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Assisted passage or passive drift: a comparison of alternative transport mechanisms for non-indigenous coastal species into the Southern Ocean

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Abstract: The introduction of invasive species may be the most profound modern threat to biological communities in high-latitude regions. In the Southern Ocean, the natural transport mechanism for shallow-water marine organisms provided by kelp rafts is being increasingly augmented by plastic debris and shipping activity. Plastic debris provide additional opportunities for dispersal of invasive organisms, but dispersal routes are passive, dependent on ocean currents, and already established. In contrast, ships create novel pathways, moving across currents and often visiting many locations over short periods of time. Transportation of hull-fouling communities by vessel traffic thus poses the most likely mechanism by which exotic species may be introduced to the Southern Ocean.

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Introduction

The impacts to native communities associated with invasive organisms are now recognized as one of the primary threats to global biodiversity (Carlton 2001, Lubchenco *et al*. 1991, Hewitt 2003). While the majority of studies examining invasions focus upon impacts in the more populated regions and in highly modified systems, the problem of exotic organisms extends to even the most remote regions of the globe (Hines & Ruiz 2000, Orensanz *et al*. 2002, Gaston *et al.* 2003, Frenot *et al.* 2005).

A recent review of introductions in the Antarctic and sub-Antarctic region reports that at least 207 alien species have been recorded from high latitude ecosystems, which represent some of the most remote environments in the world (Frenot *et al.* 2005). The potential for the establishment of non-indigenous organisms in these relatively undisturbed environments is likely to increase due to the interaction of global climate change and expanding human interests (Chown *et al*. 1998, Chown & Gaston 2000, Stachowics *et al.* 2002). International agreements, such as the Protocol on Environmental Protection to the Antarctic Treaty 1991 and the Convention on the Conservation of Antarctic Marine Living Resources 1980, have established very stringent standards of environmental stewardship for the Antarctic and the Southern Ocean, and prohibit many activities including the introduction of non-native species. However, vessel traffic and human visitation between the Southern Ocean and other regions still creates opportunities for unintended introductions (Whinam *et al.* 2004), and because other threatening or destructive activities are prohibited, these remain among the most profound modern threats to native biological communities.

Although invasions to high-latitude terrestrial ecosystems are now well described (Whinam *et al.* 2004, Frenot *et al.* 2005), the same is not true for marine systems. Recent studies have suggested some potential mechanisms for marine introductions to sub-Antarctic and Antarctic coastlines including with rafts of marine debris (Barnes 2002, Barnes & Fraser 2003) and on vessel hulls (Lewis *et al.* 2003, 2004, Whinam *et al.* 2004), and there have been several recently documented occurrences of invasive marine organisms in the New Zealand sub-Antarctic islands (Cranfield *et al*. 1998) and the Antarctic Peninsula (Clayton *et al*. 1997, Tavares & De Melo 2004). Together, these reports indicate that, despite the apparent isolation of these regions, marine introductions can occur and there is a need to examine further the biosecurity of the coastal marine ecosystems of the Southern Ocean.

Assessment of potential transport vectors for marine species in high latitudes can provide valuable information regarding the hazard of biotic interchange for the future and could enable managers to focus resources towards the mitigation of this hazard. Although Salmonid fish were previously deliberately introduced to sub-Antarctic ecosystems (Davaine & Beall 1982, 1992, Cooper *et al*. 1992) and have become established in anadromous populations that may impact marine communities, deliberate introductions are now prohibited by international

