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# Vector Pathways and the Spread of Exotic Species in the Sea

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# 1 Purpose

This document is intended to review the current state of knowledge concerning vectors of species introductions, provide a brief overview of the potential risks associated with each broad category of vectors, and identify significant knowledge gaps. It has evolved from discussions of the ICES WGITMO and SGBOSV. Reports can be found at:
http://www.ices.dk/iceswork/wgdetailacme.asp?wg=WGITMO
http://www.ices.dk/iceswork/wgdetailacme.asp?wg=SGBOSV).
Although our understanding of the vectors is reasonably good, assigning vector strengths can be difficult and largely dependent on local or regional trading activities, and political and socio-economic circumstances. Not all vectors continue to operate, and some become more powerful at specific times (e.g., Campbell and Hewitt, 1999). In this account, we attempt to outline the principal vectors that are likely to result in further non-indigenous species spread, including both introductions and transfers. Some vectors may transport fundamentally different sets of organisms (e.g. mussels attached to a ship's hull, juvenile creatures within the mussel clumps, species encrusting on the mussels, species burrowing into the mussel shells, and pathogens or microalgae inside the mussels). Conversely, some species may be spread by several different vectors (e.g., larval mussels may be transported in the plankton in ballast water; adult mussels may be transported as hull foulers, as intentional aquaculture species, or as associated species accidentally introduced with stock for culture).

# 2 Introduction

Introduction vectors are the physical means by which species are transported from one geographic region to another (Carlton, 2001). Numerous natural mechanisms contribute to the spread of species and are important for the maintenance of natural populations. Many of these processes, however, are not yet fully understood and may contribute to a secondary, natural dispersal of non-indigenous species. With the expansion of human populations worldwide, the organisms' ability to spread their range has increased, giving them the ability to colonise regions beyond their natural ranges. The ability to colonise is complicated by changing circumstances in receiving waters and predicted changes to climate (Carlton, 1996).

The spread of exotic species arises either from initial or subsequent movements, and these may operate separately, in tandem, or in series. An initial movement will involve human-mediated dispersal which consists of the inoculation and survival of a species in a locality within a separate, previously unoccupied, biological province. (Usually this involves a movement between continents, either across oceans or hemispheres.) Subsequent movements are those from a locality where an initial release has already formed a temporary or sustained population. The spread from this locality may involve the same vector process or other independent vectors. Some of these vectors may be difficult to identify. In order to control and restrict the spread of a species, two things must be understood: the precise vectors involved in its spread, and the probability (= risk) that the species will be introduced by that vector. Unfortunately, once an initial inoculation has taken place, the subsequent spread may occur quite rapidly. As the species spreads, an increasing number of opportunities are presented to increase its range. Once established, a species will expand using both natural and anthropogenic vectors. These circumstances of spread will also be modified by the mode of life of the species in transit. The expansions of the Japanese kelp *Undaria pinnatifida* (Wallentinus, 1999a), the Asian shore crab *Hemigrapsus penicillatus* (Noel *et al*., 1997; Gollasch, 1999a), and the North American spionid polychaete *Marenzelleria viridis* (Bick and Zettler, 1997; Zettler 1997; Zettler *et al.* 2002) in Europe are examples of species with expanding ranges undergoing secondary spread.

A recently established, exotic species also has the potential to extend its range using the natural processes that spread native species according to life history and morphology. Some macroalgae, even when they have become detached, remain reproductively fertile, and those that become detached and can trap air or have gas bladders, such as the brown Japanese seaweed *Sargassum muticum* (Wallentinus, 1999b), or have a prolonged or constant planktonic phase, such as the dinoflagellate *Karenia mikimotoi*, can be rapidly disseminated by wind and currents. Such a rapid spread has been noted for the buoyant brown alga *Colpomenia peregrina*. In contrast, species that are entirely sedentary, such as the Chinaman's hat limpet *Calyptraea chinensis*, are unlikely to disperse rapidly because they lack a planktonic stage. Tunicates generally have a short planktonic larval phase and so, once established, may remain locally distributed if not carried further by hull fouling. The great majority of species, however, fall between these extremes and, given suitable conditions, their spread will depend on their planktonic duration, behaviour, and reproductive characteristics. Species that are able to reproduce asexually either by fragments, such as many red algae and *Caulerpa* spp., or by parthenogenesis, such as the cladoceran *Cercopagis pengoi*, may disperse more successfully.

In order to reduce the spread of exotic species, national and international co-operation is needed to identify the vectors and contingency approaches to prevent, manage, and control these populations. Unfortunately most precautions only evolve once the species introductions are recognised and after they have had economic, social, or environmental impacts. Consequently, proactive measures by management (e.g., the prevention of introductions) are more likely to be cost-effective. A fundamental understanding of the relative strengths of vectors and the patterns of species transport is necessary to enable effective management. The opportunities afforded each species by those vectors may be assisted by additional factors, such as a rare weather events, releases to specific habitats, or changes in food availability, as in the case of eutrophication.

Dry and semi-dry ballast is either rarely or no longer used with conventional shipping whereas, historically, they almost certainly would have caused the spread of some species (e.g., the periwinkle *Littorina littorea* to North America (Carlton, 1992), the stonewort *Chara connivens* to coastal areas of the Baltic Sea, as well as several seashore plants in Europe (Wallentinus, 1999c, 2002)). Today, shipping activities are believed to be primarily responsible for the majority of modern species introductions. It is estimated that there are more than 480,000 annual ship movements providing the potential for transporting organisms. Additionally, 2–3 billion metric tonnes of ships' ballast water are transported annually, carrying as many as 4,000 to 5,000 taxa each day. These vectors, together with others, result in a new introduction forming a new population beyond its natural range about every nine weeks. In Europe, there are indications that these figures may be higher with about one introduction every three weeks during the period 1998–2000 (Figures 1 and 2, Appendix I; Minchin and Gollasch, 2002). Historically, aquaculture and stock transfers of fish and shellfish may have resulted in the significant transport of species worldwide.

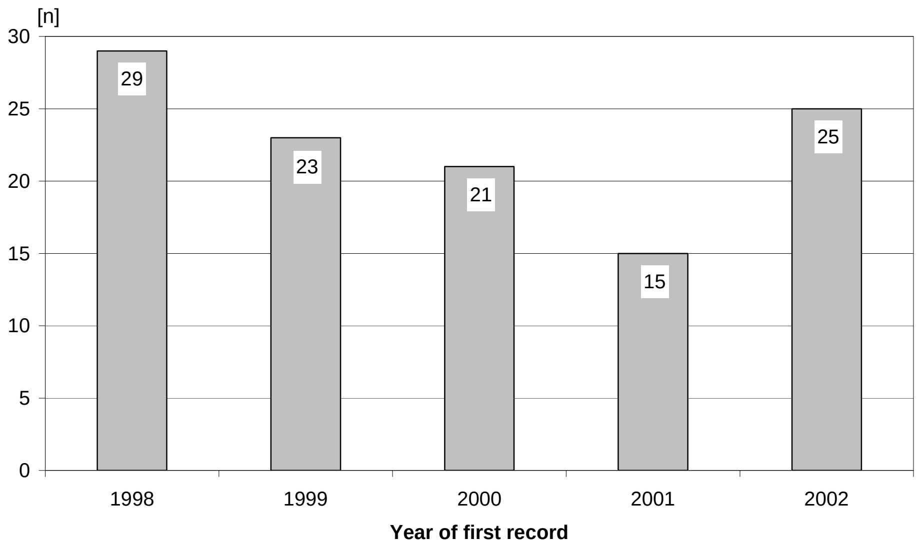


Figure 1. First records of non-indigenous species 1998–2002 world-wide (after SGBOSV and WGITMO Meeting Reports).

