The Transfer of Harmful Aquatic Organisms and Pathogens with Ballast Water and Their Impacts

Stephan Gollasch, Dan Minchin, and Matej David

Abstract The annual number of new species records world-wide has paralleled shipping and is increasing. For example, in ICES member countries a new introduction forming a new population beyond its natural range occurs approximately every 9 weeks. The introduction of non-indigenous species by ships' ballast water is known since more than 100 years, but it was not until 1970s that the first biological samples from ballast water were taken. Since, more than 1,000 species were identified from ballast tanks, including human pathogens. It was estimated that 3,000–7,000 different species are moved each day around the globe by ships and it was concluded that shipping is the prime species introduction pathway with each vessel having the potential to introduce a species. However, not all species find a suitable situation in the new environment, but it was suggested that >2,000 aquatic non-indigenous species have been introduced world-wide, of which in minimum 850 are likely introduced by ships. Not all introduced species are considered harmful, in some cases this is quite the reverse, as some support important industries. However, a number of introduced species had almost catastrophic and seemingly irreversible impacts and all of the summed impacts amount to considerable costs of billions of Euro annually. Consequently, a precautionary approach suggests that every vessel transporting ballast water should be treated as a potential risk by enabling introductions of harmful species. This chapter summarises key aspects of the current knowledge on species transfers with vessels ballast water.

Keywords Non-indigenous species • Cryptogenic species • Harmful aquatic organisms • Human pathogens • Impact • Invasion rate • Shipping • Ballast water • Biofouling

---

S. Gollasch (✉)
Gollasch Consulting (GoConsult), Hamburg, Germany
e-mail: sgollasch@aol.com

D. Minchin
Marine Organism Investigations, Ballina, Killaloe, Co Clare, Ireland
e-mail: moiireland@yahoo.ie

M. David
Dr. Matej David Consult, Korte, Izola, Slovenia
e-mail: matej.david@siol.net

M. David, S. Gollasch (eds.), *Global Maritime Transport and Ballast Water Management*, Invading Nature - Springer Series in Invasion Ecology 8,
DOI 10.1007/978-94-017-9367-4_3

Introduction

The first possible occurrence of a non-indigenous species attributed to being introduced in ships' ballast water was by Ostenfeld (1908) who reported the Asian phytoplankton species *Odontella* (*Biddulphia*) *sinensis* following its mass occurrence in the North Sea in 1903. It was not until 70 years later that the first biological ballast water sampling (BWS) study was undertaken by Medcof (1975). This was then followed by several others (e.g., Carlton 1986; Williams et al. 1988; Locke et al. 1991; Hallegraeff and Bolch 1992; Gollasch 1996, 2002; Hamer et al. 2000; Gollasch et al. 2000a, b, 2002; Murphy et al. 2002; David et al. 2007; McCollin et al. 2008; Briski et al 2010, 2011) working in different world regions.

The annual number of new species records world-wide since 1850 has paralleled trade, both by shipping and also aquaculture developments. Improvements to ship design allowing for the construction of faster and bigger vessels has led to shorter voyage durations which almost certainly provide for a higher survival of organisms in ballast tanks, and more frequent discharges of bigger quantities of ballast water.

For example, in ICES member countries these shipping species introduction vectors together with others result in a new introduction forming a new population beyond its natural range approximately every 9 weeks (Minchin et al. 2005).

Biodiversity and environmental health has been on the agenda of aquatic ecologists for several decades and of great concern is the potential of "loss of biodiversity" due to increased anthropogenic pressures. However, already in the early biodiversity debate, few scientists highlighted that we are not only facing a "loss of biodiversity" but also a "change" or "increase" of species diversity due to human intervention. These changes may also be considered as threats to ecosystem health and services (Rosenthal pers. comm.).

Species movements with ships ballast water are in the focus of this chapter, resulting in (a) transport of native species, i.e., movements within their natural region of occurrence, (b) introduction of non-indigenous (also named non-native, alien, exotic, immigrant) species, i.e., species movements to areas where they were previously unknown and (c) movement of cryptogenic species, i.e., those species where it is not known if they are native to a region or whether they have been introduced (Carlton 1996). In each of these three categories some species arrivals are simply an addition to the biological diversity of a region without causing negative impacts, whereas a smaller number of species are considered harmful, e.g., human pathogens, and some can cause drastic changes to the receiving environments with a capability of modifying economies and with consequences for human health (e.g. Gollasch et al. 2009).

Here we describe the extent of species movements with ships ballast water worldwide and also provide some examples of the species that have been transferred and have resulted in different impacts following their arrival.

Definition of Terms

There are many different terms and definitions used around the world describing introduced species and their impacts and there is no common agreement in the scientific community or embedded in regulative/management/policy. The following paragraphs define some of the key terms used in this chapter.

Non-indigenous species are species, or other viable biological substances, that entered an ecosystem beyond its historical known range, including all organisms that have been transferred from one country to another, this includes invasive species, i.e., species causing economic or environmental harm or harm to human health (ANS Task Force 1999). A similar definition refers to non-indigenous species as any individual, group, or population of a species, or other viable biological material, that is intentionally or unintentionally moved by human activities beyond its natural range or natural zone of potential dispersal, including moves from one continent or country into another and moves within a country or region; including all domesticated and feral species, and all hybrids except for naturally occurring crosses between indigenous species. Synonyms: alien, immigrant, introduced, and non-native (EPA 2001). The IMO Guidelines G7 (IMO 2007) defines non-indigenous species as "… any species outside its native range, whether transported intentionally or accidentally by humans or transported through natural processes." This definition goes further compared to the previous ones as it includes natural transport processes while other definitions limit non-indigenous species to human-mediated species movements. It should also be noted that not all non-indigenous species are negatively impacting in the receiving environment.

The negatively impacting species, which are termed invasive species, i.e., are those species which threaten the diversity or abundance of native species; the ecological stability of infested ecosystems; economic (e.g., agricultural, aquacultural, commercial, or recreational) activities dependent on these ecosystems; and/or human health. Synonyms include harmful, injurious, invader, noxious, nuisance, pest, and weed (EPA 2001). As per this definition invasive species could be either native (see outbreak forming species below), cryptogenic or non-indigenous species. A second definition addresses invasive alien species (IAS, based on Olenin et al. 2010) as a subset of established non-indigenous species, which have spread, are spreading or have demonstrated their potential to spread elsewhere and have an adverse effect on one or more of the following: biological diversity, ecosystem functioning, socio-economic values or human health in invaded regions. However, there are also native species which cause concern which becomes in many cases clear when they occur in higher densities, examples include outbreaks of native jellyfish or mass developments of native harmful algae (outbreak forming species).

The term Harmful Aquatic Organisms and Pathogens (HAOP) appears in the IMO Ballast Water Management Convention (BWM Convention) and defines it as being any aquatic organisms or pathogens, which, if introduced into the sea including estuaries, or into fresh water courses, may create hazards to the environment, human health, property or resources, impair biological diversity or interfere with other legitimate uses of such areas (IMO 2004). As a result this term HAOP includes all potentially harmful non-indigenous, cryptogenic and impacting native aquatic species including pathogens.

Natural Species Movements

Many species have the potential to spread by their own means, for example, the migrations over long distances known for, e.g., birds that may carry associates with them that may either attach to them or otherwise infect them. Cladocerans, which are free swimming crustaceans that for part of their life cycle have a relatively smaller resting stage, have been found encrusted on birds feet and so explains how they can be spread between different separated water bodies. Otherwise their spread would not have been possible, as a result birds have been implicated in the spread of many species. Similarly, turtles have been found to spread several species found either entangled or attached to the turtle shell (e.g., Oliverio et al. 1992), such as macroalgae, bryozoans, barnacles, sea squirts, molluscs which were moved over long distances in this way (Pfaller et al. 2008).

Further, ocean currents can move species and under certain rare hydrodynamic conditions, with perturbations in the strength and direction of flow, species can be moved beyond their normal geographic range, perhaps also as a result of climate alterations, for example the increased spread of the sardine, a pilchard, which is occasionally found in the southern North Sea and western Baltic as a result of a rare northeast Atlantic Ocean water inflow and warmer water temperatures (Weber and Frieß 2003).

These natural phenomena result in changes to local species richness and may only appear on a temporary basis within a region, being known as rare guests, or vagrants. Such natural appearances, especially on the fringing ranges of a species where their ability to survive is just possible are a normal part of nature’s biodiversity and is often seen as an advantage. In contrast are the human-assisted species movements which can cause irreversible negative impacts.

