typical ocean-going ship to exchange ballast.

Research on ballast water treatment options

With regard to on-board treatment of ballast water and associated sediments, the Guidelines draw attention to the need to carry out research of or developing future techniques, including:

- treatment with chemicals and biocides;
- heat treatment;
- oxygen deprivation controls;
- tank coatings
- filtering systems; and
- ultraviolet light disinfection.

Member States are being encouraged to carry out or to commission research studies into these and other relevant areas of ballast treatment techniques, and to provide information on results of such research to IMO.

In reviewing the various treatment options that are being investigated, it is apparent that no single treatment process has yet been found that is likely to achieve the required inactivation or removal of unwanted organisms. This is likely to consist of an initial preliminary mechanical treatment process, e.g., filtering or cyclonic separation, followed by disinfection or physical treatment processes, e.g., ultraviolet radiation, thermal processes and ultrasound.

With regard to chemical treatment options, the use of chlorine, chlorine dioxide, chloroamines, sodium and calcium hypochlorites and ozone, as well as bromine, potassium permanganate and hydrogen peroxide, have been investigated. Tests have further been carried out with organic biocides but their application would involve the use of detoxification agents. Electrolytically generated silver and copper ions have shown success in treating certain types of organisms but result in environmental concerns on the discharge of ballast water containing relatively high copper and silver ion concentrations in coastal or estuarine waters.

Treatment methods entailing salinity adjustments, i.e., the addition of fresh water to salt water or salt water to fresh water in order to disturb the osmoregulatory processes of the salt or fresh water organisms which are present in the ballast water have shown to be most effective and relatively simple. This is one of the options used by ships entering the North American Great Lakes.

Future development

The Ballast Water Guidelines adopted by the IMO Assembly in 1993 (resolution A.774(18)) have so far been applied in only a few IMO Member States, and in light of growing worldwide concern in relation to the introduction of non-indigenous organisms, disease bacteria and viruses through discharges of ballast water, and their effects on human health, the marine environment, fisheries, aquaculture and amenities, IMO has repeatedly drawn the attention of its Member States to the importance of this issue, urging all Governments to apply the Guidelines. Other Organizations, such as FAO, likewise requested its Member States to apply the Guidelines, as did regional bodies such as the Helsinki Commission.

During the thirty-seventh session of MEPC in September 1995 a first attempt was made to develop a set of legally binding regulations which could form a new Annex to MARPOL 73/78. These requirements shall be complemented by guidelines.

This seems to be a major breakthrough in reaching worldwide applicable legal provisions. However, the various management and control options that are available are still those referred to in the current recommendatory IMO Guidelines which are based on deep ocean exchange of ballast water.

The draft Regulations that are in development will contain:

General obligations:
requesting all Parties to promote measures "to control the spreading of non-indigenous organisms through ships' ballast water and associated sediments".

Definitions:
listing terms, such as:

harmful aquatic organisms
unwanted species
pathogens
clean ballast water
non-indigenous, alien

Application:
"shall apply to all ships"
[.. on international voyages] only

Force majeure:
due to stress of weather

[Exceptions:
for specific trade patterns]

Operational requirements:
containing references to Guidelines on Ships' Ballast Water Control and Management

Safety requirements:
are under development, taking into account ongoing work within several IMO Sub-Committees

Role of national authorities:
on implementation in districts and regional [uniform and co-ordinated?] and distribution of information on outbreaks of diseases, surveillance requirements, treatment techniques, compliance.

Another task that IMO was requested to carry out in the near future is the preparation of packages containing education and awareness material, and the establishment of clearing house functions for ballast water research. This includes a data bank on technical developments and setting up links with other related information centres, e.g., on toxic algae blooms.

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Ballast water management – an integrated approach

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Introduction

Aquatic Nuisance Species (ANS) are invading our waters at an alarming rate, causing significant ecological and economic impacts. Although there was evidence of aquatic invasions through ballast water in the United States prior to 1989, it was the discovery and rapid spread of the Zebra Mussel into the Great Lakes that brought the problem to public attention. The United States has since developed an integrated approach consisting of a combination of education and awareness and voluntary and mandatory ballast water management procedures.

The Non-indigenous Aquatic Nuisance Prevention and Control Act of 1990 (NANPCA) was passed to prevent the introduction and control the spread of ANS into the Great Lakes and contiguous waters. The five basic precepts driving NANPCA are as follows: prevent unintentional introductions; co-ordinate research and information dissemination (establish an education program); develop and implement environmentally-sound control methods; minimise economic and ecological impacts; and, establish a research and technology program beneficial to state governments. The responsibility to implement these components rests with the inter-agency Aquatic Nuisance Species Task Force established by NANPCA and co-chaired by the US Fish and Wildlife Service and the National Oceanic and Atmospheric Administration (NOAA). The Commandant of the US Coast Guard is a member.

The ANS program, consisting of the elements stated above, forms an integrated approach of which only one is a mandatory provision; mandatory ballast water management regulations for vessels operating beyond the Exclusive Economic Zone (EEZ) and visiting the Great Lakes and the Hudson River north of the George Washington Bridge. In Fiscal Year 95 the Coast Guard spent close to $1,000,000 supporting the current non-indigenous species prevention effort. This figure included funding for Marine Safety Detachment (MSD) Massena, educational efforts, regulatory development, participation on task force groups, IMO work, support of conferences and support of studies on alternative control methods.

The voluntary and mandatory provisions of NANPCA 90 use ballast exchange as the main feature in minimising the introductions and control the spread of non-indigenous species. This is a good start in dealing with the invasion of ANS in US waters, but, the limitations of this approach are now well known. Ballast water exchange does not guarantee that all water-borne organisms will be discharged during the exchange process. Alternatives to ballast water exchange need to be identified and US federal, state and private resources are being committed to testing such alternatives. Additionally, better environmental education is needed. All federal agency members of the ANS Task Force are aggressively pursuing environmental education measures. In particular, an education program directed towards recreational boaters needs to be developed and implemented. However, the United States presently has no national protocol in place to address ballast water "Hotspots" other than the Great Lakes and the Hudson River in that NANPCA provides no authority for similar regulatory efforts in other parts of the United States. A truly effective national policy must take a broader view of the issue beyond a specific region. A system of unrelated federal and state regulations can not effectively minimise the movement of species in US Waters. To this end, a comprehensive approach addressing the problem on a national scale is being considered in Congress this year. This is an attempt at forging a cohesive federal response building on the structure already in place. The reauthorization of NANPCA90 in 1996 will call for all vessels entering US waters to manage ballast water, encourage a redoubling of the national education effort, and dedicate resources to a demonstration program to assess the feasibility of alternative ANS control methods in the ballast water of vessels.

The mandatory guidelines in the Great Lakes and the Hudson River represent the only federally regulated efforts world-wide to minimise introductions of ANS from ballast water. Now that the introduction and spread of ANS through ship's ballast water is recognised as a global issue, the level of international action will change. The following four events seem to indicate an elevation in the importance of the ANS issue. First, the Chairman of The Marine Environmental Protection Committee (MEPC) of the International Maritime Organization, at the 37th session in September, 1995, declared the issue of Unwanted Aquatic Organisms in Ships Ballast Water as one of the top three priorities for the Committee over the next five years. This statement will only serve to boost interest in ANS on an international, and correspondingly on a national scale. Second, the Ballast Water Working Group (MEPC37) continues to progress on the development of a new Annex to MARPOL 73/78. The new annex based on uptake and discharge management procedures and ballast water exchange is intended to consist of a small set of regulations and revised guidelines. Third, the interest that the International Council for the Exploration of the Sea (ICES) in cooperation with the IMO, has shown in organising the joint session on ballast water during the 1995 Annual Science Conference in Aalborg, Denmark. The inclusion of this theme session by virtue of its sole focus on problems related to the unintentional transfer of ANS by ship's ballast water, as well as on regulatory aspects and experience gained with existing ballast water treatment options, highlights the growing international concern with ANS. Finally, Australia has formed a fully funded and staffed Federal agency, Centre for Research on Introduced Marine Pests, dedicated solely to dealing with the threat of ANS invasion in Australian waters. ANS and the associated impacts are creating a steadily mounting burden for the United States and the world.

National

The discovery and rapid spread of the Zebra Mussel in the Great Lakes that brought the problem aquatic non-indigenous species introductions to public attention. The prolific biofouler rapidly clogged water intake pipe and actually shut down a water treatment plant in the Great Lakes region. US lawmakers reacted quickly and took actions to prevent future introductions of ANS and to control existing introductions. Congress enacted the Non-indigenous Aquatic Nuisance Prevention and Control Act of 1990 as part of Public Law 101-646 (the Act). The Act called for the development of an Aquatic Nuisance Species Program comprised of five basic precepts: to prevent unintentional introductions; to co-ordinate research and information dissemination (establish an education program); to develop and implement environmentally sound control methods; to minimise economic and ecological impacts; and to establish a research and technology program beneficial to state governments. The formation of the Aquatic Non-indigenous Species Task Force was mandated by the Act to co-ordinate all US Federal Government activities and oversee the ANS Program.

The ANS Program, consisting of the elements stated above, form an integrated approach of which only one is a mandatory provision. The regulatory provisions of the Act called for mandatory ballast water management regulations for vessels operating beyond the EEZ and visiting the Great Lakes. The US Coast Guard was tasked by legislation with developing a ballast water management program for the Great Lakes. In March 1991, the Coast Guard published voluntary ballast exchange guidelines for all vessels entering the Great Lakes. These guidelines became mandatory on May 10, 1993. Coast Guard boarding personnel were relocated to Massena, NY, gateway to the US side of the Saint Lawrence Seaway, to monitor compliance with the regulations and educate the mariner prior to entering the Great Lakes system. A 1993 amendment to the Water Resources Bill tasked the Coast Guard with developing a program, similar to the Great Lakes, for the Hudson River which were promulgated by the Coast Guard final rule on December 30, 1994.

The regulations, found in 33 CFR 151.1502, only apply to vessels that operate outside the EEZ of either Canada or the United States, before entering the Great Lakes or the Hudson River north of the George Washington Bridge. Vessels meeting these criteria are required to exchange ballast water in the open ocean. The regulations allow for alternatives to ballast water exchange as a control method, but other than retention on board and discharge to a reception facility, none have been approved to date. The mandatory guidelines in the Great Lakes and the Hudson River represent the only regulated efforts worldwide to prevent introductions of ANS from ballast water. There are no other formal Federal efforts calling for the mandatory management of ballast water of commercial or recreational traffic. However, the Act provides no authority for similar regulatory efforts in other parts of the United States.

Although the US Coast Guard have been and continues to be very active in the issue concerning commercial vessels, there are other agencies involved in the effort to manage ballast water on a national scale. In late 1991 the US Fish and Wildlife Service added the zebra mussel to the list of injurious fish, molluscs and crustaceans. This federal action prohibits the importation, acquisition or transportation of live zebra mussels within the territorial boundaries of the US, however, does not prevent entry from European or other countries. The Army Corps of Engineers has been very active in the prevention and control of biofoulers on government maintained locks and dams. A significant amount of research has been done in this aspect of the issue that may have direct application to the biofouling problem on vessels. The US Navy promulgated an operating policy which requires all US Naval vessels to exchange ballast twice before entering port when returning from an overseas mission.

The USCG in accordance with the Act's mandate regarding ballast water management procedures published ballast water regulations and developed a mariner education program for the Great Lakes and the Hudson River. Further, the USCG has taken a proactive approach regarding ballast water management procedures reaching above and beyond the Act's mandate asking all vessels calling at US ports to voluntarily comply with ballast water management guidelines. Also, in response to the Chesapeake Bay Commission (CBC) report, The Introduction of Non-indigenous Species To The Chesapeake Bay Via Ballast Water, dated January 5, 1995, the Fifth Coast Guard District directed the Baltimore, Maryland and Hampton Roads, Virginia Marine Safety Offices to implement many of the report's recommendations. In particular both MSOs are directed to designate a point of contact, take proactive measures to educate the shipping industry, and collect basic data on ballast water management practices for all vessels inbound from foreign ports that are boarded.