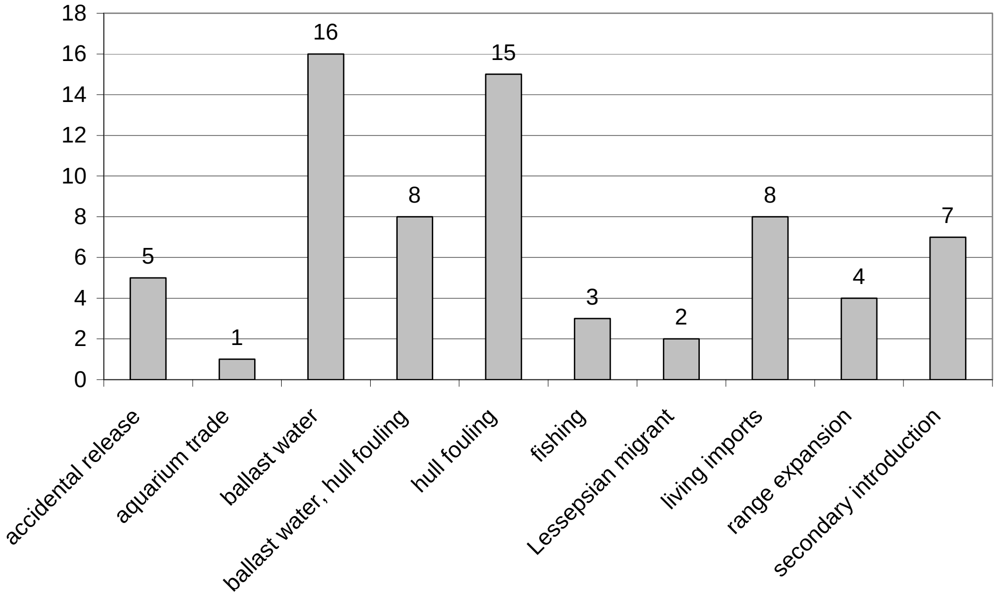


Figure 2. Frequency of first records of non-indigenous species according to likely vector of introduction in 1998–2002 (after SGBOSV and WGITMO Meeting Reports) Note that unknown vectors are not included.

# 3 Vector categories

There are several means of transporting organisms either deliberately or unintentionally (e.g., Carlton, 1988; 1994; Gollasch, 1996; Minchin, 2001). Carlton (2001) has described 15 main vector categories, Williamson *et al.* (2002) described eight and Minchin and Gollasch (2002) five. The number of these categories depends on how they are arranged as all accounts include a wide range of transmission methods. In this report, seven categories have been defined (Table 1), and some examples of exotic species spread appear in Table 2.

## 3.1 Ships, moveable structures, and other craft

Shipping has been implicated in the transmission of a great number of widely different organisms, mainly because of the preponderance of exotic species in port regions and in waterways used by shipping. These organisms include species with either planktonic or sessile stages or both, their epibionts and, in all probability, their parasites and disease agents. Further, the distribution of micro-organisms by ships may be important to the health of some organisms as well as man and, where these impact keystone species, may have significant impacts on habitats. Many unexplained diseases or marine organisms that have appeared world-wide may be associated with ship transmissions.

The conditions that provide succour and enable species to become established are elusive, but it must be significant that the majority of species introduced appear to be associated with port regions. The opportunities for species spread in recent decades may have increased because of:

- an increased number of berths in sheltered ports and estuarine regions, many of which are now situated further downstream to more marine conditions;
- construction of new berthing regions/ports servicing a specific industry, e.g. exports of graded rock products;
- overlapping of other activities that may disseminate organisms carried to that region by a primary vector;
- improvements to water quality in port regions resulting in better conditions for the establishment of those species arriving with ballast water and enabling survival of sufficient numbers to enhance opportunities of their further spread elsewhere;
- more visits to ports by vessels, many of which have shorter journeys;
- changes in shipping routes resulting in different volumes of ballast being carried. (The volumes transported depend on the nature of the trade; new routes involving one-way transmissions of bulk products may carry elevated risk.)

<u>Hulls as a vector</u>*:* Long before the development of our understanding of biogeography, species must have been carried as either fouling or boring organisms on or in the hulls of vessels used in trade and exploration. Some knowledge of the nature of the species, which may have been in transmission at that time, is based on the fouling that accumulated on settlement plates attached to the hull of a reconstructed sailing ship from the 16$^{th}$ Century (Carlton and Hodder, 1995). Boring organisms must have been a persistent problem for wooden vessels in the early years of exploration, but today, since most vessels have steel hulls, boring organisms are seldom encoun-

tered, although some may be found within dense fouling accumulations. Nevertheless, in some regions of the world there are many wooden craft that are regularly compromised by boring organisms, as in the Indian Ocean (Nagabhushanam and Sarojini, 1997). Generally, the fouling and boring biota are managed by aerial exposure, changes in salinity, or by applications to the outer hull. For steel hulls, applications also prevent oxidation of the hull, and this must be done at varying intervals to maintain the hull and reduce drag. Some structures such as oil rigs are often moved between areas, and when not in service may be held in sheltered bays or fjords. They have the potential of carrying large numbers of species that could include exotic species or populations that have become genetically distinct.

When a ship enters dry-dock, it is supported on rows of wooden blocks. Although the fouling beneath these blocks is not removed, it is crushed and is unlikely to survive; but because these areas of the hull cannot be treated with antifouling solutions, the unpainted areas readily develop a fouling community (e.g., Coutts, 1999) when a vessel departs from dry-dock. Consequently, and irrespective of the antifouling applications used, vessels can develop mature populations of species with a short life cycle soon after being returned to service. Very often cavities, such as water intake piping, sea-chests, and thruster ports may be inadequately cleaned and painted, and projections such as various instruments and crevice areas such as those associated with some rudder designs may be prone to fouling (e.g., Rainer, 1995; Coutts, 1999). Furthermore, species with microscopic life cycle stages, e.g., gametophytes of the Japanese kelp *Undaria pinnatifida,* only need minute crevices to survive, and those gametophytes can even survive on boats out of water for a month (Wallentinus, 1999a). Where in-water hull cleaning takes place, and where divers and underwater robots are used to strip hull-attaching organisms, the loosened material will almost certainly contain some viable organisms. When hulls are cleaned in dry-dock, some of the detached material may be released and survive.

Many invertebrates and seaweeds, once mature, will respond to changes in temperature by releasing gametes. Such changes in temperature may take place rapidly and promote a profuse spawning. Vessels entering shallow bays may be subjected to abrupt changes in temperature on arrival in port; such changes may occur during unloading in thermally stratified water or from diurnal temperature changes (Minchin and Gollasch, 2003). The release of gametes could lead to the formation of a substantial number of zygotes that may form a founder population following the departure of the vessel. Further, as species frequently foul hull surfaces, temperature changes may result in spawning or brood releases of pests and parasites and vertically transmitted diseases and disease agents. Indeed, Howard (1994) implied that the sporozoan disease *Bonamia ostreae* of the flat oyster *Ostrea edulis* may have been carried with oysters that foul barge hulls.

The use of some antifouling ingredients will create toxic problems particularly for shallow regions with a poor water exchange. In the past, toxic effects have been described for copper (e.g., Claisse and Alzieu, 1993), organotin antifoulants (e.g., Lee, 1991), and herbicides used in paints (e.g., Thomas *et al.,* 2001). The discontinuation of organotin biocides in antifouling paints by 2008, promoted by IMO, requires that the new generation of paints should be as effective but less toxic to biota. Recent trends in research for developing new types of marine paints have also focussed on natural antifouling substances, such as zosteric acid (Targett, 1997) or halogenated furanones (Denys *et al.*, 1995). Fast moving craft need to be more efficient in their passage. For such vessels even small amounts of fouling can result in a significant reduction in speed and added fuel consumption. Fouling on slow moving or moored structures does not receive the same attention since hydrodynamic performance is not an issue, and since the structures may have a longer interdocking period. For these reasons, such structures or craft are liable to have greater fouling burdens and therefore pose a high risk of exotic species transmission.

Studies on species introductions in Europe (Gollasch, 2002), Australia (Hewitt *et al*., 1999), New Zealand (Cranfield *et al.,* 1998), and USA (Ruiz *et al.,* 1997, 2000; Cohen and Carlton, 1998) suggest that hull fouling continues to be an important means of spreading invasive species. It is seldom possible to be certain of the exact means of transmission, since other possible vectors also need to be evaluated carefully. For example, the Japanese kelp *Undaria pinnatifida* has been dispersed unintentionally by both hull fouling and as an epibiont on Japanese oysters, as well as being intentionally introduced to some areas for aquaculture (Wallentinus, 1999a). However, historical records from over a hundred years ago suggest that a large proportion of aquatic species, already introduced, can only have arrived either as hull fouling and or with solid ballast.