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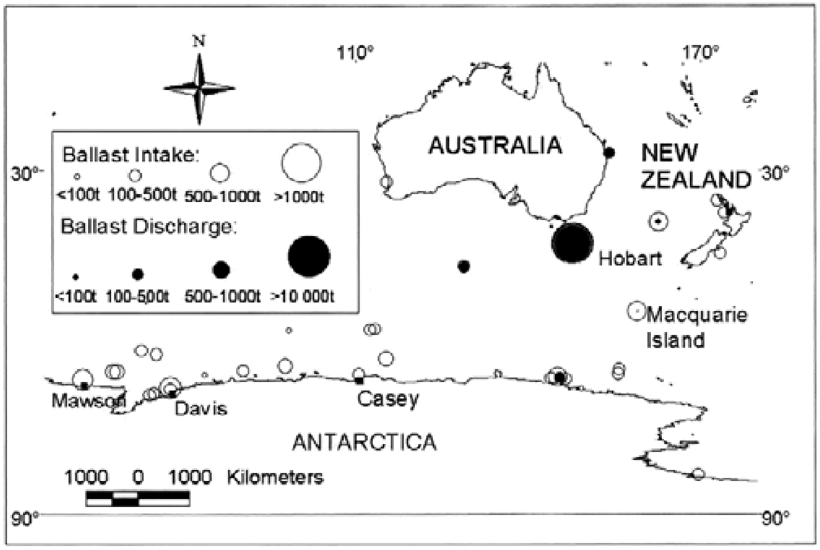

Fig. 1. Patterns of ballast usage in the Southern Ocean recorded from vessels using Hobart as the first port-of-call following a high-latitude voyage (1999–2001). Ballast is generally entrained in Antarctic waters and discharged in the Port of Hobart.

agreement in the Antarctic Treaty Area (south of latitude 60°S), and are generally prohibited by similar domestic legislation instigated by the individual countries responsible for sub-Antarctic islands. Deliberate introductions, therefore, do not play the same role in this region as in other areas, and modern introductions are almost exclusively unintentional consequences of other human activities.

Two primary, anthropogenic, marine transport pathways have been identified for the Southern Ocean; oceanic vessel traffic (Lewis *et al* 2003, 2004) and drifting plastic debris (Barnes 2002, Barnes & Fraser 2003). The transfer of species aboard barges and other objects intended to be deployed in the marine environment is also a possible pathway for marine introductions, but sound quarantine practices and targeted inspections may prevent biological transfer in association with these vectors (Whinam *et al.* 2004). Plastics and vessel traffic can not be controlled in a similar fashion and do not present the same opportunities for quarantine barriers. This paper examines the relative significance of these two pathways and shows that transport in association with oceanic vessels should be the vector of primary concern for the transport of invasive organisms to high-latitude coastlines.

Biological communities associated with transport vectors

Ships' hulls and flotsam provide the most important anthropogenic surfaces for biological settlement in oceanic habitats. While ships' hulls represent only 24% of the total area of anthropogenic structures available for settlement, they carry over 85% of the total biomass associated with these structures (Railkin 2004). In contrast, flotsam, which accounts for 70% of the total area of anthropogenic structures available for settlement, supports less than 6% of the total biomass (Railkin 2004). Therefore, although flotsam such as plastic debris presents a much greater surface area for colonization, the biomass carried by this vector is far lower than that carried by vessel hulls. These disparities are most likely a result of the largely oceanic nature of flotsam and consequently, the limited opportunity for settlement by coastal assemblages.

Vessels

Transport of marine organisms in association with ballast water has been the focus of much attention and is often considered the primary vessel-based form of non-indigenous species transport. Despite the large amount of ballast and associated biota transported around the globe each day, we have previously suggested that ballast may not play an important role in the transport of non-indigenous biota to high-latitude coastlines (Lewis *et al.* 2003). This suggestion was based on the assumption that the typical pattern of activity of vessels used to support national Antarctic research programs results in a unidirectional (northwards) transport of ballast because fuel and cargo are offloaded in the Antarctic and ballast water (and associated biological communities) is taken on board in the Southern Ocean and is subsequently discharged directly into temperate ports.

In order to test the assumption that ballast is not a major biological transport pathway to high latitude regions, the ballast records of 43 Southern Ocean voyages that used Hobart as the first port of call following high latitude voyages from 1999–2001 were examined. These records include all vessels that visited Hobart as the first port of call following a voyage to Antarctica or the sub-Antarctic islands over this period. Within this timeframe, a total of 14 486 t of ballast water was drawn from various locations in the Southern Ocean and a total of 13 470 t was discharged (Fig. 1). The home port, in this case Hobart, was the primary receiver of Southern Ocean ballast drawn from coastal regions in the Antarctic, and also from the sub-Antarctic

Table I. Non-indigenous species observed on the hulls of seven vessels operating in the Southern Ocean. Data from the vessels *Southern Supporter* and *Aurora Australis* is taken from Lewis *et al.* (2004). Species are marked to indicate if they are introduced to Australia (*), cryptogenic in Australia (†), or considered invasive elsewhere in the world (§).