The regulatory approach in the Great Lakes and the Hudson River, the US Navy program the listing of the zebra mussel by FWS, and the proactive directive from the Fifth Coast Guard District represent forward-looking management approaches to invasions by ANS via ballast water. Notwithstanding, the United States has no overarching national policy in place to address other ballast water hotspots. Currently, the federal approach to ballast water management provides, in some experts opinion, incomplete protection from the invasion of harmful ANS. The approach is certainly not comprehensive; but rather a regionalized approach that does not fully and effectively address the growing problem of ANS. A comprehensive approach addressing the problem on a national scale is needed to effectively minimise the risk of introductions of ANS throughout the United States. There has been, and will likely continue to be increased movement in this direction. Several ANS bills and amendments will be offered in the 104th Congress in an effort to forge a cohesive federal response to the problem of ANS. Additionally, the anticipated reauthorization of NANPCA9O will require the Coast Guard to meet added responsibilities under the Act to include: develop voluntary ballast exchange guidelines which apply to all vessels entering US waters; establish reporting and sampling procedures to monitor compliance; conduct ecological and ballast discharge surveys; develop voluntary guidelines for controlling the spread of zebra mussels via recreational boaters; and, develop a more comprehensive mariner education program.

Regional

In December 1993 the Chesapeake Bay Program, a regional body committed to the restoration of the Bay, adopted the Chesapeake Bay Policy for the Introduction of Non-indigenous Aquatic Species. The policy guides the signatory parties (Maryland, Virginia, Pennsylvania and the District of Columbia) in the development and implementation of management plans for both intentional and non-intentional ANS introductions. It lays out a framework of cooperative management approaches and public outreach efforts for both. It is significant that the Chesapeake Bay policy addresses the ANS issue on a regional rather than a state by state basis. It serves as an excellent model on ANS prevention and management.

The Chesapeake Bay Commission (CBC), a tri-state legislative commission serving the General Assemblies of Virginia, Maryland and Pennsylvania helps guide the states in cooperatively managing the Chesapeake Bay. CBC is the lead in an effort to explore ballast water management options for the Chesapeake Bay. In early 1995, the Commission published a report. (The Introduction of Non-indigenous Species To The Chesapeake Bay Via Ballast Water, CBC report) concerning research and policy information on ballast water management practices. It includes recommend-tions focusing, particularly on, the cross-boundary, global nature of the problem. The report recommends that the development of improved ballast exchange technologies and practices that minimise the risk of non-indigenous species introductions must occur both nationally and internationally. Successful implemen-ation of the recommendations is largely dependent upon congressional and federal agency action and support.

The relative success of the regional approach is illustrated by Senator Sarbanes' (Maryland) decision to introduce several ANS bills in the 104th Congress. The CBC report was the impetus behind Senator Sarbanes' decision to introduce several ballast water management bills. His decision to do so stemmed from the resolutions recently passed by Maryland, Virginia and Pennsylvania calling for the broader Federal action concerning ballast water management. Congressmen from Virginia and Pennsylvania are expected to fully support the bill.

Another example of a successful regional approach is the development of the Great Lakes Maritime Industry Voluntary Ballast Water Management Plan for the Control of Ruffe in Lake Superior. This plan was initially developed by the Great Lakes shipping industry and government agencies in 1993 with full cooperation and advice from the Ruffe Control Committee of the ANS Task Force. Ships that travel primarily in the Great Lakes are requested to avoid releasing ballast water west of a demarcation line between Ontonongan, Michigan and Grand Portage, Minnesota. The Lake Carriers Association and co-sponsors implemented the plan. The plan has been fairly successful in that until recently Ruffe have not been detected in shipping ports outside of western Lake Superior. Recent discoveries of Ruffe in other Great Lakes ports place a level of uncertainty on the success of the program. Further, states bordering Lake Superior have instituted aggressive education campaigns aimed at reducing the likelihood that members of the public will inadvertently spread Ruffe. Minnesota and Wisconsin prohibit the possession of Ruffe in Lake Superior and its tributaries. Several states bordering the Great Lakes are currently drafting response plans should Ruffe become established in inland waters.

Regional cooperation will prove to play an important role in the development of solutions to the ANS problems; particularly for the pervasive cross-boundary ANS problems. Additionally, cooperation between industry and government can assist in finding a viable solutions to the problem. These regional approaches clearly illustrate the viability of regional coordination in our efforts to enhance our integrated approach.

State

With the federal regulatory response limited solely to the Great Lakes and the Hudson River some states have attempted to pass their own legislation or resolutions rather than wait for additional federal actions. These efforts for the most part have failed as states lack the Constitutional authority to affect trade. Four states have pursued state legislative efforts to regulate ballast water discharges, but none has been successful, either because of resistance in their own legislature or anticipated legal challenges. A state's power in regulating ballast water exchanges is limited. The efforts of California, Washington, Hawaii and Alaska to regulate ballast water exchange management illustrate the main barriers to state legislative initiatives. The efforts of California are particularly instructive in illustrating the barriers to state regulation of ballast water and the constraints posed by the interstate commerce clause in the Constitution.

Local

Local governments have significant responsibilities relative to ANS. Local governments are forced to respond to the immediate problems of impacts, such as blockages in municipal water supplies, maintenance of municipal aquatic recreation facilities, public pressure, and raising funds to respond to the impacts. Therefore, the local governments are required to initiate ANS prevention and control activities with almost no Federal or State funds. There are various ways a local government can help and support regional and national prevention activities, environmental education and information meetings, monitoring of water supplies, development of public facility management plans etc.

Without the support and cooperation of local governments, state and federal programs for ANS management will likely remain unsuccessful. Conversely, without the support of the federal and state governing entities (especially financially), local programs for ANS management will, without question, stagnate.

Conclusion

ANS and the associated impacts are creating a steadily mounting burden for the United States. The current Federal and State guidelines and regulations provide only partial protection from the pervasive problem of ANS. In summation, there is no overarching national protocol on ANS. The current system is piecemeal, placing emphasis on regional problems without addressing the interrelationship between adjacent regions. Most Federal and State statutes, regulations and programs are not keeping pace with the spreading ANS problem. While the US explores ways to enhance the present structure the integrated concepts addressed in this paper will become the core elements of the program. Additionally, better environmental education is needed. All federal agencies involved in the ANS Task Force are aggressively pursuing ANS environmental education measures. More research and development is needed to adequately address the issue. Specifically, alternative options to ballast exchange is sorely needed. Other areas include compliance verification methods, the concept of port compatibility, and trade partner agreements. We must look for new and innovative ideas to deal with complex issue. We believe an integrated approach consisting of all the options to minimise introductions and control the spread of non-indigenous species, education, and voluntary and mandatory regimes can be a significant step towards a solution to the problem.

Policy incentives to prevent introduction of non-indigenous species via shipping

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Invasion of non-indigenous species poses an ecological threat to local environments and also has a major economic impact on local communities. Measures such as Mid-Ocean Exchange (MOE), if required by regulation to prevent such invasions, may imply additional monetary burden to the affecting party, namely, the shipping industry. Economic costs combined with difficulty in monitoring MOE may lead to non-compliance with such regulations. This paper proposes a game-theoretic approach to ensure compliance from ships. Monitoring schemes based on game theory have been shown to be superior to random monitoring schemes. This approach treats the concerned parties (monitoring agency such as the US Coast Guard and the shipping industry) as two players in a game. All ships are divided into three groups depending on their past compliance history. Probabilities of monitoring and other penalties for violation of the regulation differ according to group. This scheme is both cost effective (to the monitoring agency due to low probabilities of monitoring) and politically feasible (due to low fines and penalties). Permanent cleanup technology options are proposed by the scientific community as better alternatives to MOE. If devised properly, the proposed monitoring scheme will encourage installation of such alternative technologies and phase out the MOE eventually.

Introduction

Invasion of Non-indigenous species (NIS) can pose an ecological threat to local environments and can have a major impact on local communities. In the Great Lakes, it is estimated that the economic losses due to the invasion of Zebra Mussel alone exceeds $5 billion. Ballast water of trans-oceanic ships is mainly responsible for such accidental introductions. Mid Ocean Exchange (MOE) has been required or recommended in various jurisdictions for cleaning the ballast water. However, there are some inherent problems associated with MOE – it takes time thus delaying shipping and increasing its cost, and it jeopardises the safety of the ships in times of bad weather. From the perspective of public authorities, MOE is not 100 percent effective, especially if both the departing port and the arriving port are salt-water based, and monitoring is costly. For these reasons, MOE is considered as a transitory technology, for use until better alternatives can be found.

A variety of permanent cleanup technology options is being considered by the scientific community as better alternatives to MOE. Most of these appear to involve capital (installation) costs for the shipping industry with low variable (operating) costs. The industry would prefer to avoid high front-end costs. Nevertheless, permanent technologies are more effective than MOE and may require little or no monitoring by the monitoring agency (hereafter referred to as the 'agency').

For a comprehensive solution to this problem, engineers must develop more cost-effective permanent technologies, the scientific community needs to develop more complete information on costs and effectiveness of alternative technologies, and policy-makers need to choose appropriate policies and implement them.

In order to address the high social and economic costs of NIS introductions, a comprehensive strategy is needed to enforce compliance with MOE in the short run and encourage ships to adopt a permanent technology in the long run. Our research cannot address the identification of optimal permanent technology. Instead it seeks to develop cost-effective monitoring and enforcement strategies, assuming a permanent technology can be identified.

The purpose of this paper is to present a monitoring and enforcement mechanism that achieves the objective of preventing accidental introduction of NIS with minimal disruption to the shipping industry and minimal costs to the agency. The proposed model is developed on the premise that MOE is made mandatory for all ships entering ports after trans-oceanic voyages. MOE is the transitory technology which the agency would like to see replaced by some kind of permanent technology. This paper discusses 1) how to monitor the transitory technology effectively and efficiently, and 2) how to encourage ships to adopt a permanent technology.

Our starting point is the economic literature on optimal monitoring and enforcement. Most related studies in the monitoring literature deal with pollution emissions, where the firms that emit the pollutants are stationary in a geographical area. Some others deal with auditing taxevasions where the evading party can be pin-pointed ex-post (for examples Greenberg, 1984). Our study appears to be the first in dealing with monitoring a set of firms that must follow regulations in the open seas and are geographically mobile.

Notation and terminology

The following notation will be used in the rest of the paper:

G_1 = the group of ships with good MOE compliance record

G_2 = the group of ships with bad MOE compliance record

G_3 = the group of ships that have installed permanent technology

p_1 = probability of a ship being monitored in G_1

p_2= probability of a ship being monitored in G_2

y_1= not following any technology

y_2= MOE technology

y_3= permanent technology

R_1= cost of MOE

R_2= cost of following alternate ballast water cleaning mechanism required by the agency, in the event a ship is found in non-compliance

R_3= cost of installing and operating permanent technology

D = cost associated with time delays due to MOE

T = number of visits to the port by a ship

Components of the model

Policy objectives

Social costs that need to be considered in policy formulation include costs to ship-operators, costs to the agency and costs to society. Costs to society include the loss/reduction in trade due to these regulations; losses incurred by consumers due to increased cost of products (if costs due to regulation incurred by ships are passed on to the consumers); loss of recreational value due to the presence of NIS in native waters such as loss due to decreased fishing etc. Due to the limitations of data and necessary tools, our research objective is limited to identifying monitoring and enforcement strategies that will minimise agency costs and ship-operator cost while containing NIS introduction via shipping.