*Solid ballast, ballast water and ballast sediments:* To travel safely, ships are immersed to a specific level to provide better manoeuvrability and increased stability by adjusting the amount of ballast. Vessels carrying cargo will carry small amounts of ballast, while those without cargo will require more. Container ships may even add ballast when loading cargo. Historically, this involved the use of either sand (including wet sand–semi-dry ballast), gravel, or stones, known as solid ballast. In port regions, stone ballast was stored in heaps on the shore, known as ballast banks from where it was collected or deposited. Regulations prevented the dumping of solid ballast in ship channels. The loading and unloading of the solid ballast was labour intensive, and it was not until the late 1870s that water was used extensively as ballast.

This water is pumped into segregated water tanks distributed along the length of the ship, or in some cases into empty cargo holds. The water is normally taken on board in ports and port regions, inland waterways, and in the open ocean. Tanks for holding ballast water will have different configurations according to the ship class and are served by a network of pipes for taking on water and for adjusting water levels between tanks to improve trim. These tanks are filled and drained in different sequences either singly or collectively, according to the loading of cargo (Gollasch, 1996). Consequently, the ballast water can be composed of varying salinities and may even be sourced from more than one region and may be subject to either temperature or salinity stratification, or both. When pumped aboard, ballast water may include a great number and variety of organisms, suspended solids (e.g. sediments), and chemical and human wastes. The majority of ships take up or discharge at least some ballast water whilst in port, and when fully laden (no ballast onboard = NOBOB), some ballast water will remain because most pumps serving ballast tanks are not able to remove all of the water or sediment accumulations.

The volume of ballast water can be as much as 30% of the overall cargo carrying capacity of the ship (Gollasch 1996). The pumping of such large volumes of water takes many hours and is expensive. Consequently, when a vessel undergoes ballast water exchanges at sea, as recommended by the International Maritime Organization (IMO 1998), the large volumes displaced can result in structural stresses on the hull, and any alterations in stability may make it unsafe to undertake such exchanges under certain sea conditions. Three complete changes are recommended to purge >95% of the original ballast water onboard and thereby the biota present, but this may not be sufficient to remove organisms including the resting stages of species that accumulate in the ballast sediments. Currently there are no fully proven sterilisation techniques, although several methods showing various levels of efficacy are in different stages of development. Currently, this ballast exchange (i.e. re-ballasting in mid-ocean) is the only "preventive" management method for controlling the spread of species by ships. Exchanges at sea used to purge and kill organisms are probably most effective when freshwater is exchanged for seawater, or when passing the tropics between two temperate ports.

Planktonic species, including those with short, free-living stages, may normally be carried in ships' ballast water. Species that require a substrate in which to bury or are otherwise associated with sediments, may accumulate in the fine silts to sands within ballast tanks that may be taken on board during ballasting. Although sands are known to collect in ballast tanks, fine sediments are usually suspended in the turbid water in port areas, and following the loading of ballast, settle to form accumulations on the floor of ballast tanks. With the large volumes of water and available surface areas associated with ships, it must be expected that many transmissions will occur.

Ballast sampling has provided estimates of about >50,000 zooplankton and 110 million phytoplankton per $m^3$ (Lenz, *et al*., 2000). In a recent assessment of European ballast studies, there have been approximately 990 species of widely different taxa recorded from the water and sediments of ballast tanks ranging from micro-organisms to fishes (Drake *et al.*, 2001; Gollasch *et al*., 2002). However, the abundance of organisms in ballast tanks is difficult to quantify, because they may not be distributed evenly (Murphy *et al.*, 2002). This may be due to water circulation effects that can cause concentrations. Furthermore, the behaviour of organisms in tanks remains largely unknown. Ballast tank sediments are seldom evenly distributed on the floor of ballast tanks as a result of winnowing effects and often form small drifts against partition walls. Sampling of the soft sediment accumulations has revealed that the cysts of dinoflagellates can occur at densities of 150 to 22,500 cysts/$cm^3$ of sediment (Hallegraeff and Bolch, 1992). Such cysts as well as resting cells of diatoms can survive very harsh conditions, including anoxia, and can remain viable for 10 to 20 or more years (McQuoid *et al*., 2002).

It is difficult to ascribe an invasion as being solely due to a release of ballast water, although it would appear that ballast water is almost certainly operating as a vector. Problems of access (e.g., Sutton *et al*., 1998; Gollasch *et al*., 2003) make sampling of ballast water difficult to achieve. Yet the evidence is strong, because many species known to be capable of invading have been found within ballast tanks (Gollasch *et al*., 2002). The large volumes of water transported as ballast are likely, on some occasions, to contain sufficient numbers from which founder populations may evolve (Ruiz, 2002).

*Other:* Flying craft that land on water also have the capability of transmitting species either as water contained in the pontoons that is subsequently drained or from entanglement. Eno *et al*. (1997) suggested that the red alga *Pikea californica* may have been introduced to the southwest coast of Britain by flying boats originating in California during World War II and carried in canvas sea anchors, although other studies have shown this to be less likely (Maggs & Ward, 1996). Carlton (1979) highlighted this transport mechanism for the introduction of marine species into the inland Salton Sea of California.

### 3.2 Aquaculture activities

A small number of exotic species contribute to local economies world-wide, and more profitable species are likely to be spread in the future. In particular, those species that are highly prized as a food, easily cultivated at high densities, and have a tolerance to changing temperatures and salinities are likely to be favoured for cultivation. However, some biota once introduced can result in serious financial losses (Minchin and Rosenthal, 2002). Stock movements between areas can cause the spread of associated biota. Such movements may be part of current accepted practices.

In particular, the transmission of oysters has resulted in >100 species becoming established in different regions worldwide. Examples include the movement of American oysters from Long Island Sound, USA to Britain and Ireland (Minchin, 1996), Pacific oysters from Japan to British Columbia in the early 1900s (Quayle, 1969) both carried as deck cargo, and the Pacific oyster flown from Japan to France (Gruet *et al*., 1976). Because oysters do not bury in sediments, they provide an irregular shell surface in which biota may bore, attach, or cryptically hide, and close to 50 species of macroalgae have been introduced into Europe as likely epibionts on Japanese oysters (Wallentinus, 2002). Organisms may also be carried in the "liquor" within the mantle cavity or infest or reside within the soft oyster tissues. As stock movements normally are made up of many thousands of individuals, there are adequate opportunities for the spread of any associated biota, particularly when rapid transport enables the transmission of species that would otherwise expire (Carlton, 1992; Sindermann, 1992; Minchin, 1996). Occasionally, an industry may suffer a serious decline in production following a disease outbreak, resulting in importations of disease resistant stock or of a different species in an attempt to replace this lost production. Under these circumstances, a cautious approach is adopted, and imports, consisting of large stocking numbers of several consignments, may take place. The action is justified by social and political arguments, since a rapid response is needed. Many illegal imports and releases, especially when imported specimens are placed directly in the sea and cultured as is often the case, also pose a serious potential risk. Not only does this promote the spread of diseases and parasites, but it also encourages the introduction of epibionts that may pose a threat to the ecosystem. The same ecosystem risks also exist when trade agreements (e.g., EU Directives) allow movement of half-grown shellfish between member states for fattening, with the only requirement that they do not come from disease infested areas.

A large component of the biomass in aquaculture is made up of molluscan species. In the past ten years, several small, new parasitic species and unexplained conditions have occurred, some of which were associated with elevated temperatures (Myrand and Gaudreault, 1995). Several viruses have also been recognised in recent years (Renault, *et al*., 1994), occurring in oyster larvae and spat (Nicolas *et al*., 1992; LeDeuff, 1994) and in adult mussels (Jones *et al*., 1996). On the other hand, only one macroalgae (*Undaria pinnatifida*) has been moved in Europe for the purpose of commercial culture (Walletinus, 2002). Currently, we know less about the disease organisms carried with seaweeds than we do about fish and shellfish. Consequently, some caution should be exercised when moving seaweeds for culture.