Human-Assisted Species Movements

In contrast to natural spread, species have been transported since humans started to explore the world. Early movements will have been with solid ballast (and the damp ballast conditions will have allowed for several attaching, sediment dwelling, or otherwise associated, near-shore and intertidal species to survive and become carried) used to stabilise wooden vessels, as attached hull fouling, with boring organisms in hulls, and what might have been carried as cargo (Eldredge and Carlton 2002; Minchin et al. 2005). Many of the movements will have been unintentional and there is little historic record of what might have been transferred several centuries ago.

There will have been many further transmissions during the periods of colonisation and wrecks of vessels may have seeded species in new regions. The more modern forms of transit will have dispensed organisms with solid ballast and utilised water in its place. With this, all ships had, and have, the capacity of spreading species unintentionally (e.g., with ships fouling or ballast, associated with the cargo of vessels or transported on deck) (e.g., Gollasch et al. 2002b; Fofonoff et al. 2003; Minchin et al. 2006, 2009; Carlton and Eldredge 2009).

Ships may transfer organisms over long distances (e.g., across oceans and seas), termed a primary introduction, whereas regional transport is considered as the facilitator of secondary transfer. It should be noted that even short distance transfers are of concern (e.g., Ruiz et al. 2000; David et al. 2007) in order to avoid negative impacts of species when being moved within, e.g., one regional sea or neighbouring waterbodies via inland canals.

In aquatic environments there are seven principal categories as to how species are spread (pathways). Each pathway enables several ways a species may be transferred (vectors). Overall, there are more than 50 recognised vectors (ICES 2005; Minchin et al. 2005). Shipping is considered to be the principal pathway worldwide, by which species are spread. The prime vectors involving shipping are ballast water and sediments accumulated at the tank bottom as well as hull fouling, where also free-living (non-fouling) species were found (Faubel and Gollasch 1996; Gollasch 2002). Species have also been transported as fouling and free living stages in sea chests (Coutts and Dodgshun 2007), as fouling inside ballast tanks, with anchor chains and as fouling in the engine cooling water pipework as well as with cargo. In some cases several vectors may be responsible for the transmission of a single species (Minchin et al. 2007a, b, c).

Ballast water also contains sediments, usually obtained in estuarine areas and shallow turbid bays. These sediment accumulations, that can range from silt to sands, settle on the bottom ballast tanks, providing a niche for infaunal organisms. As a consequence ballast tanks offer three different habitats to species (1) the water itself, (2) sediments at the tank bottom and (3) the tank walls for fouling organisms.

Species in Ballast Water Tanks

According to expert estimates, 3,000–4,000 different species are moved each day around the globe by ships (Carlton and Geller 1993; Gollasch 1996). More recent estimates indicate that the number of species in transit with ships is most probably in the range of 7,000 every day (Carlton 2001) and this does not take into account the transfer of microorganisms such as bacteria and pathogens. While even the general estimates vary greatly, the dimension of species transmission must be regarded as being exceptionally high (often referred to as colonization pressure) and it was concluded that each vessel has the potential to introduce a species (Gollasch 1996).

Fig. 1 Variety of species found in ballast water samples documenting that also fragile organisms survive the ballasting processes

It is the free-living, often larval, stages in the species life-cycle that are most likely to be transported with ballast water (Hewitt and Campbell 2010). The Fig. 1 shows some examples of organisms which were found in ballast water samples. Very often such stages may be taken-up during the night, since many planktonic organisms undergo vertical migrations to appear higher in the water column during darkness. These vertical migration patterns are widely recognised within marine and freshwater environments. Adult stages of bottom living organisms may also become entrained in ballast water uptake once they occur in the water column. This may be due to strong currents, storm activity or nearby dredging operations which stir up bottom sediment and organisms.

Ballast water studies conducted since the 1980s in different parts of the world have shown that ships, to an enormous extent, facilitate the transfer of aquatic

Table 1 Summary of European BWS studies indicating each study source, when it was conducted, number of vessels sampled, number of samples and number of taxa identified

Source	When	Vessels sampled	Samples taken	Taxa identified
Belgium	1995–1998	5	32	28
Denmark	2000–2001	1	8	4
England & Wales	1996–1999	132	265	320
Germany	1992–1999	198	215	521
Lithuania	1999–2000	11	22	90
Netherlands	1999–2000	17	23	88
Norway	1996–1999	51	12	184
Scotland	1994–1997	127	226	327
Slovenia	2003	15	90	134
Sweden	1996	3	>3	41
EU-CA	1998–1999	5	705	67
Total	1994–2003	565	1598	[a]More than 1,000

Gollasch (1996), Macdonald and Davidson (1998), Gollasch et al. (2000a, b), Olenin et al. (2000), Gollasch et al. (2002) and David et al. (2007)

[a]An approximation was made because several taxa were identified in more than one study

organisms across natural barriers (e.g., Williams et al. 1988; Hallegraeff and Bolch 1992; Carlton and Geller 1993; Hay 1990; Gollasch 1996; Macdonald and Davidson 1998; Ruiz et al. 2000; Gollasch et al. 2000a, b, 2002; Olenin et al. 2000; Murphy et al. 2002; David et al. 2007; Briski et al. 2010, 2011). A summary of European shipping studies revealed that 1,598 ballast water samples were collected between 1992 and 2003 on 565 vessels of different origin (see Table 1).

The diversity of living organisms (including native, cryptogenic and non-indigenous species) found during the European BWS studies included viruses, bacteria including human pathogens, fungi, protozoa, algae (unicellular phytoplankton algae and macroalgae), invertebrates and fish. Crustaceans, molluscs and polychaetes, as well as algae, were the dominant groups found in samples and consisted of more than 1,000 identified species. The majority that occurred within ballast were small in body dimensions and better able to survive the physical forces generated by the vessel pumps during the ballasting process. Nevertheless, fishes of up to 15 cm have been found within tanks (Gollasch et al. 2002) which was also documented during BWS events when testing the performance of ballast water treatment systems (Gollasch and David, own observation). A list of all animals, plants and bacteria groups found in the European BWS studies undertaken until 2002 is available in Leppäkoski et al. (2002a, b). Since this study was completed, further studies were conducted (e.g., David et al. 2007; Drake et al. 2007; Dobbs 2008; McCollin et al. 2008; Briski et al. 2010, 2011) and altogether they provided sufficient information to support the need for ballast water management actions.

The majority of organisms taken-up in ballast water expire at an exponential rate during the first 3–5 days in a ballast tank due to a wide range of conditions that occur within them (e.g., McCollin et al. 2008; Gollasch et al. 2000a, b; Olenin et al. 2000). Ballast tanks are, for most organisms, unfavourable habitats, there is an

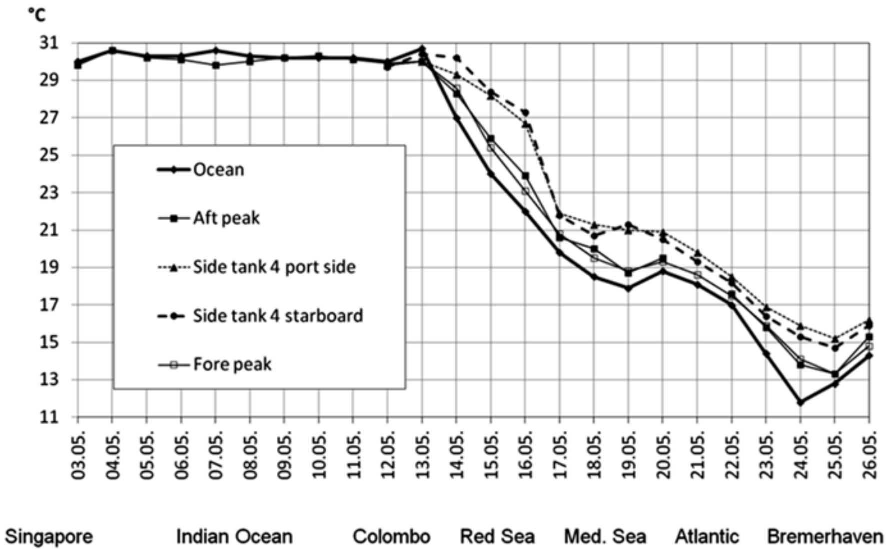

Fig. 2 Ballast water tank temperatures and sea surface temperatures during a voyage from Singapore to Bremerhaven (Reprinted from Gollasch et al. 2000a, copyright 2000, with permission from RightsLink Service, Oxford University Press)

absence of light and there can be limited resources such as oxygen, food, lack of shelter and the varying temperatures that may take place during a voyage that may considerably differ from the ballast water uptake area. Some inter-oceanic ship voyages can expose ships ballast water to wide ranges of temperature between tropical and temperate regions, this is because the ballast water gradually assumes a similar temperature to that of the ambient sea surface a ship passes through, as can happen with passages between the Pacific and Atlantic (see Fig. 2). In winter these changes can be extreme.