Ship-operator costs consists of cost of MOE, time delays associated with MOE, penalty if found in non-compliance, and cost of installing permanent technology. Cost of MOE refers to actual process cost only. The US Coast Guard (CGD 91-066) reports that on average a ship in the size range of 7000-10000 tons of ballast water incurs a cost of $1147 for each MOE operation. Most ships lose speed while conducting MOE. These time delays associated with MOE can reduce the number of trips that a ship undertakes each year. Since this has direct economic impact on the costs, the loss (in dollars) due to the delay in conducting MOE must be considered. A study conducted by Rigby *et al.* (1991) gives 12 hours as the approximate number of hours it takes for a ship size of over 140,000 tons of loaded dead weight to conduct MOE assuming that the MOE is done continuously. These costs do not take into consideration the time delays that the ship may encounter at the port due to monitoring delays. Although it is difficult to assess the cost of permanent technology, a range of costs based on Carlton *et al.* (1995) have been used in our analysis.

It is a truism in economics that compliance (e.g., with MOE mandates) can always be attained if the costs (e.g., to ship-operators) of non-compliance can be set sufficiently high. However, there are limits to the costs that one can impose on the shipping industry, given society's need for cost-effective shipping and efficient international trade. Furthermore, society often seems unwilling to impose draconian penalties for civil offences (for example: non-compliance of MOE). These limitations on shipping costs and the size of penalties for non-compliance motivate the approach we have chosen.

Monitoring and enforcement concepts

A monitoring mechanism can be effective only if it is accompanied by penalties. The agency can enforce compliance only when it monitors *and* levies penalties on violators. When an agency imposes penalties, it tries to make the present value of expected penalty for non-compliance greater than the present value of compliance costs. A potential violator, who is a cost-minimizer, thus finds it in his best interest to comply with regulation.

In the case of simple monitoring schemes (also called static or state-independent monitoring schemes), a penalty would be levied whenever a ship is found in non-compliance. This static system would have a constant probability of inspection which is independent of past outcomes. The firm calculates the probability of inspection (p), penalty if caught in non-compliance (f), and the cost of compliance(c). If $pf > c$ the firm complies, otherwise it violates. In theory, the agency can reduce monitoring costs by allowing p to fall so long as f becomes very large. But, in practice very high penalties for civil violations are seldom politically acceptable.

Under this system the agency does not use any information it may obtain about the behaviour of ships.

On the other hand, state-dependent or dynamic systems have been shown to be more cost effective to the agency than state-independent models (Harrington, 1988). The key idea is that the agency uses the information obtained from past monitoring to classify ships in terms of their record of compliance, and then focuses future monitoring on the"poor compliance" class. For instance, consider a dynamic scheme consisting of two states: G_1 and G_2. Let G_1 represent the "good" category and G_2 represent the "bad" category. A firm found in violation in G_1 is moved to G_2, where it will encounter greater monitoring pressure and, perhaps, higher penalties until it can re-establish a good compliance record. Then, a potential violator in G_1 considers not only the one-shot penalty if detected (static case) but also the entire stream of future costs associated with G_2. By manipulating penalties and monitoring pressures the agency can ensure that the cost to ship-operators in G_2 is always higher than in G_1. Compared to static strategies, this dynamic strategy can achieve compliance with lower penalties and less frequent but better targeted monitoring. Monitoring permits the agency to learn something about the ship-operators, and the agency can be more cost-effective when it makes use of this information to adjust monitoring pressures.

This paper proposes a state-dependant mechanism that allows for dynamic transition among states, so the agency can demote violators to G_2 and ship operators can with effort move from G_2 back to G_1 or from either of those states to G_3. This scheme will have low monitoring probabilities (and hence low costs to agency) and low penalties for violation (and hence should be politically feasible).

Our analysis makes use of dynamic game theory. As the name suggests, game theory treats different parties as "players" in a game, each trying to outplay the other player(s) by employing different strategies. In our model, the monitoring agency and the shipping industry are the two players in a game.

Dynamic game theory

Dynamic games can be solved using Bellman's backward recursive equations. Under this procedure, at each time period t, present values of all future costs under each decision are calculated and that decision which minimises the future stream of costs is taken. The results show the decision of the ship (follow/not follow MOE) under each group, at each time period. These results are used to calculate rate of compliance of MOE and rate of installation of y_3, which in turn can be used to simulate the future composition of the fleet.

We can obtain combinations of monitoring probabilities (p_1,p_2) that fetch compliance of MOE from ships. With the knowledge of number of ships that frequent port, we can also obtain an approximate monitoring budget that is needed.

Asset replacement

We use asset replacement principles to frame incentives for the ships to install permanent technology, y_3. An important principle of asset replacement is that asset A gets replaced by asset B when the cost of operating A equals or exceeds the cost of installing and operating B.

In choosing an asset (y_3), the motivation of the asset manager (ship owner) is to minimise the present value of the entire future stream of costs associated with the asset. The asset manager has to make two decisions regarding asset replacement: 1) *when* to replace the transitory technology by permanent technology?; and 2) *which* one of the new technologies to choose from the given array?

The policy maker (agency) wants to guide the asset manager to the "right" set of assets and also provide incentives for early adoption. If the performance characteristics differ across these new technology options, then the policy maker may have an interest in the technology choice also. As indicated above, however, our results do not address choice of permanent technology.

According to economic theory, an asset gets replaced when marginal cost of holding the old asset for a further year ≥ amortised cost of a new asset ≥ marginal cost of the old asset during preceding year. i.e.

$$MC_{t+1} \geq \text{"AC"} \geq MC_t$$

In empirical applications, the best method to determine optimal replacement age is to evaluate the middle expression of the above equation for each year, n = 1,2, 3, ... and select that integer value of n for which "AC" is minimum.

In our case, a ship will adopt a new technology at time t when

$$MC_{MOE_{t+1}} \geq AC_{newtech.} \geq MC_{MOE\ t}$$

Model

In our state-dependent monitoring scheme, we use three states -- G_1, G_2, G_3. At the beginning all ships start in G_1. Ships in G_1 are presumed to be following MOE. If found to be in non-compliance they are moved to G_2. A ship in G_2 has to build its reputation as a 'good' ship by complying k consecutive times before it is moved back to G_1. Anytime a ship adopts permanent technology (either in G_1 or in G_2), it is moved to G_3. G_3 is the "absorbing state" - any ship in G_3 will remain in G_3 for ever. Thus the transition of a ship among these groups is based not only on compliance rate but also on the technology followed. The dynamics of the game are summarised in Figure 1.

The probability of detection and penalties for non-compliance differ across the groups. The probability of a ship being monitored in G_1, i.e. p_1, is less than p_2, the probability of a ship being monitored in G_2. Penalties will be levied whenever a ship is found in non-compliance in G_1 and G_2. Penalties can also include cost of monitoring and time delays. To encourage ships to comply with MOE, penalties and monitoring should be adjusted so that the cost of performing MOE is made less than cost of non-compliance. To encourage ships to install permanent technology, y_3, at some stage t, cost of conducting MOE should exceed cost of operating y_3. Thus our strategy calls for:

$$C(y_1) > C(y_2) > C(y_3)$$

where C(y) denotes total cost of operating technology y [$y \in \{y_1,y_2,y_3\}$] to ships. $C(y_1)$ consists of (i) fine for violations, (ii) cost of alternate mechanism if caught (R_2), (iii) stream of future costs of being in G_2 if caught in G_1. $C(y_2)$ consists of (i) cost of MOE (R_1), and (ii) stream of future costs of being in G_1. $C(y_3)$ consists of cost of installing and operating y_3 (R_3).

Penalties and fines can be fine-tuned by varying parameters associated with time-delays and cost of monitoring to achieve the condition, $C(y_1) > C(y_2)$. $C(y_3)$ can be made less than $C(y_2)$ by either one of the following ways: (i) reducing R_3 via subsidies or cost-reducing innovations, or (ii) increase $C(y_2)$ relative to $C(y_3)$ by transferring cost of monitoring MOE to ships in G_1.

Given this game, the ship's problem can be characterised by the following equation:

{ i=0 P (R_2+D+fine+cost of being G_2)+ (1-p) (cost of being G_1)

Min { i=1 R_1+D+cost of being G_1

i i=3 R_3 + cost of being G_3

where i = 0 : do not follow MOE, i = 1: follow MOE, and i = 3 : move to y_3.

At each stage t, a ship in a group G calculates costs of alternate actions and takes that decision that will minimise the cost. Intuition tells us that the more often a ship comes into a particular port, the stream of costs of being in G_1 increase and will thereby bring about movement from y_2 to y_3 technology.

The game is simulated for a sample fleet of 1000 ships to illustrate the mechanism. This simulation is for bulk carriers in the range of 25,000 to 75,000 DWT. It is assumed that around 60% of the ship's weight is in the form of ballast water. The cost information includes cost of conducting MOE, cost of monitoring and time-delay costs (in dollars) due to MOE. The US Coast Guard (CGD 91-066) reports that a ship incurs a cost of $1147 for every 7000-10000 tons of ballast water exchanged. We approximate it to $1200 and obtain $3600 as the cost of MOE for a ship with 30000 tons of ballast water. The USCG incurs a cost of $750,000 per annum to maintain a monitoring unit at Massena, New York (presentation at the Chesapeake Bay Commission meeting, October 24, 1994, Washington, D.C.). Although 455 ships entered the Great Lakes in 1990 shipping season, only 198 were subject to regulation (CGD 91-066). Thus, the cost of monitoring a ship is around $3750. Time delay costs are calculated by combining results from two different studies. Branch (1992) estimates the voyage costs of a bulk carrier (26,500 DWT) on a popular US-Europe route. He reports the net profit of that ship as $4092 per day. The ship generally makes around 11 trips a year. Rigby *et al.* (1991) estimate the approximate time it takes for a ship of size 141,475 DWT to deballast its water as 12 hours. These two studies are combined to obtain an estimate of time-delay cost (in dollar terms) due to MOE as $1700 (this does not include the delay due to inspection procedures at the port).

Preliminary results show that the compliance with MOE jumps from 0 to >96% as we reach optimal combinations of (p_1, p_2). Figure 2 gives the locus of such optimal (p_1,p_2) points for a compliance of >96%. This graph is obtained by varying (p_1,p_2) combinations with a 0.1 interval, holding all other variables constant.

From the figure it can be seen that a high compliance rate can be achieved with a low p_1.

The results also show that a ship adopts permanent technology, y_3, as number of visits to port (T) increases, or as cost of installation (R_3) decreases. Further, simulations suggest that ships in G_2 adopt permanent technology before ships in G_1. These results may be used to determine the future composition of the fleet. To get started, we considered the rate at which an existing fleet might retrofit to install permanent technology. Figure 3 shows the composition of the fleet from time period 0 to time period 20 using $p_1=0.2$, $p_2=0.8$, T=20 and $R_3=\$46,000$.

All ships are assumed to start in G_1 at time period 0. As can be seen from the figure, more than half of the ships will move to G_3 by time period 20. By manipulating variables such as (p_1, p_2), the agency can control the percentage of ships in each of the groups over time.

We expect that by combining asset replacement principles with the monitoring mechanism it will be possible to develop a monitoring scheme that ensures that all newly built ships adopt permanent technology immediately. We have not yet modelled fleet composition with retrofitting and ship replacement, but it is reasonable to expect the proportion of ships under G_3 to increase more rapidly under that regime than with retrofitting alone.

Conclusion

Invasion of NIS into local environments through the ballast water of trans-oceanic ships poses a major threat to local communities. MOE is frequently used as a transitory mechanism to control this problem. A monitoring and enforcement mechanism based on incentives deduced from game theory and asset replacement principles is presented. This mechanism ensures compliance with MOE from ships in the short run and encourages adoption of some permanent clean up technology in the long run. We have provided some illustrative results showing how penalties and monitoring pressure can be adjusted to increase compliance with MOE and to increase over time the proportion of ships adopting permanent technology. Solutions specific to each port can be obtained by using dynamic programming techniques and port specific cost data. If devised properly this scheme will encourage installation of alternate technologies and phase out MOE eventually.