Once a species is successfully cultivated in one region of the world, it is likely that it will be considered as a suitable candidate for culture elsewhere. This will include species used for sport fisheries and ornamental species. For example, besides being farmed in cages in many coastal areas, especially in the Baltic Sea, the stocking of rainbow trout *Oncorhynchus mykiss* in lakes, reservoirs, and rivers has been beneficial to recreational angling throughout the world (Lelek, 1996; Löffler, 1996). In many regions, these are cultured before their release, as self-sustaining populations may otherwise not take place. Exotic salmonids held in cages in the sea could escape to compete for food or breeding space or can interbreed with different populations. Unless sufficient numbers are released, as in the case of escapes resulting from storm damage, the impacts from such competition may be minimal, unless they carry and spread pests, parasites, and diseases. In British Columbia, farmed Atlantic salmon *Salmo salar* escapees show evidence of breeding in one river (Volpe *et al*., 2000).

### 3.3 Wild fisheries

New fisheries can be developed not only in temperate to tropical environments but also in much colder seas. The release of the red king-crab *Paralithodes camtschaticus* in Russia in the 1960s resulted in its establishment and expansion to the north coast of Norway (Petryashov *et al*., 2002). Its spread has been aided by both planktonic dispersal of its larvae and by walking juveniles and adults. Dispersal of adults may also result in the spread of sessile organisms attaching to its carapace. Fish are likely species to become widely distributed. The rearing of pink salmon *Oncorhynchus gorbuscha* in Russia resulted in vagrants spreading south to Atlantic coasts (Petryashov *et al*., 2002).

Some organisms are readily spread through a trading network, which has existed for several decades, and trade in captured live species for human consumption such as the American lobster *Homarus americanus*. American lobsters have been found in the wild in several northern European regions. Their presence is thought to be due to deliberate releases. Some species may be spread because of ethnic food preferences, as may have been the case of the appearance of *Rapana venosa* in France (Goulletquer *et al.*, 2002). Unauthorised import of live food may also take place as in the case of the Chinese mitten crab *Eriocheir sinensis* that is intercepted at airports in the United States (Carlton, 2001). Many species are available for purchase over the Internet, and there is good reason to increase public awareness to the risk from such sources.

Secondary spread of species may be enhanced by fishing activities. The expansion of the tropical green alga *Caulerpa taxifolia* in the Mediterranean Sea, where plant fragments were removed by anchors and fishing gear and subsequently distributed elsewhere (e.g., Relini *et al*., 1998), is likely to continue.

Agreements between trading blocks do not usually consider the associated biota that may accompany such trade, since restrictions on a product may compromise the trading activity. Accordingly, veterinarians may classify diseases but only prevent those movements that carry the most serious of these diseases from specific geographic regions. Inevitably, some diseases, considered to be of low priority, can be distributed, and the trade may also spread undescribed or elusive diseases. Veterinarians seldom consider pest species or epibionts that may result in either compromising culture activities, other commercial activities, or the environment.

Additional vectors may be associated with the export of live consignments that may include the use of marine algae or vascular plants used as packing for living crustaceans and molluscs. Either the algae, epibionts, or other associated organisms could be established elsewhere if the packing materials were discharged into the wild (e.g., the Japanese eelgrass being brought to western North America with Pacific oysters (Wallentinus, 1999c)).

Frozen foods intended for human consumption may also spread disease. The white-spot syndrome virus (WSSV) of prawns has spread through much of Southeast Asia and may have the ability to infect other prawn species world-wide. If the frozen prawns were used as bait, the virus could gain access to new regions (Williamson *et al*., 2002).

### 3.4 Aquarium industry

Aquarium fishes, invertebrates, and plants used in aquaria or ponds are regularly moved, often over great distances. This trade frequently relies on specific collection points where specimens accumulate before a sufficient consignment can be made up for export, usually delivered by aircraft. During this holding period, there may be high mortality arising from the inability of the species to feed, from negative social interactions, and from stress and the spread of pathogens from sick fish resulting from high densities. The accidental or deliberate release from aquaria or ponds are frequent events in freshwater, but the formation of populations arising from releases to the sea are rare. Nevertheless, serious diseases may be spread by the aquarium trade such as epizootic ulcerative syndrome. This is widely distributed in the Indian Ocean and causes high mortality in cultured marine and estuarine fishes. There have been general concerns about the spread of diseases by this trade for some years (Adams *et al.,* 1970). Robertson and Austin (1994) examined exotic fishes to find organisms that may also be harmful to temperate species such as rainbow trout and salmon. In an earlier study, Shotts, *et al*., (1976) found several harmful bacteria in the supporting water in consignments of exotic fish coming from Taiwan, Singapore, Hong Kong, and Bangkok.

The majority of fish used in the aquarium trade are tropical species. These are popular because of their bright colours, interesting morphology, or unusual behaviour, and they adapt well to stable room temperatures. Normally, it is important, when transferring these species, to avoid prolonged cool periods and sudden changes in temperature. Tropical species, should they be released into the wild, are unlikely to survive and reproduce in temperate climates except perhaps in heated water discharges or warm water springs. Movements of species between regions with similar climates are likely to have a higher level of survival provided that the social interactions, food, and appropriate habitats are available. Vascular plants used in freshwater aquaria may also survive in brackish coastal areas if released, as has been the case, with the Eurasian water milfoil *Myriophyllum spicatum* in Canada and USA (Wallentinus, 1999c).

However, a tropical marine green alga, *Caulerpa taxifolia*, while in culture, developed a clone that could survive at lower water temperatures (Meinesz and Boudouresque, 1996; Wallentinus, 1999c). This form was probably released accidentally from an aquarium in Monaco, where it was first noted to form a meadow. It then spread rapidly to the northern part of the western Mediterranean and later to the Balearic Islands and the Adriatic Sea. *C. taxifolia* has also appeared in two shallow coastal bays in California (Jousson *et al*., 2000; Williams and Grosholt, 2002) and in several locations in temperate Australia (New South Wales and South Australia). The California populations appear to be the invasive clone found in the Mediterranean, while the Australian populations appear to be domestic translocations from native tropical populations in Queensland (Murphy and Schaffelke, 2003). In California, attempts to control the populations were instigated soon after discovery and appear to be successful.

### 3.5 Marine leisure tourism

Bait organisms may be exported beyond their normal range and be discarded alive into the wild to form new populations. Bait worms collected in Korea, Africa, and the USA are exported by aircraft to different world regions, including Europe. There is evidence that distribution of bait acts as an important vector. The green crab *Carcinus maenas* and the rough periwinkle *Littorina littorea* may have come from Maine to San Francisco Bay as bait worms for anglers (Cohen and Carlton, 1995).

Movements of infested fishing gear may also allow species to colonise new regions as happened with commercial fishing operations in the spread of *C. taxifolia* in the Mediterranean (Relini, *et al*., 1998). Theoretically, other equipment such as diving gear could spread fragments both of plants and other species, if the gear is not cleaned and dried before being used in other waters.

Recreational craft, many of which are held for long periods at marina berths, can transmit their fouling biota to many world regions once re-engaged. Leisure craft may be important in the secondary spread from port regions to remote estuaries and bays. The black striped mussel *Mytilopsis sallei* appears to have been transported to Cullen Bay Marina in Darwin, Northern Territory, Australia by a recreational vessel. *M. sallei* was detected in Darwin in 1999 at densities up to 24,000 individuals m², fouling all hard substrates (Bax, 1999; Willan *et al.,* 2000). A successful eradication effort was established to rid Darwin of the mussel, costing an estimated AU$2.4 million (Bax, 1999). The bryozoon *Tricellaria inopinata* was almost certainly transmitted as hull fouling by leisure craft from the Venice lagoon to the south coast of Britain (Dyrynda *et al*., 2000).

Small boats may also be carried on trailers and are implicated in overland species transmissions. These may be carried either in the bait wells as larvae or attach to the hulls on re-immersion. The bait wells may be drained and fouling biota may be rubbed off (Minchin and Gollasch, 2003). The trailer may also transmit species carried on snagged plants.

