Chapter 6
The Vessel as a Vector – Biofouling, Ballast Water and Sediments

Chad L. Hewitt, Stephan Gollasch, and Dan Minchin

6.1 Introduction

Human-mediated marine bioinvasions have altered the way we view the marine environment – virtually all regions of the global oceans have experienced the introduction of marine species (e.g., Carlton 1979; Coles et al. 1999; Cranfield et al. 1998; Cohen and Carlton 1998; Hewitt et al. 1999, 2004; Orensanz et al. 2002; Leppäkoski et al. 2002; Lewis et al. 2003; Castilla et al. 2005; Wolff 2005; Gollasch and Nehring 2006; Minchin 2006), placing marine and coastal resources under increased threat. Humans have almost certainly transported marine species since early attempts to voyage by sea. These ancient transport vectors were slow, and for the most part restricted to small spatial scales. The beginning of significant exploration and subsequent expansion by Europeans (post 1500 AD) has resulted in the transport of many thousands of species across all world oceans (Crosby 1986; diCastri 1989; Carlton 2001).

The transport of species by human vectors was recognized by early workers (Ostenfeld 1908; Elton 1958), but it is only in the last few decades that significant progress on identifying patterns and processes has been made (e.g., Carlton 1985, 1996, 2001; Ruiz et al. 2000; Hewitt et al. 2004; Castilla et al. 2005; Minchin 2006). Numerous transport vectors have been identified and described (Carlton 2001; Chap. 5, Minchin et al.); however the majority of species appear to have been associated with vessel movements, either as exploratory, military, commercial or recreational vessels (e.g., Carlton 1985, 2001; Cohen and Carlton 1998; Hewitt et al. 1999; Gollasch et al. 2002, Minchin and Gollasch 2003).

The ship as a transport vector is comprised of several sub-vectors. These include (1) the hull and other 'niche' areas, such as the propeller, rudder, on exposed surfaces of water piping, seachests, and thruster tunnels, where accumulations of growths of organisms develop (typically known as hull fouling), (2) the boring of organisms into the structure of the vessel (primarily limited to wooden hulled vessels), and (3) the uptake of organisms in association with wet or dry ballast (Carlton 1985, 1996; Ruiz et al. 2000). Several of these ship sub-vectors are no longer active. Hull boring for example, virtually ceased to exist with the use of steel

G. Rilov, J.A. Crooks (eds.) *Biological Invasions in Marine Ecosystems.*
Ecological Studies 204,

as the primary ship-building material in merchant and naval vessels. However, many pleasure boats and fishing craft are still constructed of wood (Nagabhushanam and Sarojini 1997). Similarly, dry-ballast made up of sand, gravel and rock taken from littoral environments was replaced with water as ballast beginning in the late 1800s and had become phased out by 1950.

None of these sub-vectors is species-specific, and each is likely to transport entire assemblages of species. Each may also facilitate the transport of a differing suite of species with different physiological and ecological characteristics (see Table 6.1). Biofouling primarily transports species that have attached sedentary or sessile, benthic habits, or species associated with these communities (e.g., living in, between or on other organisms) (Minchin and Gollasch 2003). In contrast, ballast water transports species associated with the plankton either as holo-plankton (species that have their whole life-cycle in the water column), mero-plankton (species with a portion of their life-cycle in the water column), or tycho-plankton (species accidentally swept into the water column), and often include pelagic species. It is difficult to establish a firm link between an already established introduced species and the vector (or sub-vector) by which it arrived in the new location (Minchin 2007). Nevertheless, attempts at assigning linkages to sub-vectors based on life history modes, timing of invasions, and association between location of incursion and sub-vectors have been deduced by reasoned argument (e.g., Hewitt et al. 1999, 2004, in press; Fofonoff et al. 2003; Ruiz et al. 2000).

Table 6.1 Some comparative aspects of ballast water and associated sediments, and hull fouling

Item	Ballast water and sediments	Hull fouling
Amount ship ballast volume/hull surface area	ca 3–10 km^3 per year (Gollasch 2002b)	In 1982: 75,000 merchant vessels have 110 million m^2 (Olesen 1982)
Management physical/ chemical	Ballast purges/ exchange at sea	Antifouling agents/paints
		In water hull cleaning
	Flocculation of sediments	Dry docking/extended periods out of water
	Salinity changes	
	Filtration	Fresh/salt water immersion
	Irradiation	
	Centrifuge	
	Evolving chemical and physical treatments	
Relief	Baffles, platforms, supports, ledges and tanks walls	Smooth surfaces, some projections and cavities (sea chests, thruster tunnels)

(continued)

Table 6.1 (continued)