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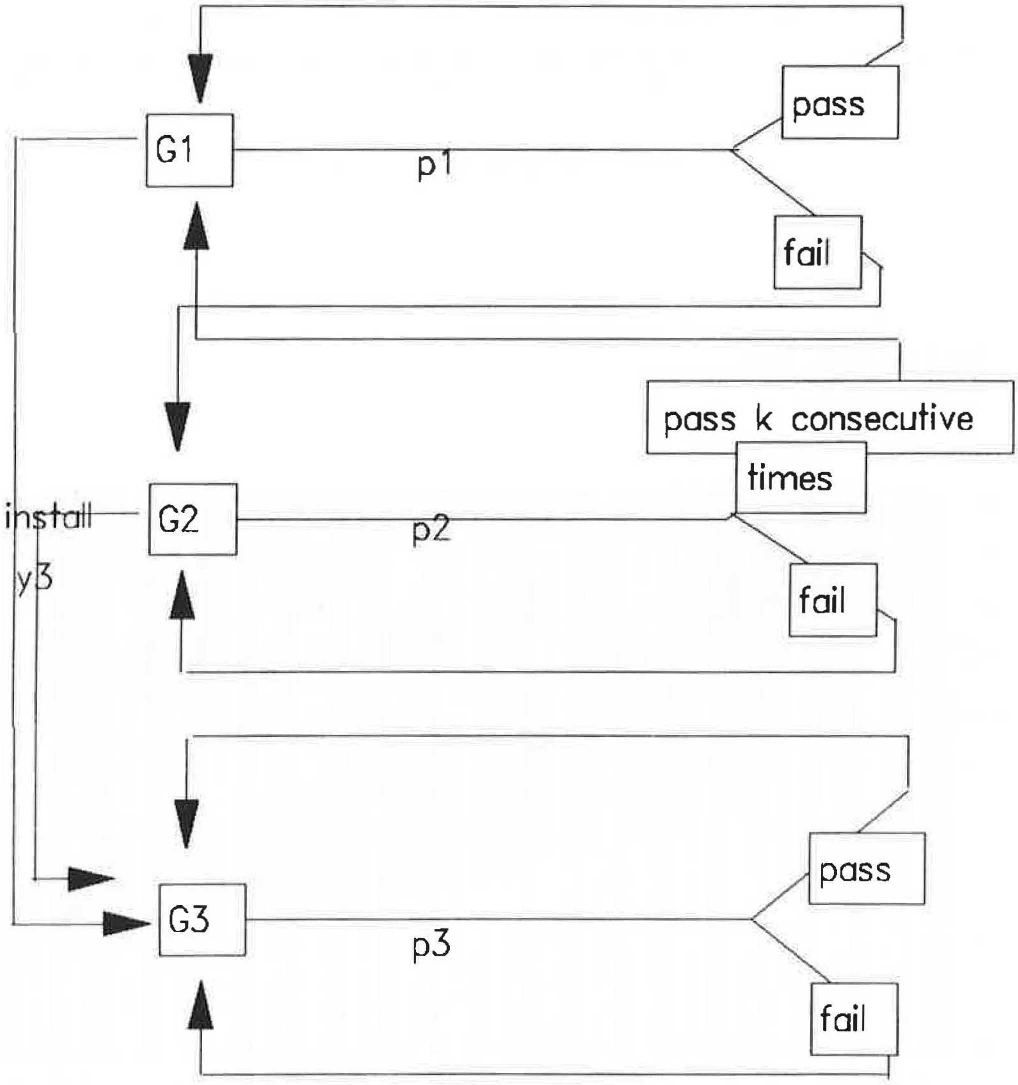

Figure 1 Structure of the Game.

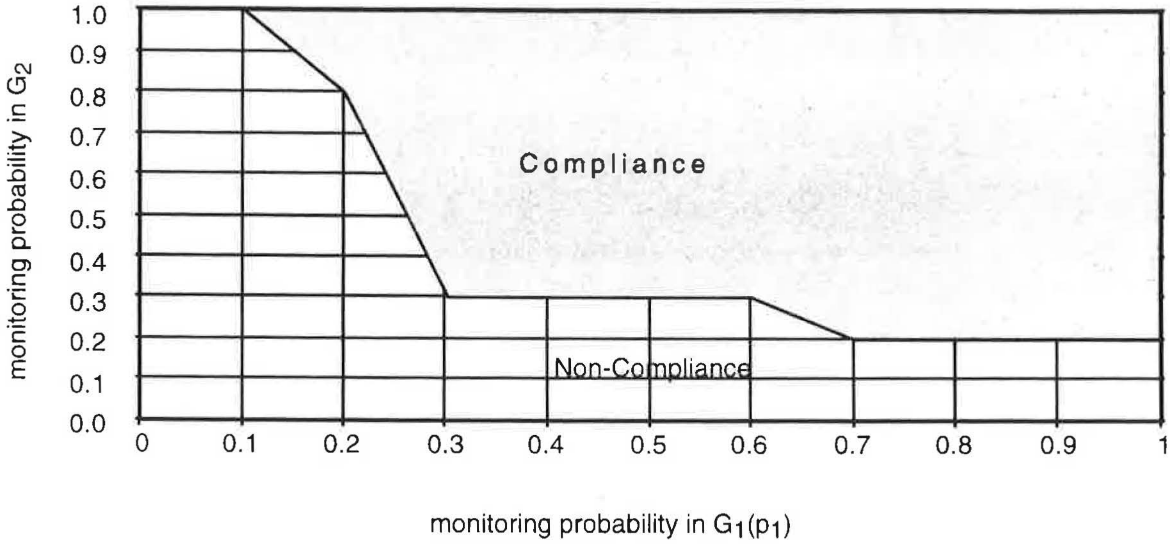

Figure 2 MOE Compliance Space.

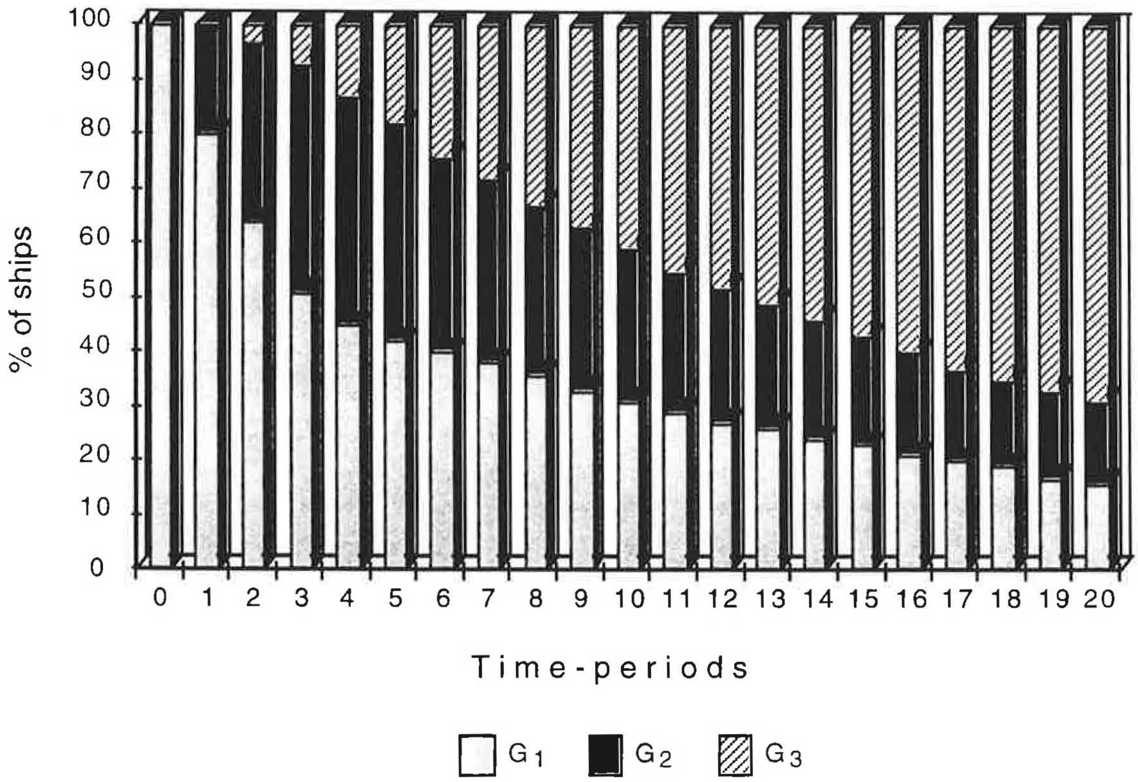

Figure 3 Composition of Fleet.

Ecological risk assessment for ballast water introductions

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An ecological risk assessment methodology is suggested as a means to investigate the efficacy of ballast water management strategies, addressing any one of a number of potential endpoints linked to the transport, release and control of non-indigenous marine organisms associated with ballast water. The methodology represents a synthesis of the ecological risk assessment framework espoused by the United States Environmental Protection Agency and the quantitative risk assessment paradigm more commonly employed in the nuclear and chemical process industries. This paper highlights some of the difficulties associated with quantifying risks within multivariate biological systems, notably the problems of stochasticity, complexity and causality. A number of mathematical and ecological techniques are identified as exhibiting some utility in this context. The paper does not purport to provide an "off the shelf" risk assessment for ballast water management, but rather offers some insights into how such an assessment might be undertaken.

Introduction

Risk is an often loosely defined term which expresses the chance of an undesirable event occurring as a result of some activity or action (including "no action"). Crucial to our understanding of risk is that it is associated with undesirable, and often unforeseen, events. One does not generally consider the risk of winning the lottery, for example.

Quantitative Risk Assessment (QRA) has its origins in the nuclear and space industries. In the last 20 years or so it has gained a more widespread acceptance in the oil, petrochemical and chemical process industries, and indeed for many other applications where the consequences of an undesirable event are potentially disastrous. The QRA paradigm is a rigorous, logical and iterative risk analysis procedure, which can be formally defined as:

- the quantitative evaluation of the likelihood of undesired events, and the
- likelihood of harm or damage being caused, together with value judgements concerning the significance of these results

The key points here are that it is a quantitative exercise and that risk is a function of two parameters; the probability of occurrence of an undesired event and the consequences of that event. The quantitative nature of the QRA paradigm is often confused with an 'objective strength of character'. In reality, however, the distinction between objective and subjective risk assessment is at best blurred and more often than not artificial. The strength of QRA lies not in its objective stance but rather in the manner that it treats subjective input.

Under the definition provided above, QRA can be viewed as a five stage procedure entailing:

i) the identification of hazards or potential undesired events;

ii) analysis of the frequency or likelihood of occurrence of the events,

iii) assessment of the effects or impacts should the undesired event(s) be realised;

iv) calculation of the risk, expressed as a product of the probability of the undesired event and its consequences; and,

v) an examination of the significance of the results often in the wider context of other social, economic or political concerns.

Importantly, however, QRA does not specify acceptance criteria for risks – this is a separate political and socio-economic decision.

The success of the QRA paradigm in the industrial context has encouraged its extension to novel areas, particularly ecological risk assessment. Again the objective in ecological risk assessments is to estimate the likelihood that some undesired event will occur. Such events are termed "ecological endpoints" (Bartell *et al.*, 1992). These endpoints are the expression of consequence and an expression of the values to be protected – that is the effects that are to be estimated and prevented or minimised by the assessment exercise.

In traditional QRA the endpoints are clear – human death or injury. In ecological risk assessment, however, the endpoints are often not as easily defined or identified. In theory ecological endpoints can be any one of numerous structural and functional ecosystem components, for example the elimination of a commercially valuable species or an overall reduction in primary production. In reality, however, the assessor may be unaware of what endpoints he is, or should be, working towards, and may have to distinguish between those endpoints he can measure (measurement endpoints) and those endpoints which he is seeking to assess (assessment endpoints), extrapolating from one to the other.