Taxa	RV *Aurora Australis*	RV *Southern Supporter*	*Sir Hubert Wilkins*	*Astrolabe*	*Viarsa*	*Volga*	*Tiama*	Reference
PLANTAE								
Alga								
Enteromorpha compressa	Y	Y						† Lewis 1999
Enteromorpha intestinalis		Y	Y		Y	Y	Y	† Lewis 1999
Ulva rigida	Y		Y	Y				† Lewis 1999
ANIMALIA								
ANNELIDA								
Polychaeta								
Hydroides ezoensis		Y						†Thorpe *et al.* 1987, §AMBS 2002
Hydroides elegans						Y		*AMBS 2002, § Hove 1974, Bagaveeva *et al*. 1999
Sabella spallanzanii						Y		*Keough & Ross 1999, §Hewitt *et al.* 2002[a]
Demonax leucaspis						Y		§ SERC 2004[b]
ARTHROPODA								
Amphipoda								
Monocorophium acherusicum	Y	Y						*Poore & Storey 1999, §Hewitt *et al.* 2002[a]
Monocorophium insidiosum					Y	Y		*Poore & Storey 1999, §Hewitt *et al.* 2002[a]
Isopoda								
Cirripedia								
Balanus amphitrite		Y			Y	Y		*§Keough & Ross 1999
Elminius modestus	Y		Y	Y			Y	†Keough & Ross 1999, §Crisp 1958
Decapoda								
Halicarcinus innominatus	Y		Y					*Pollard & Hutchings 1990
CNIDARIA								
Bougainvillia muscus	Y							*§Watson 1999
Clytia hemispherica		Y				Y		*§Watson 1999
Obelia dichotoma	Y						Y	*Watson 1999, §Carlton 1979
Ectopleura crocea	Y					Y	Y	*Watson 1999, §Carlton 1979, §Hewitt *et al.* 2002[a]
ECTOPROCTA								
Bugula flabellata	Y				Y		Y	*Allen 1953, Pollard & Hutchings 1990, §Keough & Ross 1999
Bugula neritina		Y			Y	Y		*Bock 1982, § Hewitt *et al.* 2002
Bugula stolonifera						Y		*Keough & Ross 1999
Membranipora membranacea	Y							*Keough & Ross 1999, §Berman *et al.* 1992
Tricellaria occidentalis	Y				Y		Y	*Keough & Ross 1999, §Gordon & Mawatari 1992, Dyrynda *et al*. 2000
Watersiporia subtorquata	Y	Y	Y		Y	Y		*Keough & Ross 1999, § Carlton 1979, Gordon & Mawatari 1992
Schizoporella unicornis						Y		*§Hewitt *et al*. 2002
UROCHORDATA								
Ascidiella aspersa						Y		*Keough & Ross 1999, §Hewitt *et al.* 2002[a]
Styella plicata						Y		*Keough & Ross 1999, §Hewitt *et al.* 2002[a]
Ciona intestinalis	Y		Y	Y				*Kott 1985, §Hewitt *et al.* 2002[a]
Botrylloides leachi			Y					*Keough & Ross 1999, §Hewitt *et al.* 2002[a]
Botryllus schlosseri						Y		*Keough & Ross 1999, §Hewitt *et al.* 2002[a]
MOLLUSCA								
Mytilus galloprovincialis[1]	Y	Y	Y		Y	Y		†McDonald *et al.* 1991, §Hewitt *et al.* 2002[a], §Stewart Grant & Cherry 1985, §Hewitt *et al.* 2002[a]
Crassostrea gigas						Y		*§Hewitt *et al.* 2002[a]
Total species observed	35	18	17	8	18	56	12	
% Non-indigenous	40	50	47	38	44	30	50	

[1.] This species is known to occur in Iles Kerguelen

[a] HEWITT, C.L., MARTIN, R.B., SLIWA, C., MCENNULTY, F.R., MURPHY, N.E., JONES, T. & COOPER, S. *eds*. 2002. National Introduced Marine Pest Information System. Web publication http://crimp.marine.csiro.au/nimpis