Item	Ballast water and sediments	Hull fouling
Temperature	Few sudden changes except during mid-ocean or port ballast exchanges	Fluctuations of temperature rapid and directly matching external environment during voyage
Salinity	Potential pulses of salinity associated with ballast exchanges	Salinity highly variable according to shipping routes and ports. Some species such as oysters can seal their shells for some days and avoid being exposed to changed salinity
Turbidity	Highly variable	Highly variable
	Periods of turbidity depending on ballast water uptake, port conditions (e.g., water depth, tug and dredge operations, tidal range) and sea state	Periods of turbidity depending on port conditions (e.g., water depth, tug and dredge operations, tidal range, estuarine port) and sea state
Sedimentation	Accumulation on tank floors and on ledges	Very little except within highly fouled communities or hull pockets such as sea-chests
Turbulence	Variable, according tank position, often little flow	Extreme to moderate, according to weather conditions and ships speed
Light	Little or no light	Variable light, bright to shaded
Gas exchange	May be limited locally	Continuous
Uptake of organisms	Only at specific times of ballasting	At any time, most likely when in port – associated with port residency time
Biota	Mainly free living: mero-, holo- and tycho-planktonic organisms (Gollasch 2002a)	Mainly benthic Sessile, sedentary and some mobile species present (Gollasch 2002b)
Taxonomic range (refer to table of described taxa)	Viruses, micro-organisms, plants (largely planktonic and resting stages) and animals (Porifera to Teleosts) (Gollasch 2002a)	Viruses, micro-organisms, plants (all stages of single and multi-cellular plants) and animals (Porifera to Teleosts) (Gollasch 2002b)
Communities	Generally simple except in sediments	Development of complex communities possible
Life history characteristic	Predation, scavenging, deposit feeding, dormant/resting stages	Predation, herbivory, scavenging, filter/suspension feeding
Interactions with ambient communities	Restricted	Constant

(continued)

Table 6.1 (continued)

Item	Ballast water and sediments	Hull fouling
	Only following ballast water release	May be subject to predation and grazing, exposed to infestations, pollutants particularly when anchored or berthed
Excreta, exuvae, decaying remains	Retained	Generally lost, except barnacles and serpulids/spirorbids, some molluscs
Availability of 'food'	Restricted to organisms in ballast tank – live food declining according to voyage duration (detritus increasing during voyage), no or low levels of photosynthesis; potential to feed at all times	Food in ambient water variable (oceanic –low, coastal/estuarine – high), growth of 'fouling' community continuous, high to low levels of photosynthesis according to location on hull; feeding except at times during voyages or when physiologically challenged
Sexual reproduction	Micro-organisms and some Crustacea (copepods)	Most invertebrate phyla and algae
Asexual reproduction	Bacteria, protozoa, and diatoms (production of resting stages)	Some Anthozoa and planarians
Spawning/Sporulation	Not known	Many invertebrate and algal taxa – direct evidence for some molluscs, serpulids and bryozoa. May leave behind developing embryos in ports
Larval development	Larvae known in ballast tanks	Only brooded larvae

In this chapter we evaluate biofouling of the exposed surfaces and ballast water as sub-vectors of vessels by examining similarities and differences. We do not intend to undertake a comprehensive evaluation, but provide an indication of sub-vector activity and association with species together with the potential implications for management.

6.2 Biofouling

Much research has been focused on understanding the mechanisms of attachment and subsequent impacts on vessel performance of biological growth on the immersed hull surfaces of a vessel (e.g., Gollasch 2002a). It is now recognized that the drag generated by low levels of biofouling impair a vessel's efficiency, when measured as tonnage of fuel required to maintain speed. This has led to significant efforts to improve cost-effective anti-fouling methods that reduce biofouling growths during the operational periods between dry-dockings.

Early anti-fouling methods included tar mixed with horsehair, copper cladding affixed to the vessel hull, flat-headed nails to cover a wooden hull, the use of steel, paints with biologically active compounds using copper and later tri-butyl tin (TBT). Anti-fouling paints have proven extremely effective, particularly those based on organotins (see Minchin 2006). The advent and subsequent proliferation of TBT paints from the 1970s onwards, however, resulted in significant impacts to marine communities adjacent to ports, marinas and in busy shipping lanes. Impacts occur at very low concentrations, as these organotins also act as endocrine disrupters, causing sexual deformities in a variety of invertebrate species (see review by Fent, 1996). Concern over the impacts of TBT has resulted an internationally agreed-upon ban on the use of TBT under the International Convention on the Control of Harmful Anti-Fouling Systems on Ships of the International Maritime Organization (IMO), the United Nations body which deals with shipping (AFS 2001). This has involved the discontinuation of the application of organotin based anti-fouling paints since 2003. Port areas have generally shown declines of leached organotins since then, leading to improvements in water quality that may subsequently lead to port regions becoming more invasible (Nehring 2001). For example, it was assumed that the improved water quality has enabled a re-expansion of the zebra mussels in the port of Hamburg, Germany, in the River Elbe (Gollasch 2001).