Although voyage duration affects the survival of organisms in ballast water, it is not a ballast water management option to retain the water onboard for long periods in order to ensure that all organisms die. Some organisms can survive 3 or more months between ballast uptake and discharge. In one case, where daily samples of ballast were taken during a voyage, a crustacean (a harpacticoid copepod), greatly increased their numbers, and had most probably reproduced inside the ballast tank during the voyage (Gollasch et al. 2000a). Some organisms can survive in ballast sediments for long periods when they develop resting stages. Some phytoplankton species, in particular dinoflagellates, several of which can generate toxins, form such resting stages (cysts) which may settle to the bottom sediment in a ballast tank. These may remain viable (in a dormant state) despite unfavourable conditions from months to years. This poses a risk since as viable cyst-forming species may be discharged during deballasting with disturbed sediments after several voyages from their uptake or with sediments when removed during tank cleaning (Hallegraeff and Bolch 1992).

Table 2 Summary of numbers of different organisms per litre

	No. tanks sampled	Numbers and range per litre	Mean SD per litre
Zooplankton	429	0–172	4.64 ± 0.71
Phytoplankton	273	$1–49.7 \times 10^6$	$299 \times 10^3 \pm 183 \times 10^3$
Bacteria	11	$2.4 \times 10^8–1.9 \times 10^9$	$8.3 \times 10^8 \pm 1.7 \times 10^7$
Viruses	7	$0.6 \times 10^9–14.9 \times 10^9$	$7.4 \times 10^9 \pm 2.9 \times 10^9$

From Gollasch and McCollin (2003) and IMO (2003)

There is not only a high diversity of species in transit with ships, but also large numbers of individuals that may be transported and that might survive to a destination port region. The overall numbers of organisms recorded from ballast water have been reported by the ICES/IOC/IMO Study Group on Ballast and Other Ships Vectors (SGBOSV) under the four headings: virus-like particles, bacteria, phytoplankton and zooplankton (see Table 2). The purpose was to provide guidance for the development of ballast water discharge standards for the BWM Convention. Any estimates of the numbers of the different groups to be in transit are likely to be underestimates because species that reside within sediments, and those planktonic species that pass through the plankton nets, using the standard mesh sizes 55 and 80 μm, during BWS, do not get considered (Gollasch and McCollin 2003). During the performance test of ballast water treatment systems more than 29,000 zooplankton organisms greater than or equal to 50 μm in minimum dimension per m^3 and more than 47,000 phytoplankton cells greater than 4 μm in minimum dimension per milliliter have been found in pumped ballast (Gollasch and David, unpublished). Such great numbers of living organisms taken up during ballasting indicates a high probability of a viable population evolving following discharge in new environments, often referred to as propagule pressure.

Chain of Events for a Species Introduction

The previous section of this chapter has shown that an enormous number of species in high organism concentrations are being transferred with ballast water. However, only the transport of a species does not result in a colonization of a new region, there is a chain of events that a species must endure in order to become established within a new environment (Carlton 1986; Hayes 1998). This starts with the uptake of ballast water. As many species have seasonal planktonic stages it is during those periods of abundance that sufficient surviving numbers may go on to later form a viable inoculum at discharge. Suspended sediments can also result in cysts and benthic biota becoming transmitted with the same ultimate capability. Having survived the uptake process the voyage(s) must be endured followed by the trauma during discharge. On arrival sufficient numbers will be needed to establish a population. The numbers required to develop new populations is generally unknown but theoretically some species can generate new populations with low numbers (Bailey et al. 2009). Survival depends on their tolerance to the conditions in the new environment and the degree of dispersal following discharge. Very often these windows of opportunity for establishment may depend on the precise location of ballast release. The colonization success may depend on the season during which arrival takes place, in cold climate regions warm water species may only survive discharge in summer, and might not subsequently survive any winter. Unless a species can reproduce a colonisation cannot evolve. Once a founder population is formed a species can then be spread by a wider range of human activity processes but also by natural processes.

Transfer and Impacts of Non-indigenous Species

Hewitt and Campbell (2010), Hayes and Gollasch (both unpublished) suggest >2,000 aquatic non-indigenous species have been introduced world-wide, of which in minimum 850 are thought to have been introduced by ships (Hayes and Sliwa 2003). There are some world regions that have greater numbers of recorded aquatic non-indigenous species present, these have often been in port regions, in sheltered bays and estuaries in regional seas (see Fig. 3).

In Europe >1,000 non-indigenous species are recorded from coastal and adjacent waters. The numbers of non-indigenous species in European seas have different patterns to all other world regions, this is because more than 50 % of the introductions occur in the Mediterranean Sea with more than 650 species records of which, at least

Fig. 3 Hot spots of invasive marine species. *Small circles*: <150 species, *medium circles*: 150–250 species and *large circle*: >250 species (see text for references)

325 are established. The North Sea makes up 16.2 % of the known non-indigenous species. The lowest numbers occur in Arctic waters where 18 non-indigenous species were recorded, making up only 1.3 % of the European component (Vermeij 1991; O'Mahony 1993; Boudouresque et al. 1994; Leppäkoski 1994; Eno and Clark 1994; Gollasch 1996; Olenin and Leppäkoski 1999; Reise et al. 1999; Leppäkoski and Olenin 2000; Ricciardi and MacIsaac 2000; Zaitsev and Ozturk 2001; Aladin et al. 2002; Berger and Naumov 2002; Eldredge and Carlton 2002; Golani et al. 2002; Gomoiu et al. 2002; Goulletquer et al. 2002; Hopkins 2002; Carlton and Eldredge 2009; Leppäkoski et al. 2002a, b, 2009; Minchin and Eno 2002; Occhipinti-Ambrogi 2002; Ozturk 2002; Grigorovich et al. 2003; Hewitt et al. 2004, 2007, 2009; Zenetos et al. 2004; CIESM 2005; Jensen and Knudsen 2005; Pancucci-Papadopoulou et al. 2005; Reise et al. 2005; Streftaris et al. 2005; Wolff 2005; Olenin 2005; Cardigos et al. 2006; Gollasch and Nehring 2006; Gollasch 2006; Gollasch et al. 2009; Alexandrov et al. 2007; Gittenberger 2007; Kerckhof et al. 2007; Cook et al. 2008; Olenina et al. 2010; Verlaque et al. 2010; AquaNIS 2013.[1] Katsanevakis et al. 2013).

Most species introductions almost certainly go unnoticed. Some species, either gradually or rapidly expand their populations to become invasive, a time when they become easily recognised, usually some years after an arrival. However, the great majority of non-indigenous species that are introduced are not perceived to cause harm, but it is those, that result in some form of impact, that are of concern.

The impacts of introduced species vary greatly and can cause considerable harm by modifying natural environments with consequent long-term impacts (see Box 1). While there are a comparatively small number of invasive species among all non-indigenous species that arrive, those that have impacts may have serious consequences that may endure for a considerable time. In the extreme cases these negative consequences are almost catastrophic and seemingly irreversible (e.g. Hayes and Sliwa 2003).

Box 1: Nature of Impacts

Impacts on biodiversity: predation on native communities, alteration of habitat structure and re-organisation of the trophic web, importation of diseases and disease agents, alterations of the genome (Olenin et al. 2007).

Economic losses: impacts on aquaculture production, impacts on fisheries resources, fouling of abstraction piping, impact on recreational resources.

Human health concerns: infectious cholera strains, other diseases, toxins generated by algae that contaminate foods, outbreaks of stinging jellyfish affecting swimmers, bathers cut feet on bivalve shells.

[1] AquaNIS is the information system on aquatic non-indigenous and cryptogenic species currently being developed in the European Community's Seventh Framework Programme (FP7/2007-2013) under Grant Agreement No. [266445] for the project Vectors of Change in Oceans and Seas Marine Life, Impact on Economic Sectors (VECTORS).