[b]SERC – SMITHSONIAN ENVIRONMENTAL RESEARCH CENTER. 2004. Chesapeake Bay Nonindigenous Species List. http://invasions.si.edu/NIS/NIS_CBList.htm web publication accessed 04.08.04.

islands. On only one occasion was temperate ballast water discharged at high latitudes and the position recorded (184 t; 66°S, 145°E) but an additional 457 t was discharged at sea without location records. The mid-oceanic exchange of ballast is a precaution aimed at reducing the hazard of introducing species to coastal environments and is unlikely to introduce new species to coastal regions of the Southern Ocean (Hay & Tanis 1998, Endreson *et al*. 2004). Thirty visits were made to Macquarie Island during the same three year period, but no ballast was released in the inshore coastal waters here, or at any other sub-Antarctic island.

Although transport of invasive species with ballast water has been identified as a low hazard, Southern Ocean shipping still provides a mechanism for transfer of marine species in the form of the hull fouling communities, which thrive on ocean-going vessels. These assemblages, dominated by epibenthic species, may constitute the highest risk of introduction associated with vessels operating in the Southern Ocean. Although the rate of survival of fouling communities during oceanic transport has been little studied, it is recognised that fouling continues to play a major role in the transportation of non-indigenous species in the modern era (Rainer 1995, Hewitt *et al.* 1999, James & Hayden 2000, Hewitt & Campbell 2001).

Recruitment of fouling communities on Southern Ocean vessel hulls can result in the formation of diverse assemblages of organisms (Table I). These communities include known invasive species entrained in temperate ports that are able to survive voyages to sub-Antarctic waters (Lewis *et al.* 2004).

Legitimate activities in the Southern Ocean, such as the operational support of science, legal fishing and Antarctic tourism, are well regulated under domestic legislation implementing international agreements. In addition, the tourism industry has initiated additional environmental precautions to ensure its sustainability under the voluntary industry body, the International Association of Antarctica Tourism Operators (IAATO 2002). In contrast Illegal Unregulated and Unreported (IUU) fishing in the Southern Ocean operates outside the regulatory framework designed to promote sustainable fisheries activity and to avoid detrimental environmental impacts. The hulls of two IUU vessels, the *Viarsa* and the *Volga*, which were confiscated by the Australian Fisheries Management Authority after being apprehended while fishing illegally in Australia's Heard Island Exclusive Economic Zone were examined to determine the extent to which IUU vessels could contribute to the transport of biota (Table I – see Lewis *et al.* (2004) for methodology). The higher diversity of species recorded from the *Volga* may result from the long period of port residency since detainment.

In addition to organisms transported by large vessels associated with national science operations and IUU fishing, we have recorded the presence of biological assemblages on the hull of a small (15 m) yacht *Tiama*, chartered for research in the New Zealand Auckland Islands (Table I). Despite the well-maintained condition of this yacht, the fouling assemblage contained a total of 12 species including bryozoans, isopods, hydroids, barnacles and algae (Table I). Six species, or 50% of the total community, are known to be invasive in some portion of their range. Of particular concern were the species attached to flaking paint fragments around the rudder of the vessel. Organisms attached to flakes of paint which are subsequently broken off in near-shore sub-Antarctic environments are introduced directly into the biological communities of these regions, and do not require the reproductive event that is normally essential for the liberation of invasive organisms from sessile, hull-fouling communities. While some species are able to regenerate following mechanical removal from the hull due to sheer force or abrasion (Carlton *et al*. 1995), individuals associated with detached paint flakes may be liberated as entire and healthy specimens with an increased probability of survival and subsequent recruitment to the receiving site.

Plastic debris

The large-scale increase in the quantities of plastic debris being washed into coastal waters has been associated with various detriments to the environment including risks associated with ingestion of plastics, habitat degradation and chemical pollution through the decay of plastic materials (Coe & Rogers 1997, Derraik 2002). It has also been suggested that drifting plastics provide a substratum for the attachment of benthic organisms that may subsequently be transported to new regions through passive dispersal associated with wind and oceanic currents. Upon successful land-fall, these taxa may become invasive (Winston 1982, Winston *et al*. 1997, Derraik 2002, Barnes 2002, Barnes & Fraser 2003, Aliani & Molcard 2003).