Biofouling has typically been considered to be of historic significance (Carlton 2001) as many vessels will have been lost at sea during naval engagements and storms and will have spent long durations in port without the advantages of modern hull fouling controls. In contrast, today there are fast turn around times in ports and the use of efficient anti-fouling paints that reduce the opportunities for settlement. The increased speed of modern vessels en route will result in much of the attached biota becoming detached (see Minchin 2006). Yet even recently dry-docked and painted vessels can have significant biofouling. These can be observed in untreated areas where the ship is supported on blocks during dry dock and where paint cannot be applied, on slow service vessels such as barges where high quality paints are not used, and, where such vessels or structures are seldom dry-docked (e.g., Coutts 1999; Gollasch 2002a).

A calculation of the total wetted surface area, the permanently submerged hull surface even when the vessel is only partly loaded, for the active fleet in 1982 of 75,000 merchant ships was ~110 million m^2 (Olesen 1982). This will certainly be much greater today. In Germany alone, Bettelhäuser and Ulrich (1993) calculated that 290 vessels had a submerged hull surface area of 2.9 million m^2. These areas are largely anti-fouled, however Coutts (1999) estimated that up to 20% of the total wetted surface area of some vessels are untreated dry docking support strips. Similarly, Lenz et al. (2000) found that approximately 14% of the vessel's wetted surface area was fouled, despite the general usage of TBT as an antifoulant used at that time. The findings of Lenz et al. (2000) may have been affected by the age of antifouling paint on the vessels investigated. Nevertheless, it is highly probable that biofouling today, on account of implementation of the AFS Convention to phase out all organotins in ship antifoulants by 2008, is greater.

The situation for non-merchant vessels is likely to be much less positive. Whereas merchant vessels have a strong economic incentive to maintain their vessel hulls free of fouling, slow moving vessels such as oil platforms, oceanic barges, tugs, dredges, fishing vessels, and recreational craft, do not. In addition, many slow-moving vessels also have long port tenancies and are idle for significant periods of time, during which extensive fouling communities can accumulate. For example, recreational vessels offered for sale can remain idle and in-water for long durations. Once sold, these vessels are commonly transported to new locations by water or over-land without any attempt at cleaning.

Slow moving vessels have been implicated in a number of biofouling associated introductions. One fishing vessel, the *Yefim Gorbenko* was examined by researchers in New Zealand following its operation for several months in the New Zealand Exclusive Economic Zone (EEZ). The extent of biofouling on the vessel caused operational difficulties and was brought to dry-dock where it was found to have an accumulation of over 96 tonnes (wet weight) of biological material (Hay and Dodgshun 1997).

Leisure craft have not, until recently, been considered as significant contributors to the transport of species, however it would appear these are important in spreading some marine algae and invertebrates (Minchin et al. 2006; Hewitt et al., 2007). The incursion and successful eradication of the black striped mussel, *Mytilopsis sallei*, in Darwin, Northern Territory, Australia in 1999 was almost certainly associated with a recreational cruising yacht (Bax 1999; Willan et al. 2000). Similarly, the introduction of several ascidian species, such as a form of *Didemnum* (Fig. 6.1), and several tubeworms (Fig. 6.2), continue to spread worldwide (Zibrowius 1994; Çinar 2006; Valentine et al. 2007) and are thought to be spread by recreational craft (Minchin 2006).

Currently there are few easy detection or treatment methods available to biosecurity managers. High densities of biofouling can be readily observed from the surface, or by using in-water diver or remote camera inspections. Such monitoring requires the establishment of additional inspection regimes at ports of entry (Hewitt et al. 2004). In addition, once a vessel with significant fouling has been detected, options for management are limited. The vessel can be fined and/or sent on with directions to clean the hull prior to future re-entry; or directed to a dry-docking or hoisting facility should this be readily available. In case organisms are removed from the hull and other areas in dry-dock, measures should be taken to prevent their disposal into the water unless appropriately treated. Research efforts are currently underway to develop in-water cleaning methods that safely remove organisms from a vessel and vacuum or filter any dislodged material from the water column (B. Gould, Biosecurity New Zealand, personal communication).