These problems are compounded by the difficulties of quantifying perturbations to complex, multivariate ecological systems. Natural systems exhibit close interdependence between component functions and structure, and considerable spatial and temporal variability. Ecosystem processes are stochastic, i.e. influenced by chance and timing, and more often than not non-linear in nature. Establishing causality in such a system is difficult. The way we perceive ecosystems is scale dependent. At larger scales we may witness a steady "equilibrium" state, but at smaller scales the system is often one of constant flux.

The complexity of natural systems remains a considerable hurdle to quantified ecological risk assessment. While this hurdle may remain insurmountable for the foreseeable future, the QRA paradigm still provides a rigorous and logical mechanism with which to interrogate risks arising in environmental media. In the face of this complexity, and the need to make defensible and repeatable decisions, the United States Environmental Protection Agency (US EPA) has devoted considerable resources to the issues of ecological risk assessment. The QRA approach is clearly recognisable in the resulting framework for ecological risk assessment developed by the agency (US EPA, 1992).

The risks associated with the introduction of non-indigenous organisms through ships' ballast, and the ballast water management strategies aimed at reducing or eliminating these, exhibit an interesting combination of industrial and ecological risk assessment characteristics. A synthesis of the US EPA framework for ecological risk assessment with the techniques of the quantified risk assessment paradigm is therefore suggested as an appropriate means by which to interrogate these risks.

The purpose of this paper is to investigate the means by which such a synthesis may be achieved, with a particular view to establishing the efficacy of ballast water management strategies in terms of quantifying the probability of strategy failure, and the consequences of such. The importance of such an approach is seen in terms of the need to identify cost efficient strategies for ballast water management.

Ballast water introductions and management strategies

Carlton (1986) has proposed a simple model representing the cycle of ballast water introductions, illustrated in Figure 2.1 Against this background it is possible to construct a simple, species specific, event tree for the introduction and establishment of a non-indigenous organism, as illustrated in Figure 2.2.

Ballast water management strategies attempt to break the chain of events leading to a non-indigenous introduction, and this break can be made at any one of a number of points, or at a combination of points. There are therefore a large variety of different management strategies, indeed Carlton *et al.*, (1995) suggests there are at least 32 different management options, (these are reproduced in Appendix A). Whilst some of these options are mutually exclusive, combinations of those options that are not, allows many more strategies to be applied in any given situation.

Furthermore it seems reasonable to assume that any individual strategy is unlikely to be equally cost effective for all vessels at all ports of arrival and departure. It would seem unreasonable therefore to impose a blanket strategy across the shipping industry as a whole. If we accept this line of reasoning, we are naturally led to the conclusion that the implementation of ballast water management strategies should be done on a case by case basis. But on what basis should one strategy be chosen over another?

The purpose of this paper is to suggest that a quantified ecological risk assessment approach to determining the probability of management strategy failure, and the consequences of such, provides a defensible means by which to test cost efficiency, and thereby provide effective decision criteria for such a case-by-case evaluation.

At this point it is worth pausing briefly to reflect on what has been suggested; the assumption made above is that cost efficiency is an appropriate means by which to differentiate between management strategies. This assumption must be made with care. It is not inconceivable that in certain circumstances the scientific and/or public community could adopt a zero-risk attitude. This is akin to a statement of environmental ethic; any probability of introduction and establishment of a given species, perhaps in a given location, is unacceptable. Under these circumstances applying the most cost efficient strategy may not be appropriate or desirable.

It is clear, however, that implementing ballast water management strategies will incur cost, and in certain circumstances these costs may be considerable. These costs will inevitably pass on to the public or sections thereof, and given that the public's willingness to pay for environmental protection or improvement is finite, establishing the most cost efficient management strategy is a justifiable objective. It is on this presumption that the paper proceeds.

The most cost efficient management strategy (or combination of strategies) can be defined as that option(s) which exhibits the highest risk reduction per unit cost. The endpoints towards which the risk assessment is directed becomes failure of any given management strategy. In this context we can distinguish between operational failure (or simple inefficiency) and accidental failure. For the main part this discussion will focus on the operational efficiency of control options, but the techniques discussed are equally applicable to an accidental event analysis.

The risk of control failure has two components; the frequency with which failure occurs and the consequences of such. Consider, for example, strategies designed to prevent organisms taken onboard with ballast. Failure is defined as organisms taken on board. The frequency with which this event occurs (either operationally or accidentally) and the consequences of failure – expressed as the number of organisms taken on board – defines the risk of failure.

It is possible therefore to envisage a series of "nested" risk assessment endpoints (nested in the sense of Russian dolls), applying to the various control strategies within the ballast water introduction cycle, as illustrated in Figure 2.3.

Again the objective of the risk assessment process is to quantify the risk of management strategy failure, allowing a comparative cost utility function to be determined on a case-by-case basis. Importantly, however, this approach also allows a quantitative assessment of the efficacy of combined option strategies. Applying Boolean logic, for example, to the probability of failure of any single strategy allows a determination of the probability of failure of two (or more) options in a serial or parallel fashion.

Biocide treatment risk assessment

In theory then quantitative risk assessment techniques would allow the determination of the most cost efficient combination of control options under any given circumstances. In practice, however, the assessor will be faced with many of the difficulties associated with quantitative ecological risk assessment outlined above.

The hurdles that such an assessment is likely to encounter, and some of the techniques currently available to tackle them, are perhaps best illustrated by a hypothetical example: the use of a chemical biocide as a ballast treatment option.

Hazard identification

The first stage of the quantitative risk assessment paradigm is hazard identification. The hazard identification stage should therefore elicit those events or sequences of events that contribute to a biocide's failure to eliminate organisms within the ballast tank environment.

There are a number of techniques employed within an industrial context to identify hazards. Many of these techniques have been developed to provide structured ways of eliciting the identification of hazards by prompting those familiar with the system in question to apply their expertise in a rigorous and logical manner. Fault tree analysis, for example, forces the assessor(s) to consider the necessary events that contribute to the endpoint in question. A supplementary approach is HAZOP (Hazard and Operability) analysis which uses guide words to prompt "what if" type questions for each component of the system. In this manner the assessor(s) is encouraged to apply foresight and an inductive approach to determine potential hazards. Simple examples of both of these techniques are illustrated in Figure 3.1 for the hypothetical biocide treatment option.

Frequency analysis

The purpose of the frequency analysis is to estimate the probability or frequency of the undesired events identified in the first stages of the risk assessment process. In the context of this assessment the frequency analysis would aim to quantify the probability of failure of any given control strategy. The frequency of failure is then determined by the number of vessel trips, ballasting events, etc. In a traditional industrial QRA process, frequency analysis is undertaken in one of two alternative ways:

a) quantify the extent to which the system in question has failed in the past, deriving an empirically based frequency failure rate; or

b) (in event that such data is unavailable) break down the failure event to its contributing components for which data is available and use Boolean logic to determine the overall probability of the failure scenario.

Frequency analysis within an ecological risk assessment, however, is considerably more difficult than its industrial counterpart. In the first instance it is very unlikely that a database of historical failure incidence will exist; clearly for ballast water management strategies no such database has been gathered. Furthermore establishing probability functions for the contributing events of a failure scenario are likely to be complicated by the complexity and stochastic behaviour of the system being modelled:

For the biocide control option considered above for example, the failure endpoint is survival of organisms within the treated ballast water. This endpoint, however, would be poorly represented by a single parameter, and should properly be expressed as a size/probability function of numbers of organisms (of a given species) surviving. There are two components to this endpoint:

a) the birth-death processes which occur within the ballast tank population; and,

b) the effect of the control strategy (biocide) on these processes.

In effect the aim of the control strategy is to push the ballast tank population to extinction. (This is an important analogy and one that shall be referred to further). It is worth noting at this stage that the population of the ballast tank environment properly satisfies the ecological definition of a "closed population" (McArdle, 1993), in so much as once the ballast operation is completed, there is no further immigration/emigration to or from the population over the duration of the vessel journey. In theory this simplifies the subsequent risk assessment; the ballast tank environment is more akin to a mesocosm than a ecosystem, and as such is more amenable to quantitative analysis.

The simple hazard identification exercise undertaken for the biocide example suggests that the following events could potentially contribute to the failure endpoint:

1. Inadequate biocide concentration

2. Species resistant to the biocide either generally or at a specific life cycle stage

3. Inadequate coverage of all parts of the ballast water environment

4. Inadequate "treatment" time.

In this context there are clear parallels with ecotoxicological risk assessment. However, the control strategy is analogous to the reciprocal of the traditional ecotoxicological risk assessment which aims to ensure little or no impact upon components of an environment receiving a chemical contaminant, here we are attempting to ensure complete impact on the receiving environment.

The ballast tank environment

The frequency analysis must first define the abiotic and biotic components of the ballast tank environment. These are the "ecosystem characteristics" which provide the context for the assessment. In effect the assessor is building a mesocosm model of the ballast water environment. As noted above the clearly defined spatial and temporal limits to this environment, and the closed population dynamics within it, suggest that this analysis should be considerably simpler than that for a "real world" ecosystem. The abiotic components of this environment are readily defined. The biotic components, however, are a little more intractable.

In a simple deterministic analysis the population dynamics of any given species within this environment can be expressed:

$$\frac{\delta P}{\delta t} = (b-d)\,P \qquad [1]$$

which has the solution:

δ

$$P = P_0 \exp[(b - d)t] \qquad [2]$$

where P_0 = inoculum, i.e. number of individuals taken onboard during ballasting
t = journey time
b = instantaneous fractional birth rate
d = instantaneous fractional death rate

Equation 1 above provides a very simple model that assumes constant birth and death rates and ignores such factors as density dependent mortality, predation, etc. There are numerous available techniques to incorporate predator-prey interactions (see for example Yodzis, 1994; Pimm, 1982), trophic interactions (see for example Christensen, 1992; Ulanowicz, 1992) and to explicitly acknowledge the influence of dependent, independent and intervening variables (Buncher *et al.*, 1991).

In all such approaches, however, from the simplest to the most complex, the veracity of the analysis is dictated by the parameter values incorporated into the modelling. What makes ballast water strategy risk assessment amenable to such analysis is the mesocosm characteristic of the environment. In theory the assessor should be able to utilise empirically established intrinsic birth and death rates, inoculum sizes, predator functional responses, etc.

At this stage it is worth noting that the techniques outlined above are deterministic in nature. In reality stochastic influences would produce a distribution of possible population size at the end of the ballast journey, as illustrated in Figure 3.3. Again there are a variety of statistical techniques available to reflect the influence of chance and timing on population dynamics. In a stochastic model, parameter distributions represent the actual frequency distributions of the processes in question. Where these actual frequency distributions are unknown, as is more usually the case, a deterministic model (such as that represented by equation 1) can be made to mimic stochastic behaviour by Monte Carlo sampling of the parameter values from suspected distributions. The incorporation of a priori information regarding the realistic limits to the system in question can improve the simulations considerably (O'Neill *et al.*, 1982).

The control strategy characteristics

A ballast water control strategy can be likened to an environmental stressor whose objective is to drive non-indigenous populations to extinction. With this analogy in mind the assessor can draw upon a host of risk assessment techniques.

The efficacy of a chemical biocide, for example, can be investigated with ecotoxicological risk assessment methodologies. A simple deterministic analysis may define effectiveness as the LC_{100}/PEC quotient, representing the laboratory established concentration that is lethal to all of the test individuals, over the Predicted Environmental Concentration (PEC). A more realistic analysis, however, would consider the effects and exposure profile (US EPA, 1992) of the stressor, which in this example could include:

a) LC_{100} effects profile: species sensitivity variation concentration versus dose (biological uptake variation) laboratory-environment extrapolation error time to LC_{100}

b) PEC exposure profile: fate and transport of biocide through ballast tank environment persistence, biodegradation, environmental partitioning

A simple consideration of stochastic influences on both the effects and exposure profile, as illustrated in Figure 3.4, allows the determination of the probability of effect of the control option, which in turn defines the probability of failure.