### 3.6 Research and education

Exotic species are held in some research institutions. Such captive species are not normally reported to regulating bodies, and consequently this information is not readily available. Often, the source of these species is associated with a specific geographic region or taxonomic group. The species under study could be obtained from biological suppliers, and waste from these facilities may be discharged directly into the wild. Upon completion of the studies, the species may be released, without proper consideration of all the risks to the ecosystem.

The red alga *Mastocarpus stellatus*, native to many other areas in Northern Europe did not occur on Helgoland Island in the North Sea. This apparent absence led to a study on its colonisation in the wild. It is currently well established on the island and may outcompete some native species (Bischof, *et al*., 2000).

### 3.7 Other

The existence of old canal systems and new waterways has allowed the ready transmission of species, either by moving on their own or by inadvertent transmission. Very often it remains unclear how the transmission took place. There are species flows between the Red and Mediterranean Seas, named Lessepsian immigrants, after Lessep, builder of the Suez Canal. Mainly the flow has been composed of Erythrean species from the Red Sea (Galil and Zenetos, 2002). Similarly, the Kiel Canal, connecting the North and the Baltic Seas, has been responsible for more easterly appearances of the Chinese mitten crab, *Eriocheir sinensis* (Gollasch, 1999b) and possibly the shipworm *Teredo navalis* (Hoppe, 2002). In eastern Europe, the building of canals has enabled the transmission and spread of species between the Baltic, Black, and Caspian Seas, either by dispersal through the canal system or through transfer by barge transport and ships.

Restoration of stability to mobile sediments may require the planting of either cordgrasses *Spartina* spp. on shores or seagrasses in shallow bays. Some of the species in use may be introduced, and in some areas those species have hybridized with native species, resulting in more vigorous and invasive plants, including polyploids (Wallentinus, 2002).

The large amount of flotsam and jetsam now appearing on most seas may have some impact as a vector for species that might not otherwise have been spread (e.g., Barnes, 2002). This may be composed of fishing equipment and floating plastics to which a fouling biota may attach. The reuse of old boxes for fish catches may also pose a risk of spreading diseases.

There are also examples of many unusual vectors for marine and brackish water plants. The Pacific sedge *Carex kobumugi* arrived following the wreck of a ship carrying porcelain and is now growing—as well as having been planted—on shores of the east coast of North America. This sedge was used as a packing material laid between the ware and transported in barrels. The plants drifted ashore and became established (Wotton *et al*., 2003). During the nineteenth-century, several brackish and freshwater plants came to Great Britain with wool imported from Australia, e.g. the Australian milfoil *Myriophyllum verrucosum* as well as several species of sedges *Cyperus* spp. (Wallentinus, 2002).

# 4 Management approaches

### 4.1 Intentional introductions

Most countries have laws or other legal restrictions preventing the introduction of marine organisms such as fish and shellfish., There are, however fewer restrictions on bait organisms, aquarium fish, aquatic plants, and seaweeds, although the spread of the aquaria grown tropical green alga *Caulerpa taxifolia* in the Mediterranean Sea, and its recent appearance in the USA and Australia, have resulted in a ban on its introduction or even its possession. In the USA, federal restrictions apply to some aquatic plants; these are mostly freshwater species. For invertebrates of no commercial interest, the situation may be similar to that of seaweeds. Consequently, there is a need to widen the categories of organisms to which legal restrictions apply. Nevertheless, although laws exist to control the introduction of organisms from abroad, the movement of species between different parts of the country may still be permitted even though different sea areas are involved, thus enabling either distinctly different populations of a species to be spread or enabling expansions of species. Furthermore, some national authorities, normally associated with fisheries development, may grant exemptions to perform introductions for different purposes. Illegal introductions by those involved in culture or stocking operations are not uncommon, creating an urgent need to develop public awareness to stop such actions, which can compromise production and impact the environment.

It is common for trading blocks, such as the European Community, to replace or overrule national legislation and controls that have either previously existed or have been replaced with restrictions that apply only to the most serious diseases/pathogens, parasites, and pests. These actions do not take into account the different biogeographical provinces that may now be enabled to exchange material. Consequently, when target species are moved, there is the risk of spreading their associated organisms, to or among the target species. Such movements can include species that have not been described yet or species that have not been recognised yet as being of consequence. Frequent monitoring of areas with such imports (including *in situ* holding facilities) should be considered as a basic management procedure and should be carried out following the arrival of consignments from new regions each year.

The International Council for the Exploration of the Sea Code of Practice on Introductions and Transfers of Marine Organisms (ICES, 1995; 2003) outlines how the risks of introducing a marine species can be considerably reduced. It may be argued that introduction using these procedures is costly, because they recommend that the original import should not be released from quarantine and that the filial generation is released only after histological studies indicate that it is free of potential pathogens. However, the comparatively large numbers of invertebrates and macroalgae introduced as non-target species with oyster movements, intended for culture, stress the importance of not releasing imports directly into open waters. The main difficulty with implementing the Code of Practice is that it acts as a set of recommendations and is not legally binding. Further, there is a general lack of awareness among the public and authorities on the local, regional, and national levels as well as others who make decisions relevant to the Code. This applies not only to introductions for fisheries and aquaculture, but also to e.g., coastal zone management, dune plantations, and habitat restorations.

The use of quarantine facilities is a management procedure included in the ICES Code of Practice, and may be demanded by authorities before the species is released. Originally, the purpose of the Code was to avoid unintentional introductions of disease agents and parasites. Subsequently, the Code has been refined and expanded to include genetically modified organisms and environmental issues. However, as stated above, such a procedure should also be used as a precaution to stop the spread of non-pathogenic associated organisms (see also Appendix C to the new ICES Code of Practice, 2003). The management of imported stock, or of stock that is to be transferred in the course of normal culture operations, has included treatments and recommendations, such as brine dips (Gruet *et al.,* 1976, Minchin and Duggan, 1988), which have been applied on occasion. Although some associated species may be exterminated by such a method, it is likely that not all of these will be managed in this way.

Scientists have often embraced the idea that an organism used in pilot trials can be easily eradicated once field experiments or farming tests are completed, as long as the test organisms are removed before they reach maturity. However, storms and other events can result in dispersion, and control can be lost. In one case study however, it was possible to remove the giant kelp *Macrocystis pyrifera* following cultivation trials in French Atlantic waters in the 1970s (Wallentinus, 1999c and references therein). Had it reached maturity and produced a recruiting population, it could have, on account of its size, resulted in profound changes to shallow water ecosystems. Consequently, the actions taken by scientists need to be measured, and awareness among researchers should be developed about the purpose for the ICES Code of Practice, since some experiments might be made out of ignorance. Research protocols and signs in field stations could reduce this risk.

According to the ICES Code of Practice (ICES, 2003, Appendix B), a basic risk assessment should accompany the introduction proposal. However, in the long term there is a strong need to develop more quantitative risk analyses for better management procedures.

### 4.2 Unintentional introductions

There are some precautions and management procedures that can be employed for unintentional introductions, although these may be more difficult to apply than for intentional introductions. The general public's awareness should be considered since a single person may release and subsequently cause the establishment of aquarium species or of living organisms intended for human consumption. Thus, even though some of the vectors are more difficult to manage than others, there are still many situations in which improved knowledge can reduce movements of exotic species, as in the case of zebra mussels *Dreissena polymorpha,* transported via small boats and equipment (Minchin *et al.,* 2002).

Ballast water has been recognized by the International Maritime Organization (IMO) as one of the most prominent vectors for unintentional species introductions. The IMO Ballast Water Working Group was established in the early 1990s to prepare a Ballast Water Convention. Guidelines for the control and management of ships´ ballast water to minimize the transfer of harmful aquatic organisms and pathogens were adopted as Assembly Resolution 868(20) in 1997 (IMO 1998). A Diplomatic Conference on the Ballast Water Convention took place in February 2004. Since ballast water exchange only minimizes the risks, other techniques must be developed that will be more effective in eradicating live organisms in ballast water tanks.

The global ban on the highly toxic organotin tri-butyl-tin antifouling paint demands the development of non-toxic antifouling paints. Currently, there are few, effective, long-term antifouling applications, and consequently a greater biomass of fouling biota can be expected to be in transmission. Many such applications have become specialized for particular craft and for vessels operating at different speeds. Further research on novel methods of hull fouling management will be important in the management of introductions via this vector.