Fig. 6.1 A didemnid tunicate fouling a hull of a recreational vessel in Ireland, 2005 (credit: D. Minchin)

Fig. 6.2 *Ficopomatus enigmatica*, an Indo-Pacific tubeworm, on a recreational vessel hull in Ireland, 2005 (credit: D. Minchin)

6.3 Ballast Water and Sediments

Ships' ballast water is taken on board and held within specialized tanks to maintain the trim and stability of ships, specifically when unladen. These tanks can be cargo holds temporarily used for holding ballast water; however the majority are purpose-built, complex structures designed to provide structural support for the ship. The tanks are typically distributed in different regions of a ship and are subjected to varying environmental conditions. For example, the forepeak tank, situated at the ship's bow, provides the most agitated conditions in poor weather, whereas those farther aft are not subjected to the same degree of disturbance. Almost all tanks used for holding ballast water accumulate sediments, the amount varying according to the ports vessels visit. Estuarine ports often have highly turbid water and any disturbance of the sea-bed can lead to plumes of sediment that may inadvertently be taken aboard (Fig. 6.3). These plumes may also contain biota, some of which may be in a resting state and could remain in this way, even in apparently unsuitable conditions for some months. Accumulations of sediments can become sufficient to support an infaunal community (e.g., Gollasch 2002a). These sediments are most usually silts and muds and carry a wide range of microbiota to fine web-like growths of slime-moulds (Hülsmann and Galil 2002) and more advanced metazoa (e.g., Gollasch 2002a; Gollasch et al. 2002).

Ostenfeld (1908) suggested that the use of water as ballast could form a transport mechanism for species transfers. Soon after, further evidence of ballast-water introductions took place with the first European appearance of the Chinese-mitten crab to the Aller River in Germany in ~1912 (Marquard 1926; Peters 1933). This concern has subsequently been confirmed with the identification of hundreds of species in the ballast tank environment (e.g., Carlton 1985; Carlton and Geller 1993; Gollasch et al. 2002). The uptake of water as ballast typically occurs in a port environment while the ship is at berth. As a consequence, any organism present in the water column either as a permanent member (holo-plankton and demersal species), or temporary member (mero- and tycho-plankton) will be entrained during ballast water uptake and subsequently transported with the vessel (e.g., Carlton and Geller 1993). Organisms from virtually all the major taxonomic and trophic groups have been detected in ballast water or in its accumulated sediments (Williams et al. 1988; Carlton and Geller 1993; Gollasch et al. 2002).

The dark conditions within tanks are unfavourable for photosynthesising plant stages and for those species that are dependant on sight for feeding, their numbers decline rapidly soon after ballasting. Other organisms also decline over time. Rarely have any accounts of species increasing their abundance been noted, as in the case of an harpacticoid copepod increasing its numbers in ballast tanks during a voyage, most likely due to reproduction during the voyage (Gollasch et al. 2000). The remains of those organisms that expire may become consumed by scavengers or are broken down by bacteria and fungi. Recent studies have shown that the micro-organisms that occur in ballast water are an important component of the ballast tank community, some of which can cause human diseases (Drake et al. 2001).

Fig. 6.3 Sediment disturbance in port due to vessel movement (credit: S. Gollasch)

Ballast water as a transport vector has attained the awareness of both the public and policy makers throughout the world. As discussed in Chap. 19, Hewitt et al., significant efforts at international, regional and national levels have been focused on developing appropriate management options for ballast water mediated introductions. Similar to biofouling, the IMO developed a Convention on ballast water management (BWM 2005; Gollasch et al. 2007; Chap. 19, Hewitt et al.). Existing methods include the exchange of coastal ballast water for open oceanic water while in transit. This ballast water exchange (BWE) may act to reduce the likelihood of species transport in some instances, but these activities may not dislodge any sediments that have accumulated. In addition, the practice of BWE may be both impractical and unsafe in specific locations and sea states and incorrect procedures have led to serious events at sea. At best BWE can only reduce the numbers of biota transferred by this process and is more effective if the properties of the exchanged water are different, such as in the case of fresh or brackish water being exchanged for oceanic water (Gollasch et al. 2007). For this reason, BWE can only be considered as a part-effective and temporary measure. In the meantime, technologies using varying treatment methods are being developed (e.g., Taylor et al. 2002). Unfortunately, many of these treatments take a long time and are only possible to use during long voyages and are not possible to use over short distance routes.

6.4 Discussion

Evaluations of various world regions indicates that shipping has been considered to be responsible for the majority of marine bioinvasions (e.g. Carlton 1985, 1996, 2001; Cohen and Carlton 1998; Cranfield et al. 1998; Hewitt et al. 1999, 2004; Ruiz et al. 2000; Gollasch 2002a; Leppäkoski et al. 2002; Fofonoff et al. 2003). The levels of certainty associated with assigning a specific vector to an invasion vary, in part, because few invasions are witnessed and are detected at some point following their arrival. This leads to attempts to assign responsibility to a vector as a consequence of evaluating life history characteristics, timing of arrival in relation to active vectors, and proximity to active vectors according to current use. Indeed, it appears that numerous species have the opportunity to be transported by either as biofouling or in ballast water (Hewitt et al. 1999, 2004; Minchin 2006) (Fig. 6.4).