Not all introduced species are considered harmful, in some cases this is quite the reverse, as some provide for important industries providing employment and the sustained production of valued products. Examples include the many clam species, oysters and shrimp that have been cultivated. However, some may become so prolific to create some unwanted effects, such as the recent expansion and fouling of the Pacific oyster in the North Sea following increased recruitment, arising from changes in climate (Reid and Valdés 2011). However a latent threat to the environment, human health, property or resources remains as a non-impacting species may turn into an invasive species at a later stage.

Great harm can be caused by the introduction of one harmful species. For instance, the Chinese mitten crab *Eriocheir sinensis* has resulted in economic damage to pond fisheries and damage to river banks from burrowing with the resultant accumulations leading to increased dredging costs (e.g. Gollasch 1999). The zebra mussel *Dreissena polymorpha*, originally from the Black Sea region, has expanded its range in Europe and now is extensively distributed in North America. It has resulted in environmental changes to lakes and rivers; but, on account of its ability to attach to surfaces with byssal threads, has fouled abstraction piping and thrash racks of power stations and municipal water supplies, and continues to do so (Hebert et al. 1989; Carlton and Geller 1993; Johnson and Padilla 1996; van der Velde et al. 2010). The predatory sea star *Asterias amurensis* arrived to Australia from the north-west Pacific and has caused significant changes to bottom dwelling communities, some of economic importance (Buttermore et al. 1994; Byrne and Morrice 1997; Rossa et al. 2003). A further predator, the comb-jelly *Mnemiopsis leidyi*, was inadvertently introduced to the Black Sea from the eastern coast of the Americas. Its vast numbers resulted in heavy predation on zooplankton, including the larval stages of commercially important fishes (GESAMP 1997; Vinogradov et al. 2005). Although as a result of a further comb-jelly introduction that fed on *M. leidyi* its abundance declined in the Black Sea it appeared in the Caspain Sea carried by shipping using the interconnecting Volga-Don-Canal (Ivanov et al. 2000). It has since appeared in the Kiel Bight and has spread to several Baltic countries and to the southern North Sea (Javidpour et al. 2006) and it also expanded southwards to the Eastern Mediterranean. The North Sea invasion was overlooked for some time as the species was initially misidentified as a native comb-jelly (Faasse and Bayha 2006). Using taxonomic identification with microsatellites it was possible, for the first time for comb-jellies, to show that there have been two separate invasions of *M. leidyi* colonizing European waters from two North American source areas. The results show one originating from or near the Gulf of Mexico having arrived to the Black Sea and the North and Baltic Seas population was traced to New England populations (Reusch et al. 2010).

All of the summed impacts amount to a considerable economic cost which is difficult to quantify. In the USA alone a comprehensive study concluded that the estimated annual damage and/or control costs addressing introduced aquatic non-indigenous species is $14.2 billion (Pimentel et al. 2005). A recent summary for Europe that includes costs for repair, management and the mitigation of impacts results at more than 12 billion Euros annually (Shine et al. 2010). However, this cost includes terrestrial impacts on habitats and on services. For the aquatic sector the costs are thought to be 10–15 % of this amount.

Transfer and Impacts of Potentially Harmful Phytoplankton Species

Ballasted seawater may contain 30–>100 phytoplankton species including those being potentially toxic or others forming harmful algal blooms. These are unicellular microalgae, most usually these are diatoms and dinoflagellates, and may occur at levels of a thousand to a million or more cells per litre (Hallegraeff 1993, 1995, 1998). As a result these have great potential for global transfer and 'successfully' introduction of these species.

Over 100 years ago it was claimed that the centric diatom *Odontella sinensis*, known from tropical and subtropical coasts of the Indo-Pacific, had arrived in the ballast water of a merchant vessel, and had spread to become sufficiently abundant in the North Sea to result in plankton blooms in 1903 (Ostenfeld 1908). These blooms had no known harmful effects. It was not until the 1970s, the introduction of further centric diatom, *Coscinodiscus wailesii*, to the North Sea which clogged fishing nets due to extensive mucilaginous accretions (Boalch and Harbour 1977; Laing and Gollasch 2002). For many other phytoplankton species their origin is unknown which is also due to the taxonomic uncertainties with many phytoplankton species (see cryptogenic species below).

In Australia, an investigation found that 80 % of vessels contained approximately 30 culturable diatom species, including the potentially toxic *Pseudonitzschia* species that can cause Amnesic Shellfish Poisoning (ASP) (Forbes and Hallegraeff 1998) which can debilitate humans following consumption of contaminated shellfish. Further, cultures of viable dinoflagellates *Alexandrium catenella*, *A. tamarense* and *Gymnodinium catenatum*, all known for the toxins they can produce and consequent impacts on human health, were extracted from the ballast water of 5 % of the vessels arriving from Japan and Korea (Hallegraeff and Bolch 1992). Studies of vessels entering British ports confirmed the presence of *A. minutum*, *A. catenella and A. tamarense* in 17 % of ballast water samples (Hamer et al. 2001). In one case, a single ballast tank contained as many as 300 million viable *Alexandrium tamarense* cysts (Hallegraeff and Bolch 1992). The occurrence of such numbers in ballast water discharges may well have contributed to the widespread distribution of this species. In addition, the potentially ichthyotoxic dinoflagellate *Pfiesteria piscicida* has been confirmed using molecular probes in ballast water entering US ports (Doblin et al. 2002). In conclusion, the presence of potentially harmful marine microalgae in ballast water has been firmly established.

Dinoflagellates do not always need to form blooms in order to result in toxic events. They can occur at comparatively low densities sufficient to render cultured filter-feeding molluscs toxic. However, there are national programmes that regularly monitor for these toxins to ensure that both cultured and wild molluscs are safe for human consumption. Sudden outbreaks of toxic dinoflagellate species have taken place world-wide and have been attributed to ballast water releases (Hallegraeff 1993; David et al. 2007). On occasion their occurrence and also collapses of blooms of non-toxic species can cause de-oxygenation events to result in losses to aquaculture production, fishery landings and high mortalities of bottom living species. Although monitoring programmes exist, human casualties are also reported each year due to consumption of toxin contaminated seafood and it was found that ballast water and the sediment contained in the tanks, are one of the main (if not *the* main) transfer vectors of potentially toxic dinoflagellates (Hallegraeff 1993; David et al. 2007).

Transfer and Impacts of Cryptogenic Species

There are many species whose status is unclear because they may be native species that have recently been recognised or undergone an outbreak and their native range is not clearly known. Those species not demonstrably native or introduced are termed cryptogenic species (Carlton 1996). There are several examples that include the fouling brackish water barnacle *Balanus improvisus*, the bivalve *Mya arenaria* and the ship-worm *Teredo navalis*. Due to the taxonomic uncertainties many phytoplankton species (i.e., dinoflagellates and diatoms) are seen as cryptogenic species as many are now known from many different world regions and their identification is often a highly specialised skill, improved in recent decades using new technologies (Gómez 2008). This group of species is of special concern as many are potentially toxin producers which affects many resource users (see above).

Mya Arenaria

Already the Vikings sailed the seas and their activities may have resulted in the introduction of the North American bivalve *Mya arenaria* to Europe (Petersen et al. 1992). It was suggested that Vikings when returning from North America may have kept live *Mya arenaria* onboard either intentionally as fresh food, or unintentionally may have imported them with the solid ballast on their vessels. Excavations at Haithabu, Germany, a Viking trade hub in the Baltic Sea, revealed enormous numbers of ballast stones at and near the landing pier (see Fig. 4), supporting the probability of a species introduction with this solid ballast.

Viking ships are likely to have explored sheltered estuaries in North America, and these environments would likely have had large numbers of *Mya arenaria*.

Fig. 4 Ballast stones excavated near the vessel landing pier of the Viking trade hub Haithabu, Germany

Very likely, on account of the great importance of each vessel when not in use they were likely to have been carried on muddy shore, a habitat the soft clam also occupies, and so before any journey a supply of food may have been readily available. However, Wolff (2005) stated that the transfer of *Mya* to Europe by the Vikings poses a problem. Except for an occasional event when a vessel may have been driven off course by gales, there was no direct Viking shipping activity between North America and Europe (Marcus 1980). Greenlanders sailed to North America more frequently and also travelled between Greenland and Norway. However these voyages were not undertaken by the same vessels. It may therefore be possible that *Mya* was first introduced from North America to Greenland and subsequently from Greenland to Europe (Ockelmann 1958; Petersen 1978, 1999). In contrast, a different scenario describes that there was a gradual re-expansion of this mussel into Europe following the last glaciation period from a southern locality. So in this case it remains uncertain whether this mussel was introduced or it naturally recolonised Europe.