In ports, vectors are likely to overlap because these regions are usually highly urbanized, resulting in a wide range of activities. Managing the overlap of vectors in such regions may require hard decisions restricting some activities to reduce the risk of species invasions. Studies of exotic species present in ports will almost certainly be beneficial, since it is likely that ports are acting as donor areas for non-indigenous species to other regions. All relevant activities within the port region should be evaluated where the port may act either as a donor or recipient of unwanted invasives, as was demonstrated for five north-west European port regions by Gollasch and Leppäkoski (1999). Small changes in practice could result in reduced risk. For example, it may be sufficient to reduce the probability of an inoculum becoming established by extending the ballast water discharge trails of ships on entry to a port, and by banning removal of hull fouling communities from ships by robots and divers while in vulnerable regions.

Australia has used the concept of preventing the arrival of species that are considered to pose a high risk of invasion. This target list has been developed as a precautionary measure to manage those species that may be carried by shipping. It assumes that, if such a species is known to be present in the port of departure where it may be taken up in ballast water, discharge in the arrival area could be denied. However, there are many further species, many of which are microscopic, that must also be considered, since the risk of transmission of many of these is not fully known.

In a few instances, removal of introduced species has been successful, as in the cases of the mussel *Mytilopsis sallei* in northern Australia and the green alga *Caulerpa taxifolia* in California. If detection is made at an early stage, it may be possible to undertake such measures successfully. In the Mediterranean, however, attempts to control *C. taxifolia* failed because it was already well established and widespread when eradication measures began. The attempt to remove the Japanese brown alga *Sargassum muticum* following its first appearance in southern UK also failed (Critchley *et al*., 1986). Control measures included the introduction of quicklime, chlorine, or copper compounds, as well as the use of black plastic to cover infested areas and the use of divers. Effective responses are important, and this underlines the need for a rapid response team and a national forum to enable the appropriate actions to be taken effectively and swiftly for species believed to compromise the health, economy, or ecology of aquatic environments. Such actions may need legal support in advance of events. To allow for such a rapid response, there must be personnel available with legal authority to make decisions. A strategic plan should be formulated in advance, including scenarios covering which kind of organisms and in which areas eradication is allowed, since it is likely to vary by species.

Releases from aquaria (private or commercial) are responsible for the establishment of several exotics. Increased awareness, including the incorporation of information in environmental studies in schools, can help to reduce the spread of species. Further, many local suppliers of aquatic products have arrangements to take back live, unwanted organisms for resale or for destruction. Many supplies are available via the Internet; efforts to induce sales outlets to take a greater responsibility in handling living organisms, as in the case of many aquarium institutions, may reduce releases from such sources. The products exported in the aquarium trade need to be certified, and regular health inspections would almost certainly reduce the spread of unwanted impacts. Any serious and unexplained mortalities should be investigated. The development of protocols in the rearing of aquarium species will evolve, and some endangered species are likely to be managed in facilities that may assist in conserving species. Although this may aid in conserving marine biodiversity, such facility-raised organisms could also pose the risk of becoming established in the wild.

### 4.3 Mixed activities

When an exotic species establishes a new population, further opportunities for spread may arise. Ships berthed in sheltered bays or estuaries may share the harbour region with marinas and the aquaculture facilities that rear molluscs or fishes. These areas may be near ballast water discharge areas or loading areas. Thus many ships acquire aquaculture fouling organisms on their hulls. The proximity of shipping to aquaculture activities poses the unquantifiable risk that some organism imported by ships will impair survival, compromise growth, or render the nearby cultivated product unmarketable and may render quarantine regulations useless in certain areas (Rosenthal *et al*., 2001). Ballasting by ships in port, for example, may result in the loading of untreated discharges of human sewage and bacteria, such as *Vibrio cholerae*, that may enter the food chain when released in distant ports through the marketing of locally cultured oysters.

Also of concern are newly discovered algal toxins associated with phytoplankton and their apparent spread throughout the world. Delineating pathways whereby unwanted species are likely to be introduced and providing monitoring to intercept such introductions are obvious precautions, but they are seldom practiced. It is especially important to stop the introductions of organisms that constitute missing links in a parasite's life cycle. Active search for such organisms and their rapid removal should be given high priority.

To minimize the risks associated with the wide range of operating vectors, intentional as well as unintentional, more research is needed. Also required is an improved understanding on how economic incentives could improve prevention or reduction of risk in the introduction of unwanted species. This could include the identification of all possible means of mitigating risks and ecosystem impacts, calculation of their costs, and comparison of the efficiency of different incentive mechanisms. For example, comparison of information campaigns, charges on illegal activities, producer responsibility based on the "polluter pays" principle etc., could identify the most effective and cost-efficient means of minimising the risks and preventing the introduction of invasive species.

# 5 Conclusions

Exotic species will continue to spread. Our ability to predict the rate and extent will be determined by our level of understanding about how species are transmitted and the efficacy of the measures used to manage them, backed up by appropriate monitoring and policing. It is clear that, in the absence of public awareness programmes, many of these management measures will not operate effectively, because of the many and various ways in which a species may spread following arrival. Emphasis should be put on the prevention of introductions coming from different parts of the world because their subsequent spread is more difficult to control. Once a reproducing population evolves, anthropogenic as well as natural dispersal will enable further spread, and the potential to expand increases with each new region colonised. It is notable that the majority of species introductions appear both in port and aquaculture regions; and there is concern that, where different human activities overlap, species may be effectively relayed to new regions and form populations. The full complement of organisms in transit is almost certainly greater than the present level of understanding, and it is likely that microorganisms requiring further study, either ferried with current stock movements or inadvertently transported by other means, will have implications for fisheries, aquaculture, and human health.

Studies on ships have revealed that ballast water is a significant vector, yet recent studies on hull fouling indicate that, in recent times, this has been a more important vector than was supposed and is likely to increase with the global ban on TBT. It is inevitable that new trade agreements will result in the further spread of species and will involve the transmission of species between biogeographical provinces. Carriers involved in this trade need to be made aware of this so that discarded or otherwise released organisms used in trade can be managed appropriately. Rapid response measures used in controlling new appearances of a species, if found at a sufficiently early stage, may enable the elimination of a potential founder population, as has been shown in Australia and North America. The management of species spread can be more effectively conducted with fuller international co-operation than is currently the case, based on the enthusiasm of a small number of professionals. This can be achieved by the further development of existing databases with reviews of up-to-date records and mitigation methodologies. Regions that act as potential donors of unwanted species should be encouraged to develop measures to reduce the opportunities for such species being spread.

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Table 1. List of vectors and pathways known or suspected as transport means resulting in new, introduced species in coastal areas.

| Pathway vector | Vector |
|---|---|
| Ships, moveable structures (oil platforms, barges, dredgers, floating docks, navigation buoys) other craft (commercial, fishing* and leisure vessels, and float planes)<br><br>(* see also Wild fisheries below) | • Ballast water and sediments and organisms carrying associated species on/among/within them<br>• Solid ballast and organisms carrying associated species on/within them<br>• Hull fouling and the fouling organisms carrying associated species on/among/within them<br>• Hull projections and cavities (sea chests, thrusters, internal piping, and small crevices)<br>• Hull boring organisms and associated species with and within them<br>• Aquatic cargo (wells and tanks) and organisms carrying associated species on/among/within them<br>• Anchor, anchor chains, lockers, moorings, scuppers and bulwarks<br>• Small craft trailers<br>• Dredge spoil |
| Aquaculture activities | • Intentional release and stock movements and associated species on/among/within them<br>• Accidental release incl. associated species on/among/within them<br>• Gear movements (incl. cages, lines, etc.)<br>• Discarded or lost nets, floats, traps, etc.<br>• Discarded containers, live packaging material and/or transport media, and associated species on/among/within them<br>• Discharge of feeds (live, fresh, frozen)<br>• Release of GMO biota |
| Wild fisheries | • Stock movements and associated species on/among/within them<br>• Population re-establishment and associated species on/among/within them<br>• Processing of live, fresh, and frozen foods<br>• Live bait movements and discharges of live packaging material and associated species on/among/within them<br>• Gear and transport media (water) movements<br>• Discarded and lost fishing gear<br>• Discard of target and non-target species (bycatch) when dumped away from site of harvest<br>• Intentional release of organisms intended as fish food<br>• Live food for consumption (accidental and intentional releases) and associated species on/within them |
| Aquarium industry and public aquaria | • Intentional releases and associated species on/among/within them<br>• Accidental releases and associated species on/among/within them<br>• Organisms associated with rock and sand and associated species on/within them<br>• Untreated aquarium and waste discharges<br>• Living food movements for aquarium species and associated species on/ among/within them |
| Marine leisure tourism | • Live bait movement and discharges of live packaging material and associated species on/among/within them<br>• Accidental, intentional transport and release of fishing catch and the discharge of live packaging material and associated species on/among/within these materials<br>• Diving gear and associated equipment movements<br>• Fishing gear and associated equipment movements |