Ruiz et al. (2000) considered that this ability to be transported at multiple stages of a life cycle might contribute to the invasion success by increasing inoculation pressure. The frequency of transmission along specific routes may also enhance the likelihood of successful establishment because of an increased opportunity of arriving at an optimal period for growth and reproduction. When considering the large amount of water carried worldwide, and the routes that many individual vessels undertake, it is perhaps of little surprise that organisms are carried to new regions. In addition, the extensively fouled surfaces of ships allow for the development of

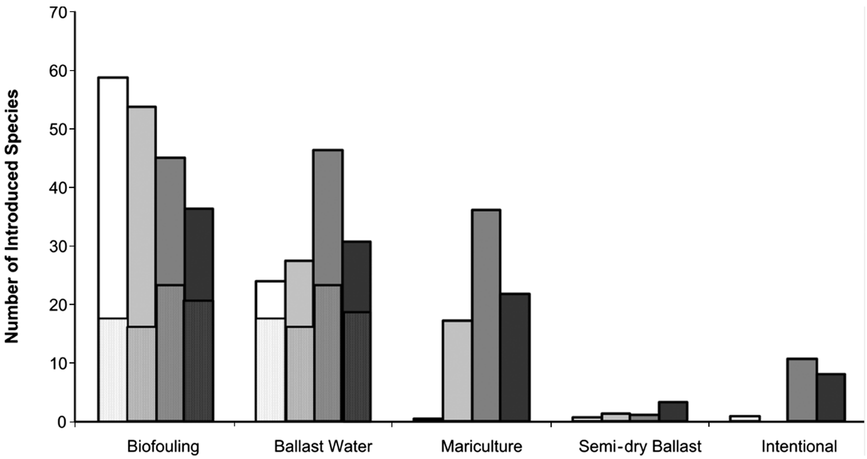

Fig. 6.4 An evaluation of historic marine bioinvasions according to five primary transport mechanisms: biofouling, ballast water, mariculture, semi-dry ballast and intentional: *white* – New Zealand (based on Cranfield et al. 1998); *light grey* – Port Phillip Bay (Hewitt et al. 1999, 2004); *dark grey* –North Sea (Jensen and Knudsen 2005; Wolff 2005; Gollasch and Nehring 2006; Minchin et al., in prep, Gollasch and Kerckhof, in prep); *black* – San Francisco Bay (Cohen and Carlton 1995); *stippled areas* represent species that can be both biofouling and ballast water

fouled species and all vessels also will have spread their compliment. While the great majority of routes for trade are now in general use, some new routes linking previously unconnected regions will undoubtedly be established as global trade increases. For example, a seasonal route is likely to evolve between the north Atlantic and north Pacific Oceans with the contraction of the Arctic ice-sheet as a consequence of global climate change.

It is of interest to managers whether biofouling or ballast water (and sediments) pose the greatest risk in distributing invasive species in the future (see Chap. 19, Hewitt et al. and Chap. 20, Campbell). With limited environmental management budgets and increasing pressures on the use of public funds, there is a need to target the most cost-effective and appropriate research and management activities that reduce the risks of costly invasions (Hewitt et al. 2004). In a recent analysis of incursions to Australia, New Zealand and the North Sea between 1995 and 2002, Australia had recorded 17 new incursions (Fig. 6.5A), New Zealand had recorded 18 incursions (Fig. 6.5B) and 20 new species were found in the North Sea (Fig. 6.5C). The Australian incursions could be divided into 13 biofouling alone (based on species' life history characteristics and locations of arrival), 2 to either biofouling or ballast water and 2 to others from non-ship vectors. In contrast, the New Zealand incursions included nine attributed to biofouling, three to ballast water, five to either biofouling or ballast water, and one to non-ship associated methods. Fifteen species reached the North Sea region with shipping (six with ballast water, six with biofouling and three in either biofouling or ballast water) and five with non-shipping vectors. In these studies it was assumed that all invasions were identified and that the appropriate vectors were correctly identified.

It is clear that both biofouling and ballast water are currently active and important vectors for the transport of marine species and will continue to spread species. Both vectors have special circumstances allowing for their transport according to the life-history stages and tolerances of biota. From a management perspective, these two sub-vectors associated with vessels require different regulatory frameworks and management responses, suggesting that further research into the relative risks of biofouling introductions vs ballast water introductions is needed to inform policy development better. Further, additional vector management options need to be developed to provide a suite of tools for appropriate management action. Examples include development of in-water hull cleaning devices for merchant and recreational vessels that will act in such a way that the removed biomass does not propagate and infect new regions; non-toxic antifouling paints to replace the current suite of organitin based paints; and ballast water treatment technologies to reduce invasion risk without increasing release of biologically active compounds in nearshore and coastal waters.