The synthesis of these considerations with the results of the hazard identification stage provide the assessor with a toolkit with which to investigate potential control failure scenarios and the frequency with which they could be expected to occur. The simple analysis undertaken above for the biocide treatment option provides a clear example of some of the difficulties that may be encountered in establishing the efficacy of ballast water management strategies, as diagrammatically idealised for a biocide treatment in Figure 3.5.

Consequence analysis

The consequences of control strategy failure are expressed in terms of the number of species, and number of individuals surviving to the next stage of the ballast introduction cycle. The significance of failure is also clearly a function of where in the ballast water cycle the survivors progress.

Determining the number of individuals surviving beyond a particular control option is critical to an estimation of the likely effects of control strategy failure because small populations are considered to be more vulnerable to extinction – a phenomena generally referred to as the "Allee" effect, (Williamson, 1989). The Allee effect manifests itself because small populations face the risk of extinction from demographic accidents – the chance fluctuations of birth and death rates – and from extreme environmental events. The concept is closely linked to that of a minimum viable population and Population Viability Analysis (PVA). PVA is a process in which the likelihood that a population will become extinct is assessed within a specified time and under particular circumstances (Possingham *et al.*, 1993).

The importance of the extinction analogy drawn above is that conservation biology risk assessment techniques provide a clear means to establish the likelihood that a given population will become extinct. A control strategy may not have to eliminate all individuals to ensure eventual extinction, i.e. non-establishment of an introduced species (refer to Burgman *et al.*, 1993).

In theory then the assessor would be able to specify the frequency with which a given control strategy eliminated a particular ballast water population below its minimum viable population size. In practice the concept of population viability is unlikely to be sufficiently developed to control or predict establishment on a case-by-case basis. Were this to prove to be the case, the assessor could alternatively adopt the approach that the greater the population surviving to the next stage, the higher the probability that the species will progress through the ballast cycle and become established in the new receiving environment. In this approach the assessor seeks that control strategy, or combination of control options, which minimises this size probability function in the most cost efficient manner.

Risk estimation and uncertainty analysis

Within the QRA paradigm risk is expressed as a function of the frequency (or probability) of undesired events and the consequence of these events. The result of the ballast water risk assessment would ideally be a cumulative probability density function expressing the probability that x% of the initial inoculum survives the control option. As intimated above this may allow some determination of the likelihood of subsequent growth and establishment of the non-indigenous species. Even where this cannot be established, however, the assessment exercise is a useful one if it is able to identify the most cost efficient means of minimising this probability density function.

The estimation of risk in any risk assessment should properly be accompanied by an expression of the uncertainty in the results of the analysis, and the extent to which this uncertainty influences the subsequent conclusions of the assessment. Uncertainty analysis plays a critical role in providing a basis for selecting among alternative management options and deciding if and what additional information is needed (Reckhow, 1994).

Uncertainty has been described as, "a measure of incompleteness of one's knowledge or information about a quantity whose true value could be established if a perfect measuring device were available"(Taylor, 1993). It is important to recognise, however, that this is only applicable to empirical quantities, and that the risk assessor and decision maker may be faced with uncertainty regarding decision variables or value parameters which may not have a "true value" (Morgan and Henrion, 1990).

Notwithstanding this last point, the major sources of uncertainty in a ballast water risk assessment are likely to be measurement error, stochastic variability and modelling approximation. The determination of sampling error, for example, is likely to be critical in ballast water management strategies in distinguishing between sampled structural zeros (the population is extinct), and sampling zeros that are due to sampling error when the population is really present (McArdle, 1993).

There are a range of techniques currently available to address these sources of uncertainty that can each be broadly defined as falling within one of three categories:

a) Sensitivity analysis – the effect of change in a model input parameter to the model output;

b) Uncertainty propagation – calculating the uncertainty in model outputs induced by the uncertainty in model parameter inputs; and,

c) Uncertainty analysis – methods for comparing the importance in input uncertainties in terms of their relative contribution to uncertainties in outputs.

Sensitivity analysis is most useful in the first instance by identifying those parameters/variables that contribute to the lion's share of uncertainty in the model result and therefore warrant further analysis. In this context it is important to be able to judge what is significant and what is negligible when dealing with uncertainty in risk assessment, since the blind pursuit of accuracy for its own sake may squander resources better spent in a more selective manner (The Royal Society, 1983).

Table 4.1 provides a summary of some types of uncertainty that may be encountered during a ballast water management risk assessment, together with some of the techniques available to address these.

The question of uncertainty is intimately linked to that of complexity. The cycle of introduction and establishment of non-indigenous organisms associated with ballast water discharges is undeniably complex. Addressing this issue (and the costs associated with controlling it) in a single analysis is therefore likely to result in potential variations in the analysis results, as uncertainty in individual elements are combined in the overall system. The results of a recent bio-economic risk assessment of ballast water introductions provides a good example of this phenomena. In attempting to quantify the risks associated with toxic dinoflagellate introductions across Australia, and the costs to the nation as a whole of treatment strategies (as opposed to no treatment), the analysis provides a point estimate for the cost of no treatment as $200 million although acknowledges that "the plausible range is wide....suggesting a band from around $40 million to around $400 million" (AQIS, 1994) - a difficult basis from which to make a risk-benefit decision.

Table 4.1 Uncertainty analysis summary – Ballast water management strategy risk assessment.

Assessment parameter	Characteristic	Biocide treatment risk assessment example	Methods for reducing uncertainty
Empirical quantity	Measurable (at least in principle) property of real world systems.	Majority of the parameters in the biocide treatment risk assessment will be empirical. For example birth/death rates, predation coefficients, PEC's, LC_{100} diffusivity coefficients, etc.	Simple analytical techniques where the number of variables is low. For example discrete probability distributions, scenario trees, first order Gaussian approximation. Where the number of variables is high; Monte Carlo simulation sampling from n dimensional space defined by ranges in n uncertain parameters.
Index variable (independent variable)	Identifies a location or cell in the spatial or temporal domain.	Geographical extent of analysis, journey times, ports of ballast/deballast.	Careful ring fencing of analysis. It does not make sense to be uncertain about index variables.
Model domain parameter	Domain or scope of the system being modelled generally defined by the range and increments for index variables.	Discrete versus continuous population models, time increments within discrete models, granularity or resolution of spatial index, *a priori* limits to physical/biological parameters.	Chosen as a balance between ensuring the model deals adequately with the full range of the system of interest and computational costs. No 'true' value, but can be uncertain about appropriate value. A prior truncation of biological parameters can be drawn from empirical evidence.
Value parameter	Aspects of the preferences of decision makers or the people they represent.	Acceptability of failure probability, zero tolerance versus risk benefit assessment, BATNEEC decisions.	Again no 'true' value. Switchover techniques allow explicit analysis of when and why decision change. ALARP principle for acceptable/-unacceptable risk (assuming acceptance criteria defined). Catalogue of decisions currently made to create market value.

(Adapted after Morgan & Henrion 1990).

Complex problems are, however, often decomposable into subsystems with a hierarchical structure (Morgan and Henrion, 1990). Careful ring fencing of an analysis, defining those interactions within a subsystem that are of interest to the objective and those that can be ignored for the purposes of the analysis, allows the decomposition of a complex system into more manageable parts. By minimising the uncertainty within each of the individual parts the analyst may be able to avoid results which, due to massive uncertainty, are effectively useless as decision aids.

Assessing the risks associated with ballast water introductions and control strategies is therefore best tackled in a piecemeal, but strategic fashion, minimising uncertainty in individual studies that contribute to the overall view.

Conclusions

Environmental improvement strategies are often implemented under the auspices of cost benefit or risk benefit assessments. If we accept this approach for ballast water control strategies (as opposed to the zero risk tolerance approach) then quantified risk assessment provides a means of establishing the cost utility of individual or combined control options. This cost utility is expressed as the probability of strategy failure multiplied by the cost of implementing the control strategy.

Ballast water management exhibits an important asymmetry in that the introduction of control strategies ensures higher shipping costs for a probable reduction in environmental risk (AQIS, 1994). Determining cost utility within a probabilistic quantified risk assessment framework is therefore an appropriate approach.

Furthermore ballast water introduction risk assessment exhibits a curious mixture of ecological and more traditional risk analysis problems; the population dynamics and establishment of a non-indigenous species entails the stochastic complexity of biological modelling but within a mesocosm-like environment whose variables are relatively well defined and uniform. The "mesocosm" nature of the ballast tank environment reduces uncertainty in a number of assessment parameters, making it more amenable to quantified analysis.

There are a number of points within the ballast/deballast procedure where the cycle of introduction can be interrupted. The significance of the probability of failure of control strategies at different stages in the cycle are not, however, equal when viewed in light of the overall objective of any management strategy: the prevention of the introduction of non-indigenous species. The cost utility function described above can only be compared across control option acting at the same point within the ballast cycle unless some allowance is subsequently made for the probability of organisms progressing through the chain becoming established as alien species.

In this context, conservation risk assessment techniques can further contribute to the evaluation of whether a given population size, surviving a particular control strategy, will progress to extinction or not. Two conclusions are evident from these considerations:

a) a given control strategy need not necessarily eliminate all organisms to ensure that the surviving population does not establish itself; and,

b) the most cost effective control strategies may prove to be those which entail combinations of control options, working in harmony with the ballast/deballast cycle, to drive inoculum populations to extinction.

Quantified ecological risk assessment provides a means to investigate and quantify the extent of control strategy elimination; the likelihood of surviving population establishment; and the efficacy of combined control options.

The ballast water introduction cycle is undoubtedly complex. Decomposing this cycle into its component parts, however, provides manageable risk assessment units. By focusing on the component parts of the cycle the assessor is able to reduce a complex procedure into clearly defined subsystems, as exemplified by the nested endpoint approach for a ballast water risk assessment. This encourages precision in assessment results and helps avoid large uncertainties which may effectively render the assessment useless as a decision aid.

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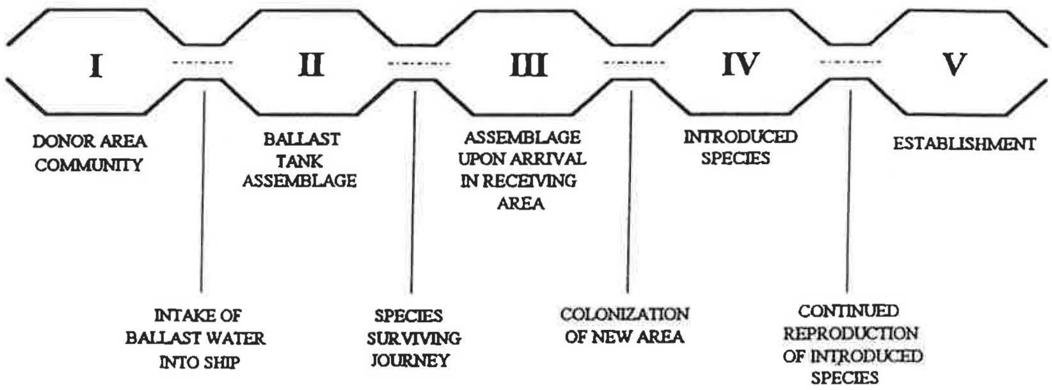


(after Carlton 1986)

Figure 2.1 The Ballast Water Introduction Cycle.