Teredo Navalis

The shipworm, which is not actually a worm, but a 'worm-like' mollusc, which bores into wood, is one of the oldest invaders known. They naturally spread with wooden material, within the hulls of wooden vessels from early times and is so widely spread that its native origin has become obscured. It was first recorded in Europe in 1731 (Sellius 1733), when it destroyed wooden dyke gates in the Netherlands, causing a terrible flood. At this time the Dutch believed it was introduced from Asia, possibly sent as a punishment from God (www.waddensea.org). Many naval engagements at sea may have been lost on account of the weakening effects of the boreholes on the hull and many vessels will have been disabled and wrecked on account of this damage. It was also proposed that the vessels of the Spanish armada, while waiting in French and Portuguese harbours to prepare for the invasion of England in 1588, may have been weakened in stability by the ship-worm so that the fight was lost. It was proposed that the 'shipworm' originated in the North Atlantic area (Schütz 1961) on account of its tolerance to low temperatures. This could support a possible origin from northern or southern Atlantic waters. Nowadays *T. navalis* is known to occur in Northern Europe, Indonesia, Japan, Australia, Brazil, the Atlantic and Pacific US and Canadian coasts. Many attempts were made to deter their colonisation of hulls over the centuries. Today they continue to have impacts, but on account of the usage of steel as vessel hull material, these impacts are to harbour pilings, as has happened in recent years on the Kiel Canal, Germany.

Transfer and Impacts of Human Pathogens

Human pathogens and microorganisms are also transferred with ship's ballast water (Ruiz et al. 2000; Drake et al. 2001, 2007; Casale 2002; Dobbs and Rogerson 2005; Dobbs 2008).

Particular strains of cholera, have and continue to, threaten human health worldwide. There is evidence that ships spread the pathogenic strain of this bacterium, *Vibrio cholera* O1. In 1991 the virulent form was found in Mobile Bay, Alabama, in the Gulf of Mexico (McCarthy and Khambaty 1994). It appeared in oysters that had filtered the virus arising from the discharges of ballast water (Motes et al. 1994). During a standard inspection, the US Food and Drug Administration isolated *Vibrio cholerae* O1 from the stomach content of a fish caught in Mobile Bay. The strain was similar to that found in Latin America where many humans died (Casale 2002). Indeed, the epidemic occurring in Peru was directly related to ships ballast discharges and spread to many regions in South America. In 1991 more than a million people had become infected; and by 1994 there were >10,000 victims although it is believed that their number was underestimated due to inappropriate coverage. This particular form of cholera had previously been known only in Bangladesh (Casale 2002) thereby highlighting the likelihood that ballast water transport contributed to this disease outbreak.

A study of ships in Hamilton and Toronto (Canada), at the entrance to the Great Lakes of North America, conducted in 1995 found within 71 ballast water samples a frequency of 45 % of the faecal coliform bacteria, *Escherichia coli*, and 80 % of the samples contained enterococcal bacteria (Whitby et al. 1998). Furthermore, streptococcal bacteria were found in four ballast water samples taken during this Canadian study.

Future Issues and Concerns

Monitoring of ballast water receiving habitats to document newly introduced species is rarely undertaken. Coastal monitoring programmes exist, but in many cases they lack sampling stations in ports where the ballast water is discharged or taken up. Only when new introduced species are recognized soon after introduction an eradication programme is advisable, should the newly found species cause concern. Regular monitoring using a rapid assessment approach is more likely to encounter targeted species at an earlier time (Minchin 2007b) so that those found at an early stage might be eradicated (Bax 1999). The longer a species occurs unnoticed the more unlikely an eradication programme will be successful, as during the intervening time, the species is likely to have spread over a wider area.

The identification of species is often dependent upon taxonomic skills which are not easily acquired. It may well be possible that such services, due to the reducing number of specialists, will become less available creating a consequent confusion in the area of biogeography and biological invasion science. Taxonomic skills are needed as the invasion status of an organism can normally only be assessed when the species level is identified. The lack of taxonomic expertise may also lead to overlooking introduced species, as had happened with *Mnemiopsis leidyi* in the North Sea. The presence of this species was possibly overlooked for almost a decade as the comb jellies found were confused with native species (Van Ginderdeuren et al. 2012).

Although there is an impressively high number of new non-indigenous and/or harmful species being introduced every day all around the world, relatively few cases of 'successful' invasions have been recognised. Despite relatively few invasions, a number of cases have had significant (almost catastrophic) and seemingly irreversible impacts. Consequently, a precautionary approach suggests that every vessel transporting ballast water should be treated as a potential risk by enabling introductions of harmful species.

Acknowledgements The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007–2013) under Grant Agreement No. [266445] for the project Vectors of Change in Oceans and Seas Marine Life, Impact on Economic Sectors (VECTORS).

References

Aladin NV, Plotnikov IS, Filippov AA (2002) Invaders in the Caspian Sea. In: Leppäkoski E, Gollasch S, Olenin S (eds) Invasive aquatic species of Europe, distribution, impacts and management. Kluwer Academic Publishers, Dordrecht, pp 351–359

Alexandrov B, Boltachev A, Kharchenko T, Lyashenko A, Son M, Tsarenko P, Zukinsky V (2007) Trends of aquatic alien species invasions in Ukraine. Aquat Invasion 2(3):215–242

ANS Task Force (1999) Aquatic Nuisance Species (ANS) Task Force. http://anstaskforce.gov/default.php. Accessed 12 Feb 1999

AquaNIS (2013) Information system on aquatic non-indigenous species. World Wide Web electronic publication. www.corpi.ku.lt/databases/aquanis, version 2.36+. Accessed 13 Nov 2013

Bailey SA, Vélez-Espino LA, Johannsson OE, Koops MA, Wiley CJ (2009) Estimating establishment probabilities of Cladocera introduced at low density: an evaluation of the proposed ballast water discharge standards. Can J Fish Aqua Sci 66(2):261–276

Bax NJ (1999) Eradicating a dreissenid from Australia. Dreissena! 10:1–5

Berger VJA, Naumov AD (2002) Biological invasions in the White Sea. In: Leppäkoski E, Gollasch S, Olenin S (eds) Invasive aquatic species of Europe, distribution, impacts and management. Kluwer, Dordrecht, pp 235–239

Boalch GT, Harbour DS (1977) Unusual diatom off the coast of south west England and its effect on fishing. Nature 269:687–688

Boudouresque CF, Briand F, Nolan C (1994) Introduced species in European coastal waters. European Commission. In: Boudouresque CF, Briand F, Nolan C (eds) Ecosystem research report 8

Briski E, Bailey S, Cristescu ME, MacIsaac HJ (2010) Efficacy of 'saltwater flushing' in protecting the Great Lakes from biological invasions by invertebrate eggs in ships' ballast sediment. Freshw Biol 55:2414–2424

Briski E, Bailey S, MacIsaac HJ (2011) Invertebrates and their dormant eggs transported in ballast sediments of ships arriving to the Canadian coasts and the Laurentian Great Lakes. Limnol Oceanogr 56(5):1929–1939

Buttermore RE, Turner E, Morrice MG (1994) The introduced northern Pacific seastar *Asterias amurensis* in Tasmania. Mem Qld Mus 36(1):21–25

Byrne M, Morrice MG (1997) Introduction of the northern Pacific asteroid *Asterias amurensis* to Tasmania: reproduction and current distribution. Mar Biol 127(4):673–685

Cardigos F, Tempera F, Avila S, Goncalves J, Colac A¸ Santos RS (2006) Non-indigenous marine species of the Azores. Helgol Mar Res 60:160–169

Carlton JT (1986) Transoceanic and interoceanic dispersal of coastal marine organisms. The biology of ballast water. Oceanogr Mar Biol Ann Rev 23:313–371

Carlton JT (1996) Biological invasions and cryptogenic species. Ecology 77(6):1653–1655

Carlton JT (2001) Introduced species in U.S. coastal waters: environmental impacts and management priorities. Pew Oceans Commission, Arlington

Carlton JT, Eldredge LG (2009) The introduced and cryptogenic marine and estuarine animals and plants of the Hawaiian archipelago, vol 4, Bishop museum bulletin in cultural and environmental studies. Bishop Museum Press, Honolulu