Additional work is needed on the transmission of parasites and diseases associated with biofouling species and in ballast water. These organisms are likely to create risks to aquaculture operations within and adjacent to ports and marinas. A number of commercially farmed molluscs or closely related species are found on the hulls of ships and capable of surviving long journeys (Minchin and Gollasch 2003). While these species are likely to have been transported and introduced to

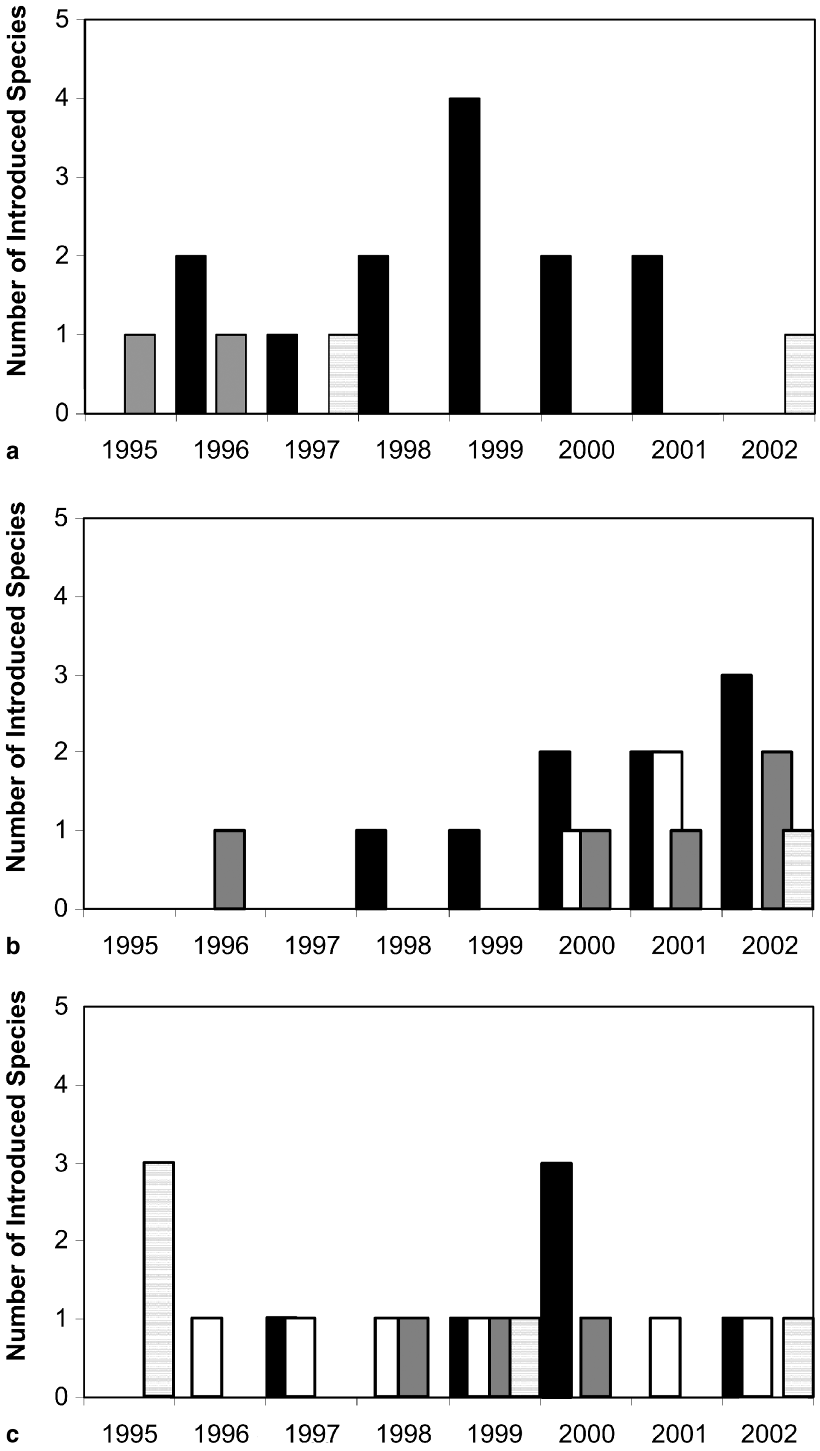

Fig. 6.5 An evaluation of recent Australian (**a**), New Zealand (**b**) and North Sea (**c**) incursions by sub-vector type based on life history characteristics, location of incursion, or observed vector associations: *black* – only hull fouling; *white* – only ballast water; *solid grey* – both hull fouling and ballast water; *stippled grey* – other non-shipping associated method

new regions, it is equally likely that parasites and pathogens were transported within these organisms. The further transport of these molluscs either through intentional stock transfers or with commercial or recreational vessel movements to new port regions may also lead to the further transfer of parasites and pathogens.