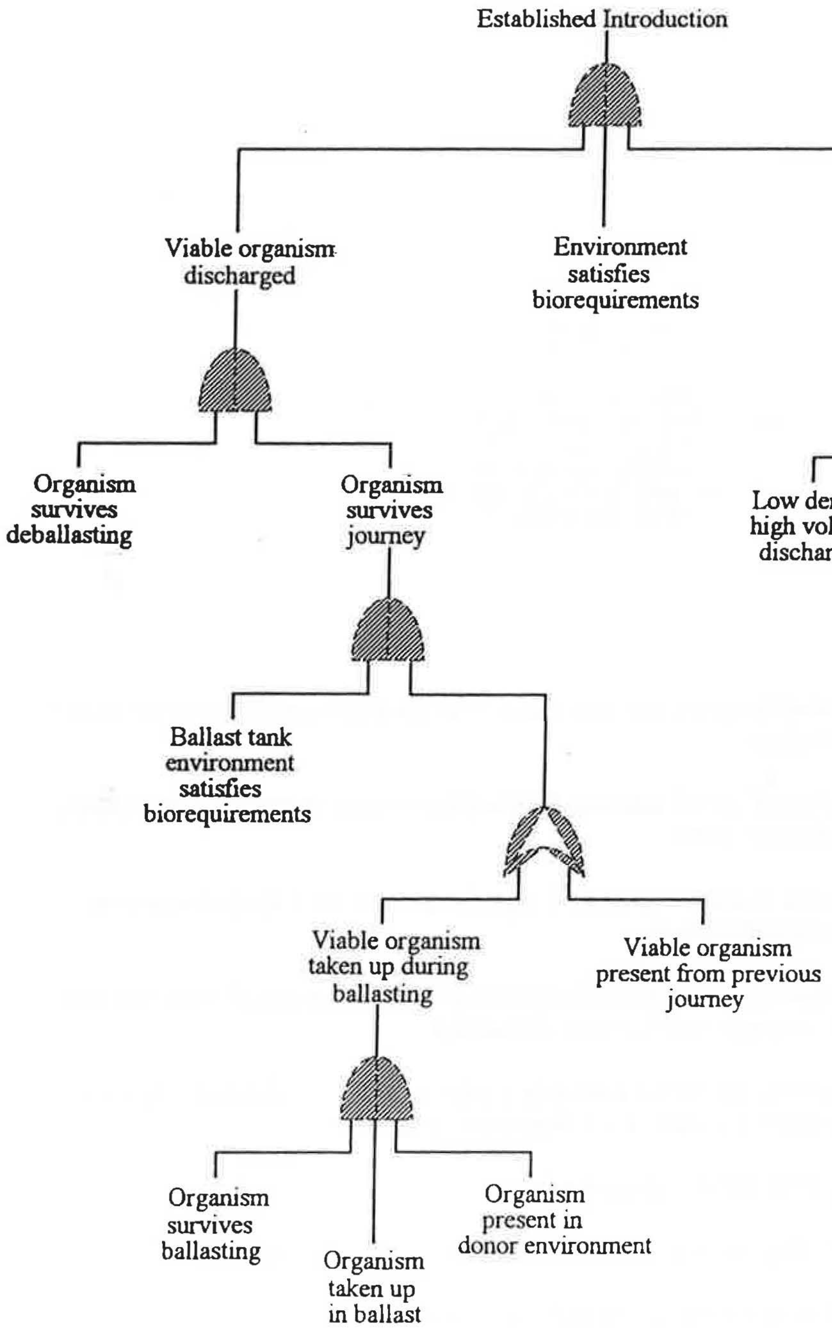
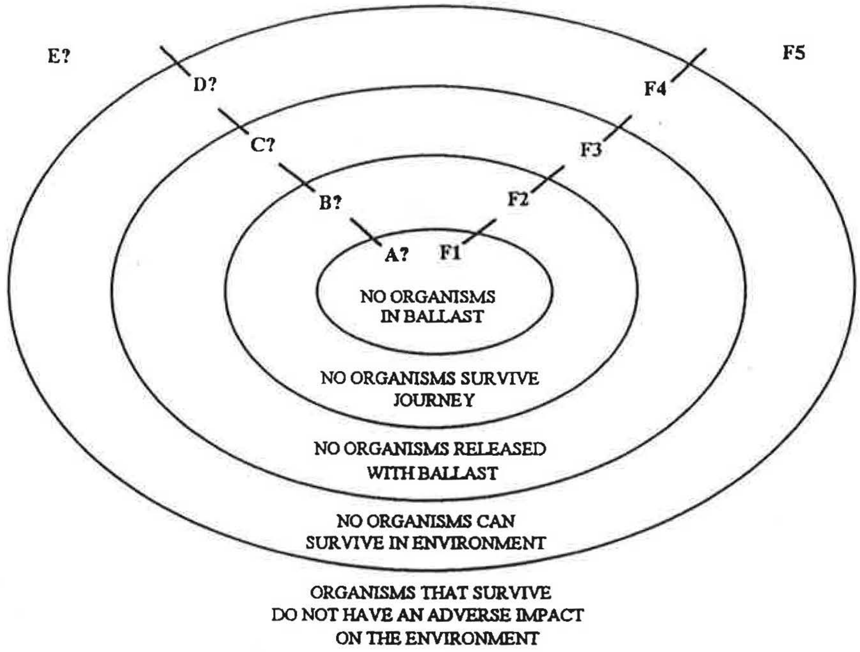


Figure 2.2 Simple fault tree for ballast water introduction.



Notes

F1	Endpoint #1	Failure of control option(s) designed to prevent organisms taken up during ballasting
F2	Endpoint #2	Failure of control option(s) designed to eliminate organisms within ballast tank environment
F3	Endpoint #3	Failure of control option(s) designed to prevent the release of organisms during deballasting
F4	Endpoint #4	Failure of control option designed to prevent the release of organisms into environments in which they can survive
F5	Endpoint #5	Failure of option that aims only to release organisms that will not have a detrimental impact on the receiving environment
A?	Question(s)	e.g. what organisms and how many?
B?	Question(s)	e.g. what survival strategies, which life stages, how many?
C?	Question(s)	e.g. which organisms, how many, how viable?
D?	Question(s)	e.g. organisms bio-requirements, environment characteristics?
E?	Question(s)	e.g. what impacts, what is adverse impact, what is acceptable?

Figure 2.3 Nested risk assessment endpoints for ballast water management strategies.

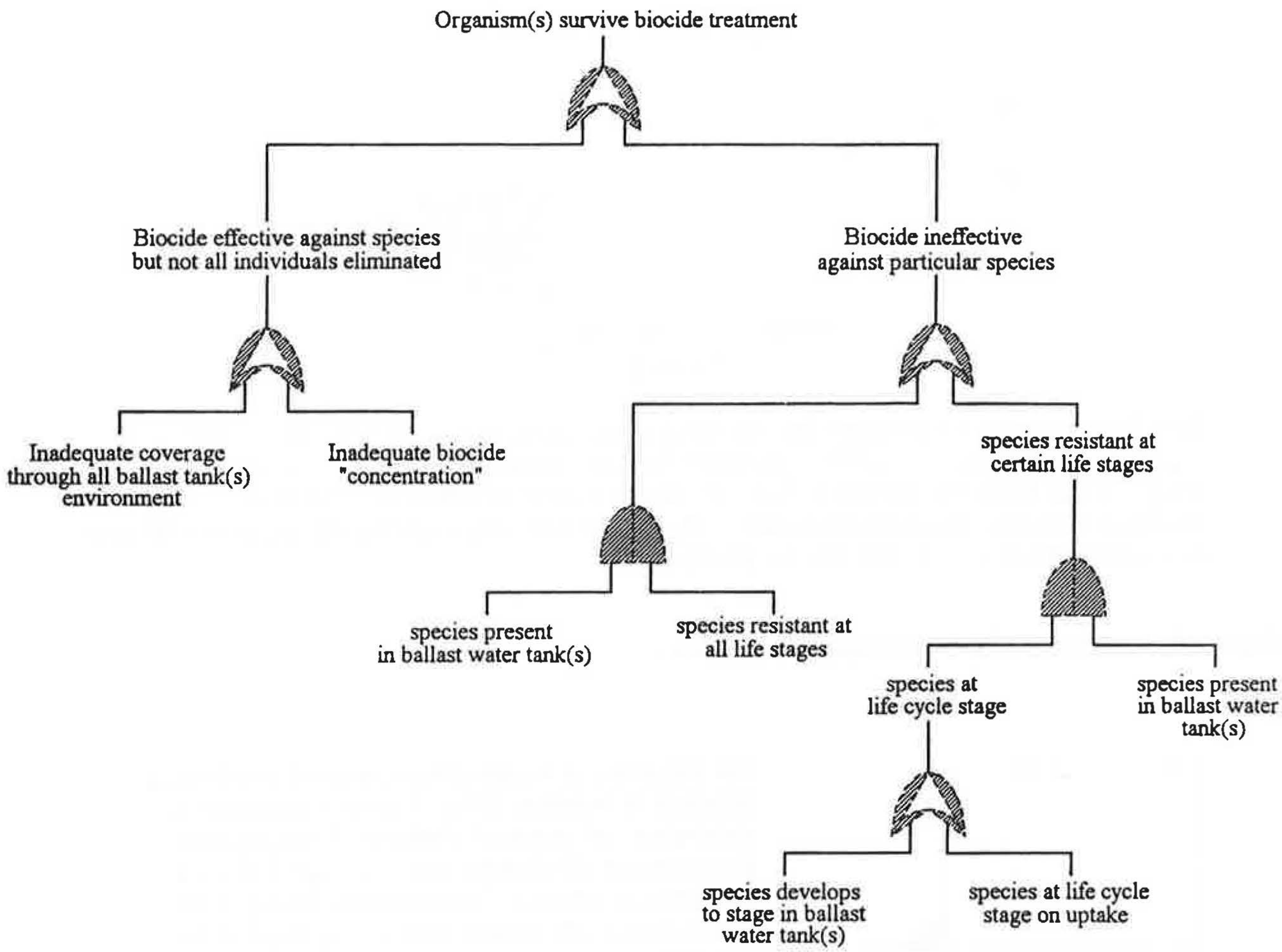
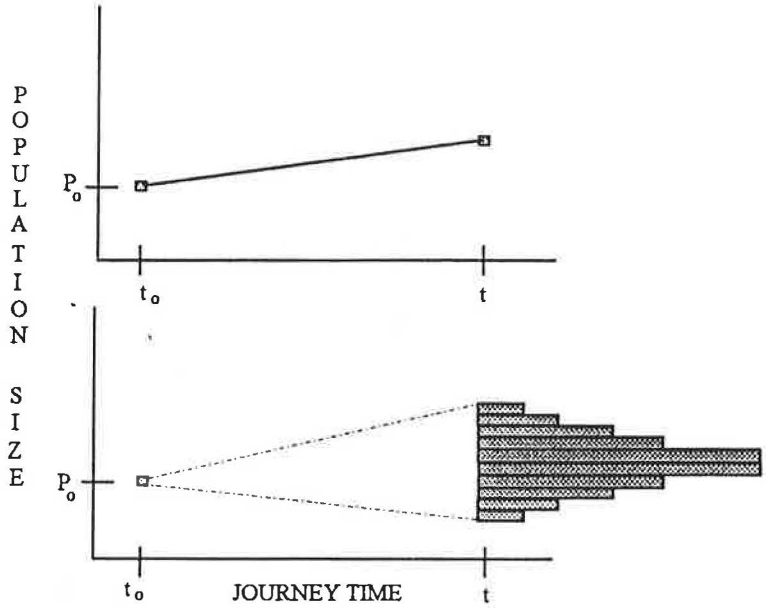


Figure 3.1 Fault tree for biocide control failure.