Carlton JT, Geller JB (1993) Ecological roulette: the global transport of non-indigenous marine organisms. Science 261:78–82

Casale GA (2002) Ballast water – a public health issue? GloBallast Programme, IMO London, Ballast Water News. Issue 8

CIESM (2005) Alien marine organisms introduced by ships in the Mediterranean and Black seas. CIESM workshop monographs 20

Cook EJ, Ashton G, Campbell M, Coutts A, Gollasch S, Hewitt C, Liu H, Minchin D, Ruiz G, Shucksmith R (2008) Non-native aquaculture species releases: implications for aquatic ecosystems. In: Holmer M, Black K, Duarte CM, Marbà N, Karakassis I (eds) Aquaculture in the ecosystem. Springer, Heidelberg, pp 155–184

Coutts ADM, Dodgshun TJ (2007) The nature and extent of organisms in vessel sea-chests: a protected mechanism for bioinvasions. Mar Pollut Bull 54(7):875–886

David M, Gollasch S, Cabrini M, Perkovič M, Bošnjak D, Virgilio D (2007) Results from the first ballast water sampling study in the Mediterranean Sea – the Port of Koper study. Mar Pollut Bull 54:53–65

Dobbs FC (2008) Ship ballast tanks: how microbes travel the world. Microbiol Today 35:78–81

Dobbs FC, Rogerson A (2005) Ridding ships' ballast water of microorganisms. Is it even possible to remove, kill, or "inactivate" all of them—and if so, should we try? Environ Sci Tech 39:259A–264A

Doblin MA, Drake LA, Coyne KJ, Rublee PA, Dobbs FC (2002) Pfiesteria species identified in ships' ballast water and residuals: a possible vector for introductions to coastal areas. In: Steidinger KA, Landsberg JL, Tomas CR, Vargo GA (ed) Harmful Algae 2002. Florida Fish and Wildlife Conservation Commission, Florida Institute of Oceanography and Intergovernmental Oceanographic Commission of UNESCO. St. Petersburg, FL, pp 317–319

Drake LA, Choi K-H, Ruiz GM, Dobbs FC (2001) Global re-distribution of bacterioplankton and virioplankton communities. Biol Invasion 3:193–199

Drake LA, Doblin MA, Dobbs FC (2007) Potential microbial bioinvasions via ships' ballast water, sediment, and biofilm. Mar Pollut Bull 55:333–341

Eldredge LG, Carlton JT (2002) Hawaiian marine bioinvasions: a preliminary assessment. Pac Sci 56:211–212

Eno N C, Clark RA (1994) A review of non-native marine species in British waters. Appendix 1: information sheets for non-native marine species. Joint Nature Conservation Committee

EPA (2001) United States Environmental Protection Agency http://www.epa.gov/gmpo/2001annualreportfinal.pdf. Accessed 14 July 2001

Faasse MA, Bayha KM (2006) The ctenophore *Mnemiopsis leidyi* A. Agassiz 1865 in coastal waters of the Netherlands: an unrecognized invasion? Aquat Invasion 1(4):270–277

Faubel A, Gollasch S (1996) *Crptostylochus hullensis* sp. nov. (Polycladida, Acotylea, Platyhelminthes): a possible case of transoceanic dispersal on a ship's hull. Helgol Mar Res 50(4):533–537

Fofonoff PW, Ruiz GM, Steves B, Carlton JT (2003) In ships or on ships? Mechanisms of transfer and invasion for non-native species to the coasts of North America. In: Ruiz GM, Carlton JT (eds) Invasive species: vectors and management strategies. Island Press, Washington, pp 152–182

Forbes E, Hallegraeff GM (1998) Transport of potentially toxic *Pseudo-nitzschia* diatom species via ballast water. In: Proceedings of the 15th international diatom symposium, Perth, pp 509–520

GESAMP (1997) Opportunistic settlers and the problem of the ctenophore *Mnemiopsis leidyi* invasion in the Black Sea. GESAMP Rep Stud 58:1–84

Gittenberger A (2007) Recent population expansions of non-native ascidians in the Netherlands. J Exp Mar Biol Ecol 342:122–126

Golani D, Orsi-Relini L, Massutí E, Quignard JP (2002) CIESM atlas of exotic species in the Mediterranean, vol 1 Fishes. Briand F (ed) CIESM Publishers, Monaco

Gollasch S (1996) Untersuchungen des Arteintrages durch den internationalen Schiffsverkehr unter besonderer Berücksichtigung nichtheimischer Arten. Diss., Univ. Hamburg; Verlag Dr. Kovac, Hamburg

Gollasch S (1999) Current status on the increasing abundance of the Chinese Mitten Crab *Eriocheir sinensis* H. Milne Edwards, 1854 in German rivers. United States Fish and Wildlife Service

Gollasch S (2002) The importance of ship hull fouling as a vector of species introductions into the North Sea. Biofouling 18(2):105–121

Gollasch S (2006) Overview on introduced aquatic species in European navigational and adjacent waters. Helgol Mar Res 60:84–89

Gollasch S, McCollin T (2003) Report of the ICES/IOC/IMO Study Group on Ballast and Other Ship Vectors (SGBOSV). ICES, Copenhagen

Gollasch S, Nehring S (2006) National checklist for aquatic alien species in Germany. Aqua Invasion 1(4):245–269
Gollasch S, Lenz J, Dammer M, Andres HG (2000a) Survival of tropical ballast water organisms during a cruise from the Indian Ocean to the North Sea. J Plankton Res 22:923–937
Gollasch S, Rosenthal H, Botnen H, Hamer J, Laing I, Leppäkoski E, MacDonald E, Minchin D, Nauke M, Olenin S, Utting S, Voight M, Wallentinus I (2000b) Fluctuations of zooplankton taxa in ballast water during short-term and long-term ocean-going voyages. Int Rev Hydrobiol 85(5–6):597–608
Gollasch S, MacDonald E, Belson S, Botnen H, Christensen JT, Hamer JP, Houvenaghel G, Jelmert A, Lucas I, Masson D, McCollin T, Olenin S, Persson A, Wallentinus I, Wetsteyn LPMJ, Wittling T (2002) Life in ballast tanks. In: Leppäkoski E, Gollasch S, Olenin S (eds) Invasive aquatic species of Europe distribution, impact and management. Kluwer Academic Publishers, Dordrecht, pp 217–231
Gollasch S, Haydar D, Minchin D, Wolff WJ, Reise K (2009) Introduced aquatic species of the North Sea coasts and adjacent brackish waters. In: Rilov G, Crooks J (eds) Biological invasions in marine ecosystems: ecological, management and geographic perspectives, vol 204, Ecological studies. Springer, Heidelberg, pp 507–525
Gómez F (2008) Phytoplankton invasions: comments on the validity of categorising the non-indigenous dinoflagellates and diatoms in European seas. Mar Pollut Bull 56(4):620–628
Gomoiu M-T, Alexandrov B, Shadrin N, Zaitsev Y (2002) The Black Sea – a recipient, donor and transit area for alien species. In: Leppäkoski E, Gollasch S, Olenin S (eds) Invasive aquatic species of Europe, distribution, impacts and management. Kluwer, Dordrecht, pp 341–350
Goulletquer P, Bachelet G, Sauriau PG, Noel P (2002) Open Atlantic coast of Europe – a century of introduced species into French waters. In: Leppäkoski E, Gollasch S, Olenin S (eds) Invasive aquatic species of Europe. Distribution, impacts and management. Kluwer Academic Publishers, Dordrecht, pp 276–290
Grigorovich IA, Therriault TW, MacIsaac HJ (2003) History of aquatic invertebrate invasions in the Caspian Sea. Biol Invasion 5(1–2):103–115
Hallegraeff GM (1993) Human activities and the apparent global increase of harmful algal blooms. In: Sixth international conference on toxic marine phytoplankton 92
Hallegraeff GM (1995) Transport of toxic dinoflagellates via ship's ballast water: an interim review. Bd. O:15, ICES Annual Science Conference, Aalborg
Hallegraeff GM (1998) Transport of toxic dinoflagellates via ships' ballast water: bioeconomic risk assessment and efficacy of possible ballast water management strategies. Mar Ecol Progr Ser 168:297–309
Hallegraeff GM, Bolch CJ (1992) Transport of diatom and dinoflagellate resting spores in ships' ballast water: implications for plankton biogeography and aquaculture. J Plankton Res 14(8):1067–1084
Hamer JP, McCollin TA, Lucas IAN (2000) Dinofagellate cysts in ballast tank sediments: between tank variability. Mar Pollut Bull 40(9):731–733
Hamer JP, Lucas IAN, McCollin TA (2001) Harmful dinoflagellate resting cysts in ships' ballast tank sediments; potential for introduction into English and Welsh waters. Phycologia 40:246–255
Hay CH (1990) The dispersal of sporophytes of *Undaria pinnatifida* by coastal shipping in New Zealand, and implications for further dispersal of Undaria in France. Br Phycol J 25:301–313
Hayes KR (1998) Ecological risk assessment for ballast water introductions: a suggested approach. ICES J Mar Sci 55:201–212
Hayes KR, Sliwa C (2003) Identifying potential marine pests—a deductive approach applied to Australia. Mar Pollut Bull 46:91–98
Hebert PDN, Muncaster BW, Mackie GL (1989) Ecological and genetic studies on *Dreissena polymorpha* (Pallas): a new mollusc in the Great Lakes. Can J Fish Aquat Sci 46:1587–1591
Hewitt CL, Campbell ML (2010) The relative contribution of vectors to the introduction and translocation of invasive marine species. Commissioned by The Department of Agriculture, Fisheries and Forestry (DAFF), Canberra