| Pathway vector | Vector |
|---|---|
| (* see also Ships and Wild fisheries above) | • Water skis and other water sport equipment movements<br>• Live souvenirs and their associated species on/among/within them |
| Research and education | • Intentional release including field experiments and associated species on/among/within them<br>• Accidental release and associated species on/among/within them<br>• Water and waste discharges and flow-through aquaria systems, discharged demonstration material<br>• Living food movements and associated species on/among/within for maintained organisms<br>• Diving gear movement<br>• Field and experimental gear movement<br>• Restoration, mitigation and rehabilitation |
| Others | • Alteration of water courses and flow regimes<br>• Navigation canals<br>• Irrigation canals (including saline ponds)<br>• Habitat management (soil/sand/gravel, seagrasses/marshgrasses, plants for dune stabilization, filterfeeders for better water quality)<br>• Horticulture of plants tolerating brackish water (incl. their subsequent spreading to coastal areas)<br>• Biological control<br>• Municipal and other waste treatment discharges<br>• Discharged live packing material used for fragile products<br>• Imported wool with entangled seeds/propagules |

Table 2. Examples of exotic species spread in European and North American coastal waters other than by natural dispersal mechanisms. Some of the acting vectors will also involve transport by ship, aircraft, and land vehicles. Asterisks in the centre column refer to the species listed in column three.

| **Principal activity (cf. Table 1)** | **Main vectors or means of transmission/establishment** | **Species** |
|---|---|---|
| Shipping and floating structures (drilling platforms, dry docks) | Ballast water and sediment*****, hull fouling******, cargo*******, ships equipment | *Coscinodiscus wailesii* – planktonic diatom*****<br>*Marenzelleria viridis* – spionid polychaete*****<br>*Mnemiopsis leidyi* – comb jelly*****<br>*Ensis americanus* – American razor clam*****<br>*Balanus improvisus* acorn barnacle******<br>*Elminius modestus* – Australasian barnacle******<br>*Eriocheir sinensis* – Chinese mitten crab***** *Hemigrapsus penicillatus* – Asian shore crab******<br>*Neogobius melanostomus* – round goby***** or ******* |
| Recreational vessels | Contamination or fouling of boats********, fishing equipment | *Undaria pinnatifida* – Pacific kelp********<br>*Dreissena polymorpha* – zebra mussel******** |
| Aquaculture | Imports for culture*****, transport equipment******, unintentionally with untreated shell*******, host tissues******** | *Aeromonas salmonicida*- finfish disease********<br>*Antithamnion pectinatum* – red alga******* *Sargassum muticum* – brown alga*******<br>*Bonamia ostreae* – oyster disease********<br>*Anguillicola crassus* – eel nematode********<br>*Crepidula fornicata* – slipper limpet****** or *******<br>*Crassostrea gigas* – Pacific oyster***** |
| Fishing activities, new fisheries development, stock enhancement | Releases to the wild and spread*****, releases******, infested stock*******, equipment transfer, bait fishes, fish food organisms******** | *Paralithodes camtschaticus* – red king crab*****<br>*Acipenser spp.* - sturgeon*****<br>European and Pacific salmonids*****<br>*Gyrodactylus salaris* – salmonid ectoparasite*******<br>*Oncorhynchus mykiss* – rainbow trout******<br>*Hemimysis anomala* – opossum shrimp******** |
| Food processing | Untreated waste, disposal of imported produce, exports of tissue | Fish diseases, no confirmed examples |
| Live food trade | Escapes, releases*****, disposal of tissue or contaminated water | *Rapana venosa*- predatory whelk*****<br>*Homarus americanus* – American lobster***** |
| Aquarium trade | Escapes*****, releases******, disposal of tissue or contaminated water | *Caulerpa taxifolia* – mutant green alga***** or ******<br>*Elodea canadensis* – Canadian waterweed***** or ******<br>*Pterois volitans* - lionfish***** or ****** |
| Marine leisure tourism | Live bait*****, packaging material******, gear movement | *Fucus spiralis* – flat wrack ****** (to the Mediterranean)<br>nereid baitworms***** |
| Research studies | Releases, experiments *in situ******, disposal****** | *Mastocarpus stellatus* – red alga***** (on Helgoland)<br>*Bonnemaisonia hamifera* – red alga****** (on Helgoland) |
| Others | Opening of new water links, canals*****, movements of sediment, aggregates, shore management******, biocontrol (suggested and tested organisms, but not known to be released in the sea)******* | *Lophocladia lallemandii* – red alga*****<br>*Halophila stipulacea* – seagrass*****<br>*Rhopilema nomadica* – scyphozoan<br>*Brachiodontes pharaonis* – mytilid bivalve<br>*Mya arenaria* – soft shelled clam******<br>*Teredo navalis* – shipworm*****<br>*Spartina* spp. – cordgrasses******<br>(*Beroe* sp. – comb jelly for *Mnemiopsis*) *******<br>(Ascoglossan snails for *Caulerpa taxifolia*) ******* |

Appendix I. First records of non-indigenous species 1998–2002 world-wide including uncertain introductions. Entries are sorted by name of taxa (after National Reports and Abstracts in recent ICES WGITMO and ICES/IOC/IMO SGBOSV Meeting Reports).

| **Species (including higher taxon)** | **Year of first record** | **Region of first record** | **Population status** | **Impact or potential impact** | **Likely introducing vector** | **Native range** |
|---|---|---|---|---|---|---|
| *Acentrogobius* (cf) *pflaumi* Fish | 2002 | New Zealand | unknown | unknown | unknown | Japan and Korea |
| *Acipenser stellatus* Fish | 1999 | USA, Great Lakes | unknown | unknown | stocking | Ponto-Caspian |
| *Acrochaetium balticum* Red alga | 1998 | Netherlands | unknown | minimal | unknown | Baltic |
| *Agardhiella subulata* Red alga | 1998 | Netherlands | unknown | unknown | unknown | North America |
| *Alcyonidium sp.* Tentaculata | 2002 | USA | unknown | fouling? | unknown | |
| *Alexandrium catenella* Phytoplankton, Dinoflagellate | 1998 | Catalonia, Spain | established | potentially causing harmful algal blooms | ballast water | unknown |
| Ampharetidae Polychaete | 2001 | Gulf of Noto, Sicily, Italy | unknown | unknown | Lessepsian migrants or transferred via ballast water | Indian Ocean |
| *Anadara demiri* Bivalve | 2000 | Central Adriatic | unknown | unknown | hull fouling? | Indian Ocean |
| *Anguillicola crassus* Nematode | 1998 | Ireland | common locally | parasite | living imports, secondary introduction | Japan. NW Pacific |
| *Anguillicola crassus* Nematode | 2002 | Finland | rare | parasite | living imports, secondary introduction | Japan. NW Pacific |
| *Aplysia dactylomela* Gastropod | 2002 | Italy (near Sicily) | unknown | unknown | unknown | circum-tropical |
| *Asperococcus scaber* Brown alga | 1998 | Netherlands | unknown | minimal | unknown | Mediterranean |
| *Aurelia aurita* Jelly fish | 1998 | Caspian Sea | unknown | zooplankton predator | ballast water? | Cosmoploitan |
| *Batophora sp.* Green alga | 2002 | Italy (Ionian Sea) | unknown | unknown | unknown | |
| *Beroe cucumis* Comb jelly | 1998 | Black Sea | common | zooplankton predator | ballast water | North Atlantic |
| *Beroe ovata* Comb jelly | 1999 | Black Sea | unknown | zooplankton predator | ballast water | USA, Atlantic Coast |
| *Beroe ovata* Comb jelly | 2001 | Caspian Sea | unknown | zooplankton predator | ballast water | USA, Atlantic Coast |
| *Botryllus schlosseri* Tunicate | 2002 | Canada (Prince Edward Island) | unknown | fouling? | shipping? | Asia |
| *Bugula neritina* Bryozoan | 1999 | Belgium | occasional records | fouling | hull fouling | unknown |
| *Bugula simplex* Bryozoan | 2000 | Belgium | established? range extension | fouling | hull fouling | unknown |
| *Callinectes sapidus* | 2002 | Belgium | unknown | predation | unknown | |