While a large volume of literature describes the association of marine communities with vessel hulls and other anthropogenic structures (Skerman 1960, James & Hayden 2000, Railkin 2004), and fouling has been reported as the most significant vector in the introduction of invasive species to most areas (Pollard & Hutchings 1990, Cranfield *et al.* 1998, Thresher 1999), little attention has been paid to the association of marine biota with drifting plastics (reviewed in Winston *et al*. 1997). The literature that is available indicates that a considerable range of species associate with drift plastics.

Bryozoans, in particular, have a propensity to colonize plastic drift and to dominate fouling communities (Winston 1982, Stevens 1992, Winston *et al*. 1997). For example, in a review of three studies examining the species found on plastic debris washed ashore in Florida, Winston *et al*. (1997) record more than 26 spp. of bryozoan amidst a total of more than 64 species including nine phyla (algae, foraminifera, cnidaria, annelida, porifera, chordata (hemichordate), mollusca and crustacea). Despite this total diversity, only five pieces of drift plastic contained a community of more than 10 species and the large majority of 228 recorded items contained only a single species of bryozoan (Winston *et al.* 1997). Other studies show a lower total diversity of fouling on plastic debris reflecting a lower number of items examined. For example, Aliani & Molcard (2003) documented 22 macrobenthic species in a survey that included 14 samples of plastic debris collected from the Mediterranean. In a study of recruitment to moored plastics, Stevens (1992) records over 90 species; this is higher than the species richness found on comparable quantities of drift plastic suggesting that factors associated with plastic debris in the marine environment may reduce the likelihood of settlement, or subsequent survival, of fouling taxa. For example, if an item of drift plastic spends the majority of time in open oceanic water this would reduce the likelihood of settlement by the shallow water, coastal benthic species that are most commonly found in fouling communities.

In the high latitude areas of the Southern Hemisphere, the incidence of debris-associated species is much lower than elsewhere (Barnes 2002). However, the tendency for bryozoans to dominate these assemblages appears to continue into the Southern Ocean. For example, five species of bryozoans were found in a community of 11 species fouling a single piece of plastic (Barnes & Fraser 2003). The diversity of organisms recorded by Barnes and Fraser (2003) is abnormally high for an item of drift plastic and indicates that it had been available for settlement for a long period of time. All the species described were endemic to the location in which the plastic was found, indicating that colonization probably took place regionally. Thus, the presence of these species is not conclusive evidence that transportation of species is occurring over the large geographical distances required to facilitate biological introductions to the Antarctic region.

Communities associated with plastic drift items are often composed of species normally found in the local vicinity in which the item was recorded, or of species generally associated with natural drift items such as kelp rafts, and which are deposited on local coastlines by natural processes (Winston *et al.* 1997). However, there are exceptions. For example, the bryozoan *Electra tenella*, which is not generally found in association with kelp rafts or hull-fouling communities, is found on plastic debris. Winston (1982) suggests that this potentially provides a mechanism for *Electra tenella* to extend its range, although it has not yet been reported from regions where it was previously unknown. Winston (1997) describes the delivery on plastics of individuals of a non-indigenous species of bryozoan washed ashore in Florida (*Thalamoporella evelinae*) and a species of oyster (*Lopha cristagalli*) washed ashore in southern New Zealand from where it had not been previously recorded (the species is known from the North Island of New Zealand). Thus, although no established, non-indigenous populations can be attributed conclusively to transport by plastic debris, these observation demonstrate that transport by floating plastics beyond natural ranges does occur.