Hewitt CL, Campbell ML, Thresher RE, Martin RB, Boyd S, Cohen BF, Currie DR, Gomon MF, Keough MJ, Lewis JA, Lockett MM, Mays N, McArthur MA, O'Hara TD, Poore GCB, Ross DJ, Storey MJ, Watson JE, Wilson RS (2004) Introduced and cryptogenic species in Port Phillip Bay, Victoria, Australia. Mar Biol 144:183–202

Hewitt CL, Campbell ML, Schaffelke B (2007) Introductions of marine macroalgae – accidental transfer pathways and mechanisms. Bot Mar 50:326–337

Hewitt C, Gollasch S, Minchin D (2009) The vessel as a vector – biofouling, ballast water and sediments. In: Rilov G, Crooks J (eds) Biological invasions in marine ecosystems: ecological, management and geographic perspectives, vol 204, Ecological studies. Springer, Heidelberg, pp 117–129

Hopkins CCE (2002) Introduced marine organisms in Norwegian waters, including Svalbard. In: Leppäkoski E, Gollasch S, Olenin S (eds) Invasive aquatic species of Europe, distribution, impacts and management. Kluwer, Dordrecht, pp 116–119

ICES (2005) International Council for the Exploration of the Sea (ICES) Code of practice on the introduction and transfers of marine organisms. Copenhagen

IMO (2003) Comments on draft Regulation E-2. Concentrations of organisms delivered in ships' ballast water in the absence of any treatment: establishing a baseline for consideration of treatment efficacy. Submitted by the International Council for the Exploration of the Sea (ICES) to the Marine Environment Protection Committee as document MEPC 49/2/21

IMO (2004) International convention on the control and management of ship's ballast water and sediments. International Maritime Organization, London. www.imo.org

IMO (2007) Guidelines for risk assessment under regulation A-4 of the BWM convention (G7). IMO, Marine Environment Protection Committee, Resolution MEPC.162(56), 13 July 2007. International Maritime Organization, London

Ivanov VP, Kamakin AM, Ushivtzev VB, Shiganova T, Zhukova O, Aladin N, Wilson SI, Harbison GR, Dumont HJ (2000) Invasion of the Caspian Sea by the comb-jellyfish *Mnemiopsis leidyi* (Ctenophora). Biol Invasion 2(3):255–258

Javidpour J, Sommer U, Shiganova T (2006) First record of *Mnemiopsis leidyi* A. Agassiz 1865 in the Baltic Sea. Aquat Invasion 1(4):299–302

Jensen KR, Knudsen J (2005) A summary of alien marine benthic invertebrates in Danish waters. Oceanol Hydrobiol Stud 34(S1):137–162

Johnson LE, Padilla DK (1996) Geographic spread of exotic species: ecological lessons and opportunities from the invasion of the zebra mussel *Dreissena polymorpha*. Biol Conserv 78:23–33

Katsanevakis S, Gatto F, Zenetos A, Cardoso AC (2013) How many marine aliens in Europe? Manag Biol Invasion 4(1):37–42

Kerckhof F, Haelters J, Gollasch S (2007) Alien species in the marine and brackish ecosystem: the situation in Belgian waters. Aquat Invasion 2(3):243–257

Laing I, Gollasch S (2002) *Coscinodiscus wailesii* – a nuisance diatom in European waters. In: Leppäkoski E, Gollasch S, Olenin S (eds) Invasive aquatic species of Europe: distribution, impacts and management. Kluwer Academic Publishers, Dordrecht, pp 53–55

Leppäkoski E (1994) Non-indigenous species in the Baltic Sea. In: Boudouresque CF, Briand F, Nolan C (eds) Introduced species in European Coastal Waters. Report of an international workshop. Bd. 8, European Commission, Luxembourg, pp 67–75

Leppäkoski E, Olenin S (2000) Non-native species and rates of spread: lessons from the brackish Baltic Sea. Biol Invasion 2:151–163

Leppäkoski E, Gollasch S, Gruszka P, Ojaveer H, Olenin S, Panov V (2002a) The Baltic – a sea of invaders. Can J Fish Aquat Sci 59:1175–1188

Leppäkoski E, Gollasch S, Olenin S (eds) (2002b) Invasive aquatic species of Europe distribution, impact and management. Kluwer Academic Publishers, Dordrecht

Leppäkoski E, Shiganova T, Alexandrov B (2009) European enclosed and semi-enclosed seas. In: Rilov G, Crooks J (eds) Biological invasions in marine ecosystems: ecological, management and geographic perspectives, vol 204, Ecological studies. Springer, Heidelberg, pp 529–547

Locke A, Reid DM, Sprules WG, Carlton JT, van Leeuwen HC (1991) Effectiveness of mid-ocean exchange in controlling freshwater and coastal zooplankton in ballast water. Can Tech Rep Fish Aquat Sci 1822:1–93

Macdonald EM, Davidson RD (1998) Ballast water project. Fisheries Research Services report 3/97. FRS Marine Laboratory, Aberdeen

Marcus GJ (1980) The conquest of the North Atlantic. The Boydell Press, Woodbridge

McCarthy SA, Khambaty FM (1994) International dissemination of epidemic *Vibrio cholera* by cargo ship ballast and other non-potable waters. Appl Environ Microbiol 60(7):2597–2601

McCollin T, Shanks AM, Dunn J (2008) Changes in zooplankton abundance and diversity after ballast water exchange in regional seas. Mar Pollut Bull 56:834–844

Medcof JC (1975) Living marine animals in a ships' ballast water. Proc Natl Shellfish Assoc 65:54–55

Minchin D (2007a) A checklist of alien and cryptogenic aquatic species in Ireland. Aquat Invasion 2(4):341–366

Minchin D (2007b) Rapid coastal survey for targeted alien species associated with floating pontoons in Ireland. Aquat Invasion 2(1):63–70

Minchin D (2007c) Aquaculture and transport in a changing environment: overlap and links in the spread of alien biota. Mar Pollut Bull 55:302–313

Minchin D, Eno C (2002) Exotics of coastal and inland waters of Ireland and Britain. In: Leppäkoski E, Gollasch S, Olenin S (eds) Invasive aquatic species of Europe: distribution, impact and management. Kluwer, Dordrecht, pp 267–275

Minchin D, Gollasch S, Wallentinus I (2005) Vector pathways and the spread of exotic species in the sea. ICES cooperative research report 271

Minchin D, Floerl O, Savini D, Occhipinti-Ambrogi A (2006) Small craft and the spread of exotic species. In: Davenport J, Davenport JL (eds) The ecology of transportation: managing mobility for the environment. Springer, Berlin, pp 77–97

Minchin D, Gollasch S, Cohen AN, Hewitt C, Olenin S (2009) Characterizing vectors of marine invasions. In: Rilov G, Crooks J (eds) Biological invasions in marine ecosystems: ecological, management and geographic perspectives, vol 204, Ecological studies. Springer, Heidelberg, pp 109–115

Motes M, DePaola A, Zywno-Van GS, McPhearson M (1994) Occurrence of toxigenic *Vibrio cholera* O1 in oysters in Mobile Bay, Alabama: an ecological investigation. J Food Protect 57(11):975–980