References

AFS (2001) International Convention on the Control of Harmful Anti-Fouling Systems on Ships. International Maritime Organization, London, United Kingdom; www.imo.org, accessed 30 January 2006

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

Bettelhäuser F, Ullrich P (1993) Die Suche nach dem sozial- und umweltverträglichen Schiff - Die ersten Schritte. Arbeitskreis andere nützliche Objekte der Bremer Vulkan Werft, 1–92

BWM (2005) International Convention on the Control and Management of Ship's Ballast Water and Sediments. International Maritime Organization, London, United Kingdom; www.imo.org, accessed 30 January 2006

Carlton JT (1979) History, biogeography and ecology of the introduced marine and estuarine invertebrates of the Pacific Coast of North America. PhD Dissertation. University of California, Davis, California, USA

Carlton JT (1985) Transoceanic and interoceanic dispersal of coastal marine organisms: the biology of ballast water. Ocean Mar Biol Ann Rev 23:313–371

Carlton JT (1996) Pattern, process, and prediction in marine invasion ecology. Biol Cons 78:97–106

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

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

Castilla JC, Uribe M, Bahamonde N, Clarke M, Desqueyroux-Faúndez R, Kong I, Moyano H, Rozbaczylo N, Santilices B, Valdovinos C, Zavala P (2005) Down under the southeastern Pacific: marine non-indigenous species in Chile. Biol Inv 7:213–232

Çinar ME (2006) Serpulid species (Polychaeta: Serpulidae) from the Levantine coast of Turkey (eastern Mediterranean), with special emphasis on alien species. Aquat Invas 4:223–240

Cohen AN, Carlton JT (1995) Biological study: non-indigenous aquatic species in a United States estuary: a case study of the biological invasions of the San Francisco bay and delta. US Fisheries and Wildlife and National Sea Grant College Program Report, NTIS Number PB96-166525, Springfield, Virginia, USA, 273 pp

Cohen AN, Carlton JT (1998) Accelerating invasion rate in a highly invaded estuary. Science 279:555–558

Coles SL, DeFelice RC, Eldredge LG, Carlton JT (1999) Historical and recent introductions of non-indigenous marine species into Pearl Harbor, Oahu, Hawaiian Islands. Mar Biol 135:147–158

Coutts ADM (1999) Hull fouling as a modern vector for marine biological invasions: investigation of merchant vessels visiting northern Tasmania. Masters Thesis, Australian Maritime College, Launceston, Tasmania, Australia

Cranfield HJ, Gordon DP, Willan RC, Marshall BA, Battershill CN, Francis MP, Nelson WA, Glasby CJ, Read GB (1998) Adventive marine species in New Zealand. NIWA Technical Report 34. National Institute of Water and Atmospheric Research, Wellington, New Zealand

Crosby AW (1986) Ecological imperialism: the biological expansion of Europe, 900–1900. Cambridge University Press, Cambridge

di Castri F (1989) History of biological invasions with specieal emphasis on the Old World. In: Drake JA, Mooney HA, di Castri F, Groves RH, Kruger FJ, Rejmánek M, Williamson M (eds) Biological invasions: a global perspective. SCOPE 37. Wiley, New York, pp 1–30

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

Elton CS (1958) The ecology of invasions by animals and plants. Methuen, London, United Kingdom

Fent K (1996) Ecotoxicology of organotin compounds. Crit Rev Toxicol 26:1–117

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

Gollasch S (2001) German National Report. In: Report of the ICES Working Group on Introductions and Transfers of Marine Organism (WGITMO). Barcelona Meeting, pp 38–43

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

Gollasch S (2002b) Ballast water management in the north-east Atlantic. In: Tjallingii F (ed) Report to aid decision making on ballast water in the Oslo-Paris Commission (OSPAR). Biological Diversity Committee. North Sea Directorate, the Netherlands, p 48

Gollasch S, David M, Dragsund E, Hewitt CL, Fukuyo Y (2007) Critical review of the IMO International Convention on the Management of Ships' Ballast Water and Sediments. Harmful Algae 6: 585–600

Gollasch S, Lenz J, Dammer M, Andres HG (2000) 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, 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, The Netherlands, pp 217–231

Gollasch S, Nehring S (2006) National checklist for aquatic alien species in Germany. Aquat Invas 1(4):245–269

Gollasch S, Kerckhof F (in prep) National checklist of introduced aquatic alien species for Belgium

Hay C, Dodgshun T (1997) Ecosystem transplant? The case of the Yefim Gorbenko. Seafood N Z 13–15

Hewitt CL, Campbell ML, Thresher RE, Martin RB (eds) (1999) The introduced species of Port Phillip Bay, Victoria. Centre for Research on Introduced Marine Pests Technical Report No. 20. CSIRO Marine Research, Hobart

Hewitt CL, Campbell ML, Thresher RE, Martin RB, Boyd S, Cohen BF, Currie DR, Gomon MF, Keogh 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