Transport directions

Vessel hulls and floating plastic both provide surfaces for the settlement of biological communities, yet the characteristics of these two vectors are very different. It is these differences that are likely to influence their potential

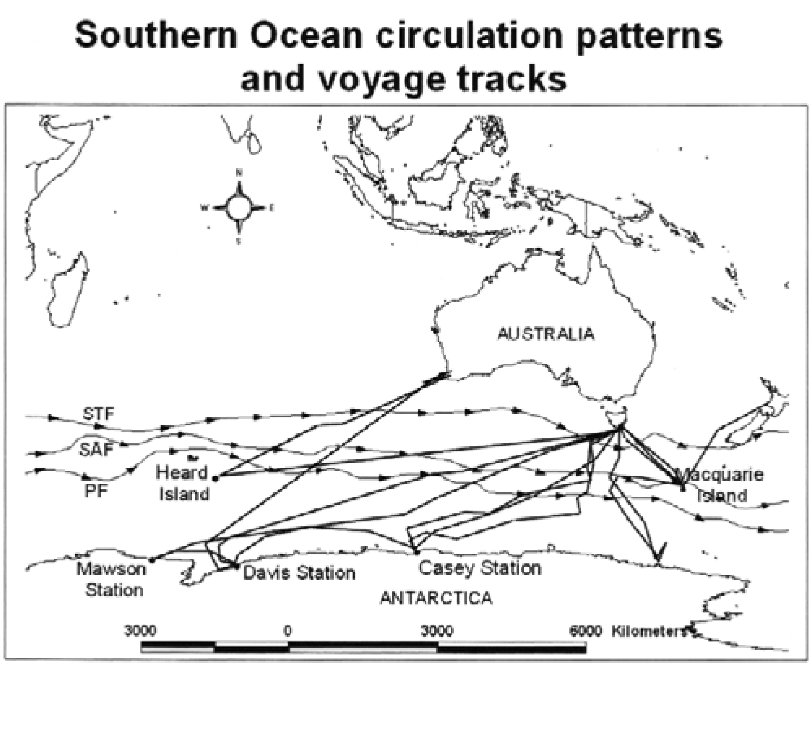

Fig. 2. Direction of transport enabled by the operation of floating plastics and vessel hulls acting as vectors for the delivery of invasive organisms. Plastics are restricted to unidirectional (west to east) transport in association with the west wind drift (→), and are restricted in the north–south plane by the existence of frontal regions (STF = Subtropical front, SAF = sub-Antarctic front, PF = Polar front). Vessel tracks (—) are a selection of voyages undertaken between 2002–04 to demonstrate some of the common shipping lanes.

to deliver invasive species to new locations. The key question determining the relative hazard presented by different vectors is whether or not they create a new transport pathway between locations that were not previously connected by natural mechanisms or, alternatively, whether they simply augment a connection that was already established. Despite the open nature of the world's oceans and the connectivity of regions created by the ocean's circulation system, the scale of transport enabled by human vessel traffic provides new opportunities for direct and rapid transport of organisms in directions that are contrary to typical oceanic currents. Floating plastic is an increasing and persistent presence in the environment. However, the restriction of this vector to natural transportation on wind and ocean currents, with no opportunity for rapid delivery of organisms, means that plastics simply provide the potential for increased transport between locations using mechanisms already available to natural vectors such as kelp, pumice and wood.

Oceanic shipping crosses major biogeographical barriers in order to transport humans to desired locations. As an example of the nature of biological transport enabled by shipping in the Southern Ocean, historical traffic has provided links between the sub-Antarctic Macquarie Island and ports as distant as London and Russia (Cumpston 1968). Modern visitation to the island comes from three main, last-port-of-call regions: Australia, New Zealand and Antarctica. However, several of the vessels travelling to the sub-Antarctic islands and the Southern Ocean also operate in the Northern Hemisphere for some of the year and may thus facilitate transport of boreal communities. Tasmania and New Zealand supply the bulk of modern traffic (Fig. 2) because of national science programs operating out of Hobart, and the popular tourism pathway that runs between Hobart, New Zealand and the sub-Antarctic islands.

Opportunities for biological transport to the eastern section of the Antarctic continent are limited due to the removal of biological material from exposed surfaces of ships' hulls during the passage through substantial sea ice required to approach shore (Lewis *et al.* 2004). As a result, northward traffic to the sub-Antarctic islands coming from eastern Antarctica is also unlikely to create a significant hazard for biological transfer. However, vessels travelling southward to ice-free sub-Antarctic islands from the temperate ports of Hobart (Australia), Bluff and Lytellton (New Zealand) may spend extended periods in temperate ports prior to departure, particularly at the start of the season, and as vessels do not pass through sea-ice during transit to the sub-Antarctic, fouling communities are not exposed to the same mechanical damage that removes organisms during visits to the Antarctic continent. Likewise, the avoidance of significant sea ice by tourism and fisheries operators in the Antarctic Peninsula region may facilitate the biological transport to the Antarctic continent in this area. As a result voyages that pass directly from temperate ports to sub-Antarctic islands and operations in the Antarctic Peninsula region are considered to pose a high hazard of biological transport.