Murphy KR, Ritz D, Hewitt CL (2002) Heterogeneous zooplankton distribution in a ship's ballast tanks. J Plankton Res 24(7):729–734

Occhipinti-Ambrogi A (2002) Current status of aquatic introductions in Italy. In: Leppäkoski E, Gollasch S, Olenin S (eds) Invasive aquatic species of Europe, distribution, impacts and management. Kluwer, Dordrecht, pp 311–324

Ockelmann WK (1958) The zoology of East Greenland. Marine lamellibranchiata. Medd Grønland 122(4):1–256

Olenin S (2005) Invasive aquatic species in the Baltic States. Monograph. University of Klaipeda, Coastal Research and Planning Institute

Olenin S, Leppäkoski E (1999) Non-native animals in the Baltic Sea: alteration of benthic habitats in coastal inlets and lagoons. Hydrobiologia 393:233–243

Olenin S, Gollasch S, Jonushas S, Rimkute I (2000) En-route investigations of plankton in ballast water on a ships' voyage from the Baltic Sea to the open Atlantic coast of Europe. Int Rev Hydrobiol 85:577–596

Olenin S, Minchin D, Daunys D (2007) Assessment of biopollution in aquatic ecosystems. Mar Pollut Bull 55(7–9):379–394

Olenin S, Alemany FA, Cardoso C, Gollasch S, Goulletquer P, Lehtiniemi M, McCollin T, Minchin D, Miossec L, Occhipinti Ambrogi A, Ojaveer H, Jensen KR, Stankiewicz M, Wallentinus I, Aleksandrov B (2010) Marine strategy framework directive – Task Group 2 report. Non-indigenous species. Luxembourg: Office for Official Publications of the European Communities

Olenina I, Wasmund N, Hajdu S, Jurgensone I, Gromisz S, Kownacka J, Toming K, Vaiciūtė OS (2010) Assessing impacts of invasive phytoplankton: the Baltic Sea case. Mar Pollut Bull 60:1691–1700

Oliverio M, Gerosa G, Cocco M (1992) First record of *Pinctada radiata* (Bivalvia:Pteriidae) epibiont on the loggerhead sea turtle *Caretta caretta* (Chelonia:Cheloniidae). Boll Malacologico 28(5–12):149–152

O'Mahony JHT (1993) Phytoplankton species associated with imports of the Pacific oyster *Crassostrea gigas* from France to Ireland. ICES CM 1993/F:26. 8

Ostenfeld CH (1908) On the immigration of Biddulphia sinensis Grev. and its occurrence in the North Sea during 1903–1907. Medd Komm Havunders Ser Plankton 1(6):1–46

Ozturk B (2002) The Marmara Sea, a link between the Mediterranean and the Black Sea. In: Leppäkoski E, Gollasch S, Olenin S (eds) Invasive aquatic species of Europe, distribution, impacts and management. Kluwer, Dordrecht, pp 337–340

Pancucci-Papadopoulou MA, Zenetos A, Corsini-Foka M, Politou CY (2005) Update of marine aliens in Hellenic waters. Medit Mar Sci 6:147–158

Petersen GH (1978) Life cycles and population dynamics of marine benthic bivalves from the Disko Bugt area of West Greenland. Ophelia 17:95–120

Petersen GH (1999) Five Recent *Mya* species, including three new species and their fossil connections. Polar Biol 22:322–328

Petersen KS, Rasmussen KL, Heinemeier J, Rud N (1992) Clams before Columbus? Nature 359:679

Pfaller JB, Frick MG, Reich KJ, Williams KL, Bjorndal KA (2008) Carapace epibionts of loggerhead turtles (*Caretta caretta*) nesting at Canaveral National Seashore, Florida. J Nat Hist 42(13–14):1095–1102

Pimentel D, Zuniga R, Morrison D (2005) Update on the environmental and economic costs associated with alien-invasive species in the United States. Ecol Econ 52:273–288

Reid PC, Valdés L (2011) ICES status report on climate change in the North Atlantic. ICES cooperative research report no. 310

Reise K, Gollasch S, Wolff WJ (1999) Introduced marine species of the North Sea coasts. Helgol Meeresunters 52:219–234

Reise K, Dankers N, Essink K (2005) Introduced species. In: Essink K, Dettmann C, Farke H, Laursen K, Lüerßen G, Marencic H, Wiersing W (eds) Wadden Sea water quality status report 2004. Wadden Sea ecosystem no. 19. Common Wadden Sea Secretariat, Wilhelmshaven, pp 155–161

Reusch TBH, Bolte S, Sparwek M, Moss AG, Javidbour J (2010) Microsatellites reveal origin and genetic diversity of Eurasian invasions by one of the world's most notorious marine invader, *Mnemiopsis leidyi* (Ctenophora). Mol Ecol 19:2690–2699

Ricciardi A, MacIsaac HJ (2000) Recent mass invasion of the American Great Lakes by Ponto-Caspian species. Trends Ecol Evol 15(2):62–65

Rossa DJ, Johnsona CR, Hewitt CL (2003) Variability in the impact of an introduced predator (*Asterias amurensis*: Asteroidea) on soft-sediment assemblages. J Exp Mar Biol Ecol 288:257–278

Ruiz GM, Fofonoff PW, Carlton JT, Wonham MJ, Hines AH (2000) Invasion of coastal marine communities in North America: apparent patterns, processes, and biases. Ann Rev Ecol Syst 31:481–531

Schütz L (1961) Distribution and dispersal of the borer *Teredo navalis* L. and its entering of the Kiel Canal near Kiel. Kieler Meeresforsch 17:228–236

Sellius G. (1733) Historia naturalis teredinis seu xylophagi marini tubulo conchoidis speciatim Belgici. Trajecti ad Rehenum, [xxxiv]+356

Shine C, Kettunen M, Genovesi P, Essl F, Gollasch S, Rabitsch W, Scalera R, Starfinger U, ten Brink P (2010) Assessment to support continued development of the EU Strategy to combat invasive alien species. Final report for the European Commission. Institute for European Environmental Policy (IEEP), Brussels

Streftaris N, Zenetos A, Papathanassiou E (2005) Globalisation in marine ecosystems: the story of non-indigenous marine species across European seas. Oceanogr Mar Biol Ann Rev 43:419–453

Van der Velde G, Rajagopal S, bij de Vaate A (2010) The zebra mussel in Europe. Backhuys Publishers, Leiden

Van Ginderdeuren K, Hostens K, Hoffman S, Vansteenbrugge L, Soenen K, De Blauwe H, Robbens J, Vincx M (2012) Distribution of the invasive ctenophore *Mnemiopsis leidyi* in the Belgian part of the North Sea. Aquat Invasion 7(2):163–169

Verlaque M, Ruitton S, Mineur F, Boudouresque C-F (2010) CIESM atlas of exotic macrophytes in the Mediterranean Sea. http://www.ciesm.org/atlas/appendix4.html visited 22 Oct 2010)

Vermeij GJ (1991) Anatomy of an invasion: the trans-Arctic interchange. Paleobiology 17(3):281–307

Vinogradov ME, Shushkina EA, Lukasheva TA (2005) Population dynamics of the ctenophores *Mnemiopsis leidyi* and *Beroe ovata* as a predator-prey system in the near-shore communities of the Black Sea. Oceanology 45(1):S161–S167

Weber W, Frieß CC (2003) Are southern species expanding into the North Sea and Baltic? Inf Fischwirtsch Fischereiforsch 50(4):163–165

Whitby GE, Lewis DP, Shafer M, Wiley CJ (1998) A microbiological, chemical and physical survey of ballast water on ships in the Great Lakes. In: Proceedings eighth international zebra mussel & aquatic nuisance species conference, Sacramento, pp 102–109

Williams RJ, Griffiths FB, Van der Wal EJ, Kelly J (1988) Cargo vessel ballast water as a vector for the transport of non-indigenous marine species. Estuar Coast Shelf Sci 26:409–420

Wolff W (2005) Non-indigenous marine and estuarine species in the Netherlands. Zool Med 79:1–116

Zaitsev Y, Ozturk B (eds) (2001) Exotic species in the Aegean, Marmara, Black Azov and Caspian seas Turkish Marine Research Foundation, Istanbul

Zenetos A, Gofas S, Russo G, Templado J (2004) CIESM atlas of exotic species in the Mediterranean, vol 3 Molluscs. CIESM Publishers, Monaco