Hülsmann N, Galil BS (2002) Protists – a dominant component of the ballast – transported biota. In: Leppäkoski E, Gollasch S, Olenin S (eds) Invasive aquatic species of Europe: distribution, impact and management. Kluwer, Dordrecht, the Netherlands, pp 20–26

Jensen K, Knudsen J (2005) A summary of alien marine invertebrates in Danish waters. Oceanolog Hydrobiol Stud 34(Suppl 1):137–162

Lenz J, Andres H-G, Gollasch S, Dammer M (2000) Einschleppung fremder Organismen in Nord- und Ostsee: Untersuchungen zum ökologischen Gefahrenpotential durch den Schiffsverkehr. UBA Project Water: 102 04 250, Umweltbundesamt, Berlin, Texte 5

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

Lewis PN, Hewitt CL, Riddle M, McMinn A (2003) Marine introductions in the Southern Ocean: an unrecognised hazard to biodiversity. Mar Pollut Bull 46:213–223

Marquard O (1926) Die Chinesische Wollhandkrabbe, *Eriocheir sinensis* Milne- Edwards, ein neuer Bewohner deutscher Flüsse. Fischerei 24:417–433

Minchin D (2006) The transport and the spread of living aquatic species. In: Davenport J, Davenport JL (eds) The ecology of transportation: managing mobility for the environment. Springer, Berlin Heidelberg New York, pp 77–97

Minchin D (2007) Aquaculture and transport in a changing environment: overlap and links in the spread of alien biota. Mar Pollut Bull 55(7/9):302–313

Minchin D, Bishop J, Cook E (in prep) Alien and cryptogenic species in brackish and marine regions of Britain

Minchin D, Gollasch S (2003) Fouling and ships' hulls: how changing circumstances and spawning events may result in the spread of exotic species. Biofouling 19:111–122

Minchin D, Gollasch S, Wallentinus I (2005) Vector pathways and the spread of exotic species in the sea. ICES Coop Res Rep 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 Heidelberg New York, pp 99–118

Nagabhushanam R, Sarojini R (1997) An overview of Indian research efforts on marine woodboring and fouling organisms. In: Nagabhushanam R, Thompson M-F (eds) Fouling organisms of the Indian Ocean, biology and control technology. A.A. Balkema, Rotterdam, p 538

Nehring S (2001) After the TBT era: alternative antifouling paints and their ecological risks. Senckenbergiana Marit 31:341–351

Olesen G (1982) Antifouling paint – a source of pollution. Schiff Hafen 34(7):18–19

Oresanz JM, Schwindt E, Pastorino G, Bortolus A, Casas G, Darrigran G, Elías R, López Gappa JJ, Obenat S, Pascual M, Penchaszadeh P, Piriz ML, Scarabino F, Spivak ED, Vallarino EA (2002) No longer the pristine confines of the world ocean: a survey of exotic marine species in the southwestern Atlantic. Biol Inv 4:115–143

Ostenfeld CH (1908) On the immigration of Biddulphia sinensis Grev. and its occurrence in the North Sea during 1903–1907. Meddelelser Fra Kommissionen Fur Danmarks Fiskeri-og Havundersogelser. Serie Plankton 1, No 6

Peters N (1933) B. Lebenskundlicher Teil. In: Peters N, Panning, A (eds.) Die chinesische Wollhandkrabbe (Eriocheir sinensis H. MILNE-EDWARDS) in Deutschland. Akademische Verlagsgesellschaft mbH, Leipzig, pp 59–156

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

Taylor A, Rigby G, Gollasch S, Voigt M, Hallegraeff G, McCollin T, Jelmert A (2002) Preventive treatment and control techniques for ballast water. In: Leppäkoski E, Gollasch S, Olenin S (eds) Invasive aquatic species of Europe: distribution, impacts and management. Kluwer Academic Publishers, Dordrecht, The Netherlands, p 583

Valentine PC, Carman MR, Blackwood DS, Heffron EJ (2007) Ecological observations on the colonial ascidian *Didemnum* sp. in a New England tide pool habitat. J Exp Mar Biol Ecol 342:109–121

Willan RC, Russell BC, Murfet NB, Moore KL, McEnnulty FR, Horner SK, Hewitt CL, Dally GM,Campbell ML, Bourke ST (2000) Outbreak of *Mytilopsis sallei* (Recluz, 1849) (Bivalvia: Dreissenidae) in Australia. Molluscan Res 20(2):25–30

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. Est Coast Shelf Sci 26:409–420

Wolff WJ (2005) Non-indigenous marine and estuarine species in The Netherlands. Zool Meded 79-1:1–116

Zibrowius H (1994) Introduced invertebrates: examples of success and nuisance in the European Atlantic and Mediterranean. In: Boudouresque CF, Briand F, Nolan C (eds) Introduced species in European coastal waters. European Commission, Luxembourg, pp 44–49