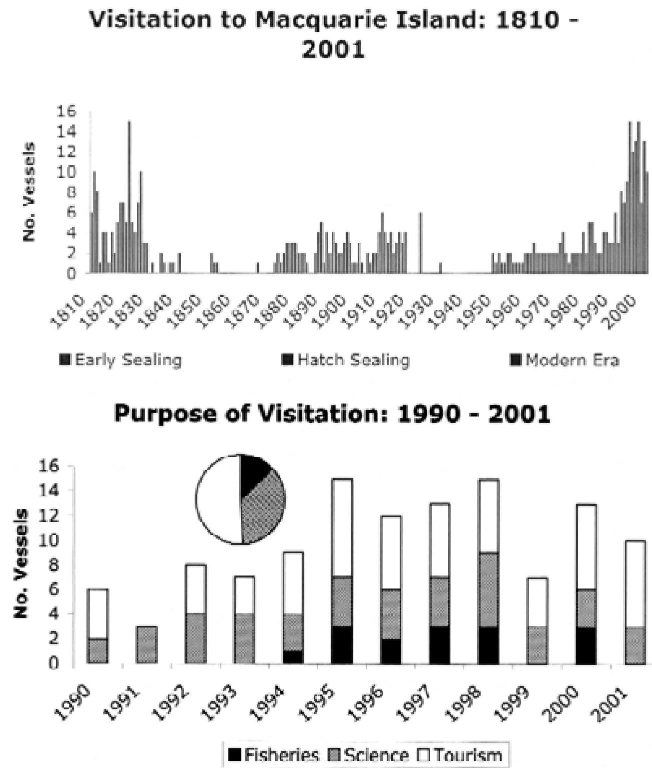

Fig. 3a. Ship visitations to Macquarie Island since its discovery in 1810. Three peaks of visitation are clearly discernable and are described as the period of early sealing (1810–40), the "Hatch" sealing era (1841–1920) and the modern era (1971–present). Vessel traffic records were extracted from Cumpston (1968) and from ANARE historical visitation records. **b.** Purpose of vessels visiting Macquarie Island in the period 1990–2001. The pie graph displays total visitation proportions for this period and indicates that tourism provides the bulk of traffic.

In contrast to the active pathway created by vessels, transport associated with floating plastics is passive and determined by natural currents. Figure 2 shows the natural oceanic currents in the sub-Antarctic region of Macquarie Island and indicates the direction that biological transport is likely to take in association with plastics and with modern vessel activity. Vessels provide a mechanism for dispersal of organisms that would not be possible by natural processes such as long-lived planktonic larvae, or by association with natural drift objects. Despite their relative persistence in the marine environment and the documented increase in the quantity of plastic debris, drift plastics do not represent a novel route for the transport of biological communities, but act as an anthropogenic supplement to a natural dispersal pathway. Indeed, at least across sub-Antarctic latitudes, the role of dispersal by floating debris may be insignificant in comparison to that provided by kelp rafts. Kelp raft surveys between Hobart and Macquarie Island indicate an average of 3.7 kelp rafts km^{-2} of ocean, which extrapolates to over 70 million rafts afloat at any one time across this band of the Southern Ocean (Smith 2002). The kelp habitat, and in particular the holdfast, supports diverse assemblages of invertebrate species at all sub-Antarctic islands (Smith & Simpson 1995, 2002) and transport by detached kelp has been hypothesized to explain the present circum-sub-Antarctic distribution of a number of taxa (Knox & Lowry 1977, Helmuth *et al*. 1994).