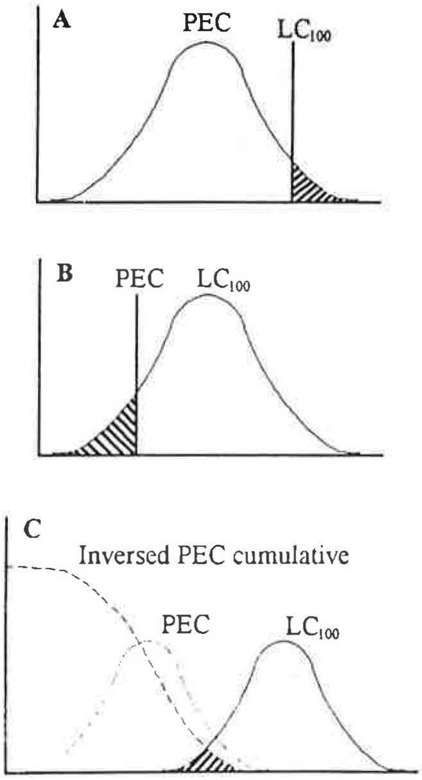
Control mechanism	**Guide word**	**Event**
Chemical biocide	Too much	Effective, but expensive, and may entail environmental damage upon deballasting, and/or damage to ballast tanks
	Too little	Probability failure increases, not all organisms eliminated
	Too slow	Inadequate coverage through all ballast water tanks over journey time
	Too quick	Inadequate treatment through all ballast water tanks over journey time

Figure 3.2 Simple HAZOP analysis for biocide treatment option.



This figure illustrates the difference between deterministic and stochastic models of population dynamics (adapted after Burgman *et al* 1993). The upper diagram represents the results of a deterministic model such as that illustrated in equation 1. The lower diagram represents the results of a model incorporating stochastic influences on population dynamics. P_0 represents the inoculum size (the population taken on board during ballasting), t represents the journey time.

Figure 3.3 Stochastic influence on population dynamics.



The probability of biocide effectiveness (adapted from Schobben & Scholten 1993). Figure A represents a distribution of potential Predicted Environmental Concentration (PEC) compared to a single LC_{100} for the species in question. The estimated efficacy of the control option (the shaded area) is expressed as the probability of $LC_{100} < PEC$.

Alternatively Figure B represents a distribution of single species LC_{100} compared to an assumed homogenous PEC in the ballast tank environment. The efficacy of the control option (the shaded area) is expressed as the probability of $PEC > LC_{100}$.

Combination of A and B above (Figure C), produces an integrated efficacy probability. This integral probability can be calculated by multiplying the inverse cumulative probabilities of PEC with the frequency distribution representing LC_{100}.

Figure 3.4 Stochastic influence on exposure/effects profile for chemical biocide.

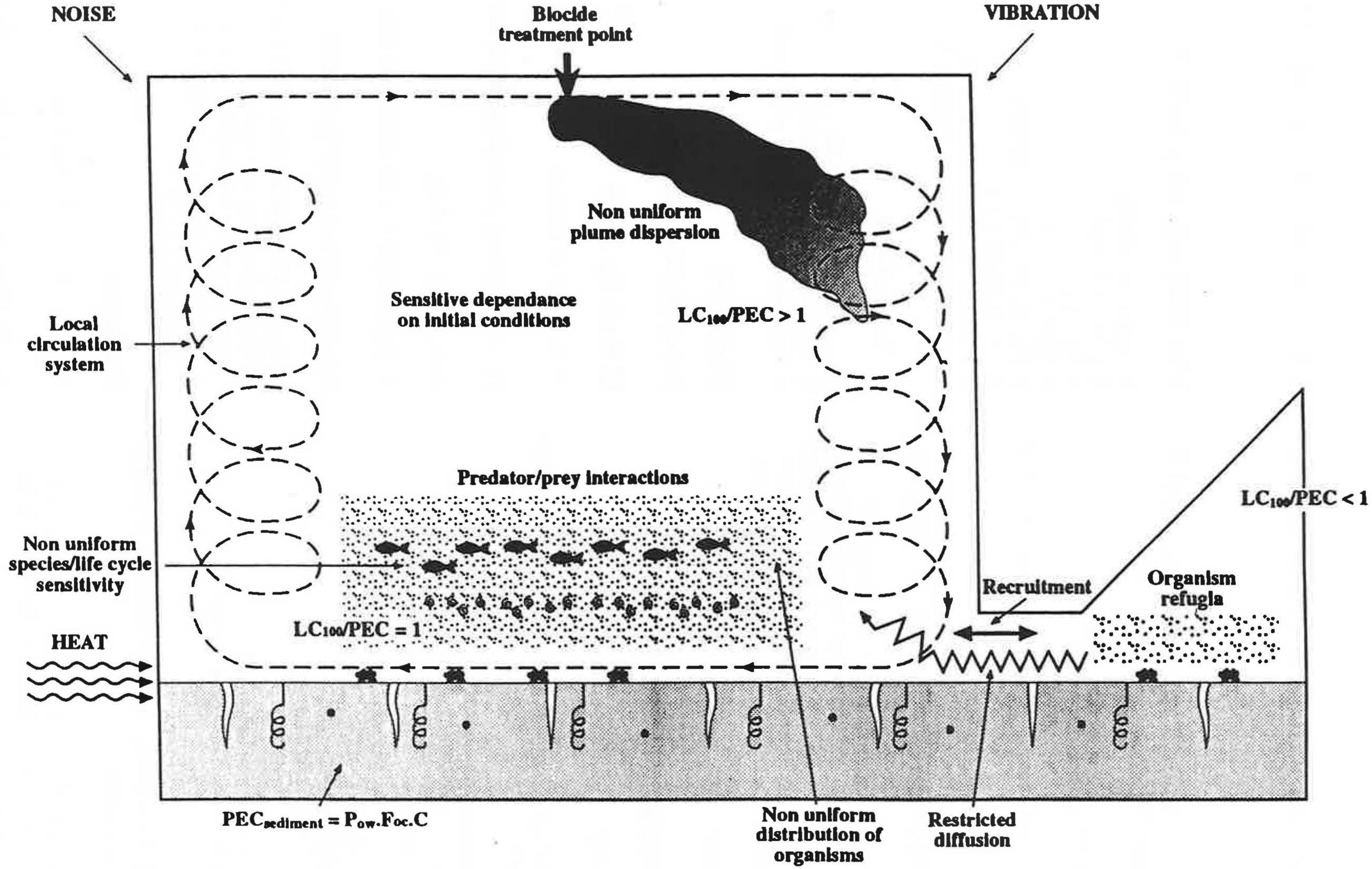


Figure 3.5 Idealised ballast water treatment strategy (biocide) problems.

Appendix A

Ballast Water & Sediment Management Options (from Carlton *et al.*, 1995)

I On or before departure from Port-Of-Ballast Water origin

Water Supply Uptake

1. Specialised shore facility provides treated salt or fresh water
2. Port provides city fresh water

Prevention of Organism Intake: Ballasting Management

3. Site: Do not ballast in "global hot spots"
4. Site: Do not ballast with high sediment loads
5. Site: Do not ballast water in areas of sewerage discharge or known disease incidences
6. Site/time: Do not ballast at certain sites at certain times
7. Site/time: Do not ballast at night

Prevention of Organism Intake: Mechanical

8. Filtration

Extermination of Organisms Upon Ballasting (Ballast Treatment)

9. Mechanical agitation
    a) water velocity
    b) water agitation mechanism

10. Altering water salinity
    a) add fresh water to salt
    b) add salt water to fresh

11. Optical: ultraviolet treatment
12. Acoustics (sonic): ultrasonic treatment

II On Departure and/or while Underway (En Route)

Extermination of organisms after ballasting (while at port-of-origin or while underway, but before arrival at destination port)

Active Disinfection (Ballast Treatment)

13. Tank wall coatings
14. Chemical biocides
15. Ozonation
16. Thermal treatment
17. Electrical treatment (including microwave)
18. Oxygen deprivation
19. Filtration/ultraviolet/ultrasonic underway
20. Altering water salinity; partial exchange

Passive Disinfection

21. Increase length of voyage
22. Exchange (deballast/reballast)
23. Sediment removal and at sea disposal

Deballast only

24. Deballast/No reballasting

III Back Up Zones

25. Exchange or deballast

IV On Arrival At Ballast Discharge Port

Water Supply: Discharge

26. Shore facility receives treated and untreated water

Prevention of Discharge to Environment

27. Discharge to existing sewage treatment facilities
28. Discharge to reception vessel
29. Sediment removal and onshore disposal
30. *In situ* extermination of organisms upon arrival (options 8, 11, 14)

Non Discharge

31. Non discharge of ballast water

V Return To Sea: Exchange Water

32. Vessel returns to sea and undertakes exchange

Annex A

ICES 1995 Annual Science Conference

(83rd Statutory Meeting)
21 - 29 September 1995
Aalborg, Denmark

OPEN LECTURE in the GENERAL ASSEMBLY
Thursday 21 September 1995, 09.00 (Europahallen)

"Ballast Water: The Ecological Roulette of Marine Biological Invasions" by Professor J. T. Carlton

Followed by:

THEME SESSION O

on

"Ballast Water: Ecological and Fisheries Implications"

A Symposium Co-Sponsored by

The International Maritime Organization
The International Oceanographic Commission

Order of the Day

Thursday 21 September 1995, 11.30-18.00 (Little Theatre)

		Time
Opening and Appointment of Rapporteur		11.30
Prologue Remarks by Theme Session Convener (J. T. Carlton)		11.35
The Ecology and Biology of Ballast Water I		
0:7	G. Ruiz *et al.* (U.S.A.) USA Research Program in ballast water invasions: monitoring and experimental studies in Chesapeake Bay	11.45
0:1	D. Minchin and J. Sheehan (Ireland): The significance of ballast water in the introduction of exotic marine organisms to Cork Harbour, Ireland	12.00
0:10	E. M. Macdonald (UK Scotland) Dinoflagellate resting cysts and ballast water discharges in Scottish ports	12.15
0:2	I. Laing (UK England and Wales): Ballast water discharge into coastal waters of England and Wales	12.30
0:13	S. Gollasch *et al.* (Germany): Non-indigenous organisms introduced via ships into German waters	12.45
LUNCH		13.00
The Ecology and Biology of Ballast Water II		
0:16	B. Hayden (New Zealand): A New Zealand Perspective on ballast water	14.30
0.15	G. Hallegraeff (Australia): Transport of toxic dinoflagellates via ship's ballast water	14.45
Management Issues and Approaches I		
0:6	H. Rosenthal (Germany): Ballast water and mariculture in coastal areas: growing concerns about potential conflicts	15.00
0:12	T. Ikegami (Japan): The possible methods to prevent transference of harmful plankton by ship's ballast water	15.15

		Time
0:4	R. E. Thresher and R. Martin (Australia): Reducing the impact of ship-borne marine introductions: focal objectives and development of Australia's new Centre for Research on Introduced Marine Pests	15.30
0:11	G. Rigby and A. Taylor (Australia): Ballast water: its impact can be managed	15.45

COFFEE BREAK 16.00

Coffee break including Posters:

*	0:5	D. Gauthier and D. A. Steel (Canada): A synopsis of regulations and scientific knowledge concerning ship transported ballast water in Canada
*	0:9	D.V. Subba Rao *et al.* (Canada): Concern for the introduction of exotic phytoplankton via ballast water into mariculture sites on Canada's east coast

Management Issues and Approaches II

0:8	M. Nauke (IMO): Provisions of the control and management of ballast water to minimize the transfer of harmful aquatic organisms and pathogens	16.30
0:14	R. M. Gaudiosi (U.S.A.): Ballast water management – an integrated approach	16.45
0:17	H. Gollamudi (U.S.A.): Policy initiatives to prevent introduction of non-indigenous species via shipping	17.00
0:3	K. Hayes (UK Scotland): Ecological risk assessment for ballast water introductions	17.15

General Discussion	17.30
Closing Remarks by Theme Session Convener	17.55
Adjournment	18.00