Delivery of propagules

Fouling communities have been shown to be capable of surviving journeys to sub-Antarctic latitudes (Lewis *et al*. 2004) and the likelihood of introductions will increase as the number of ship visits increases. Three peaks in shipping activity to Macquarie Island have occurred since its discovery in 1810 (Fig. 3a). The first (1810–27) was associated with the initial exploitation of seals, and the second (1875–1920) was associated with a second period of exploitation commonly referred to as the “Hatch” sealing era (Cumpston 1968). A final, larger, peak associated with the Australian National Antarctic Research Expeditions (ANARE) scientific exploration, and with the growing tourism industry, is obvious over the period 1971–present. This recent peak is likely to continue to rise as tourism in the region grows (Frenot *et al.* 2005).

Even though ship traffic has increased significantly in recent years, at a maximum of only 15 visits per year, it is still remarkably low compared to mainland ports. For example, Port Phillip Bay currently receives over 3000 visits per year (Joanne Weinert, AQIS, personal communication 2004). From shipping records, it can be estimated that the total number of ship visits to Macquarie Island since its discovery numbers only 458 (Fig. 3a). Over the past decade tourism (51%) has been the reason for most ship visits to Macquarie Island (Fig. 3b), followed by science (26%) and fisheries (13%). Although the total volume of traffic is low, without precautionary measures, the risk of marine introductions can only increase as the number of visits per year increases.

Conclusions

Transport in association with floating plastic debris (Barnes 2002, Barnes & Fraser 2003), and biological transfer via vessel traffic (Lewis *et al.* 2003) have been suggested as possible mechanisms for the transfer of non-indigenous marine organisms to sub-Antarctic coastal waters in the Southern Ocean. We conclude that rubbish of human origin is unlikely to have doubled or tripled the rafting opportunities for biota as suggested by Barnes (2002). While we agree that plastics in the environment have increased in abundance, and that they offer a viable and persistent surface for colonisation, we suggest that several properties of plastic debris serve to limit the potential for this transport pathway to effectively deliver new species to high latitude coastlines. Specifically, most plastics in high latitude regions are sourced from refuse dumped in mid-ocean regions by fishing activities and thus offer a transport mechanism for cosmopolitan pelagic species rather than coastal communities likely to represent a hazard of invasion. Furthermore, the passive dispersal of plastic flotsam means that rather than offering a novel pathway, this vector acts to supplement existing natural pathways. Kelp rafts are abundant and provide a natural transport mechanism, which presumably has been available since the initial establishment of kelp communities on sub-Antarctic islands. Drifting plastics thus represent a small addition to the opportunity for transport already provided by kelp rafts and other natural floating materials such as pumice and wood.

In contrast, fouling on vessel hulls creates entirely new transfer pathways for biological communities across substantial biogeographical barriers. The nature of shipping is such that it can result in the rapid transfer of established assemblages directly from one coastal region to another. Marine invasive species of concern are almost exclusively shallow coastal species (Hewitt *et al*. 1999, Carlton 2001, Railkin 2004). In the Southern Ocean, fishing is by far the greatest source of marine debris, including fishing gear and rubbish discarded from fishing boats (Slip & Burton 1991, Eriksson & Burton 2001, Burton & Schulz 2001). Much of this material will have entered the sea in open ocean locations. It is not known what proportion of marine debris eventually reaches coastal waters but, clearly, only a certain sub-set of the marine debris in the ocean will move from one shallow coastal area to another. This is not the case for ships. Almost all shipping traffic is from one coastal location to another, thus there is the potential for rapid transfer of obligate, shallow water species between coastal areas.

If the integrity of Southern Ocean biodiversity is to be conserved, it is essential that pathways for marine introductions are understood, and that, where appropriate and necessary management measures are initiated to limit biotic transfer. These should include the acquisition of baseline data to ensure that alien species are recognized as such, and long-term monitoring programs. However, the latter will only indicate whether an incursion has taken place and response guidelines are essential if there is to be any attempt to control an incursion. Experience in other parts of the world indicates that invasive species, particularly marine invasives, once established, are virtually impossible to control. Thus, the only effective method is to reduce the opportunities for incursion – this requires a good understanding of the likely pathways. We suggest that the most likely scenario for future marine invasions in the Southern Ocean is that the natural barrier to dispersal will be breached by species transported in hull-fouling communities; these species may then be spread within the region principally by kelp rafts and also, but to a lesser extent, by attachment to debris of human origin.

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