| Species (including higher taxon) | Year of first record | Region of first record | Population status | Impact or potential impact | Likely introducing vector | Native range |
|---|---|---|---|---|---|---|
| Decapod | | (Oostende) | | | | |
| *Caprella mutica* Amphipod | 1998 | Belgium (buoys of Zeebrugge harbour) | established | unknown, clogging of gear? | ballast water, hull fouling? | Coastal waters of East Asia and Siberia |
| *Caprella mutica* Amphipod | 2000 | USA, Massachusetts and Rhode Island | unknown | unknown, clogging of gear? | ballast water, hull fouling? | Coastal waters of East Asia and Siberia |
| *Caprella mutica* Amphipod | 2000 | Norway | unknown | unknown, clogging of gear? | ballast water, hull fouling? | Coastal waters of East Asia and Siberia |
| *Caprella mutica* Amphipod | 2003 | West coast of Scotland | established | unknown, clogging of gear? | ballast water, hull fouling? | Coastal waters of East Asia and Siberia |
| *Carcinus maenas* Decapod | 1998 | Canada (Prince Edward Island) | established? | ecosystem engineer, predation | secondary introduction from Fundy Bay or range expansion | Atlantic Europe |
| *Carcinus maenas* Decapod | 1999 | Canada (West coast) | rare specimen (not established) | ecosystem engineer, predation | secondary introduction from US Pacific Coast or range expansion | Atlantic Europe |
| *Caulerpa taxifolia* Green alga | 1998 | Tunisia and Croatia | established | competition, habitat modification | aquarium trade, secondary introduction | Mediterranean Sea strain |
| *Caulerpa taxifolia* Green alga | 1999 | Australia (near Sidney) | unknown | unknown | range expansion | native strain |
| *Caulerpa taxifolia* Green alga | 2000 | USA, San Diego | eradication effort in progress | competition, habitat modification | unknown (aquarium trade?) | Mediterranean Sea strain |
| *Ceramium bisporum* Red alga | 2002 | Italy (Tuscany) | unknown | minimal | unknown | |
| *Cercopagis pengoi* Cladoceran | 1998 | USA, Great Lakes | established | competition, predation on zooplankton, clogging of fishing gear | ballast water | Ponto-Caspian Region |
| *Cercopagis pengoi* Cladoceran | 1999 | Poland | established | competition, predation on zooplankton, clogging of fishing gear | secondary introduction | Ponto-Caspian Region |
| *Charybdis japonica* Decapod | 2000 | New Zealand, Auckland region | established | nuisance to fishers, gets into nets and very aggressive to re- | unknown | Japan, Korea, Malaysia |

| Species (including higher taxon) | Year of first record | Region of first record | Population status | Impact or potential impact | Likely introducing vector | Native range |
|---|---|---|---|---|---|---|
| | | | | move | | |
| *Chattonella* cf. *verruculosa* Phytoplankton, Rhaphidophycean alga | 1998 | Norway, Sweden (North Kattegat, Skagerrak) | established | potentially causing harmful algal blooms | ballast water? | Pacific? |
| *Chrisallida fisheri* Gastropod | 2002 | Italy (Adriatic Sea) | unknown | unknown | range expansion? | Red Sea, eastern Mediterranean Sea |
| *Cochlodinium polykrikoides* Phytoplankton, Dinoflagellate | 1998 | Canada (West coast) | increasing | fish kills (salmon farming) | ballast water? | Korea? |
| *Codium fragile* subsp. *tomentosoides* Green alga | 1998 | Belgium | established, secondary introduction | habitat modification, fouling on shellfish and gear | oyster imports?, range expansion | Japan |
| *Corella eumyota* Sea squirt | 2002 | France (Brittany) | unknown | unknown | unknown | southern hemisphere |
| *Crepidula fornicata* Gastropod | 1999 | Norway | unknown | competition | oyster imports? | East coast of North America |
| *Daphnia lumholtzi* Cladoceran | 1999 | USA, Great Lakes | established | unknown | ballast water | Africa, India, Australia |
| *Dasya baillouviana* Red alga | 2002 | Germany | unknown | unknown | secondary spread, range expansion | Southern Europe (incl. Mediterranean Sea) and western Atlantic |
| *Dasysiphonia sp. (Heterosiphonia japonica)* Red alga | 1999 | Norway | established, spreading | overgrows other algae | shipping | unknown |
| *Desmarestia viridis* Brown alga | 1998 | Italy | unknown | overgrows other algae | unknown | unknown |
| *Didemnum* sp. Ascidian | 2000 | USA, Massachusetts and Rhode Island | unknown | fouling | unknown | Japan |
| *Dispio uncinata* Polychaete | 2001 | Gulf of Noto, Sicily, Italy | unknown | unknown | unknown | Atlantic, Pacific and Red Sea |
| *Dreissena polymorpha* Bivalve | 2000 | Canada (West Coast) | not found in the environment, but on boat hull trailered from Michigan | severe fouling | hull fouling | Ponto-Caspian |
| *Dreissena polymorpha* Bivalve | 2001 | Ebro River, Spain | unknown | severe fouling | hull fouling, ballast water? | Ponto-Caspian region |
| *Echinogammarus ischnus* Amphipod | 1998 | USA, Great Lakes | established | unknown | ballast water | Ponto-Caspian |

| Species (including higher taxon) | Year of first record | Region of first record | Population status | Impact or potential impact | Likely introducing vector | Native range |
|---|---|---|---|---|---|---|
| | | | | | | Region |
| *Ectocarpus siliculosus* Brown alga | 1998 | Venice, Italy | unknown | competition | fishing | unknown |
| *Epinephelus coiodes* Fish | 2001 | Italy | unknown | unknown | unknown | Red Sea |
| *Eriocheir sinensis* Decapod | 1998 | Ukraine | occasional records | predation, competition, habitat modification | ballast water, hull fouling | China |
| *Eriocheir sinensis* Decapod | 2001 | Spain (Guadalquivir Estuary) | established | predation, competition, habitat modification | ballast water, hull fouling | China |
| European Sheatfish Virus (ESV) | 2002 | Finland | unknown | fish disease | unknown | |
| *Favonogobius exquisites* Fish | 2001 | New Zealand | unknown | unknown | unknown | Australia |
| *Ficopomatus enigmaticus* Polychaete | 1998 | Ireland (Shannon Estuary) | established | small fouling impact | hull fouling, ballast water | Indo-Pacific |
| *Gymnodinium catenatum* Dinoflagellate | 2000 | Black Sea | unknown | harmful algal bloom, PSP | ballast water | unknown |
| *Gymnodinium catenatum* Phytoplankton, Dinoflagellate | 2000 | New Zealand | recorded during bloom | harmful algal bloom, PSP | ballast water? | unknown |
| *Haliplanella lineata* Anthozoan | 1998 | Belgium | established, range extension | fouling? | oyster imports? | Pacific |
| *Haminoea cyanomarginata* Gastropod | 2001 | Mediterranean Sea | unknown | unknown | Shipping, Lessepsian migrant? | Red Sea |
| *Haplosporidium nelsoni* (disease agent causing MSX disease) | 2002 | Canada (Nova Scotia) | First observation | Disease of oysters | Unknown. Shipping possible | Found along Atlantic coast of USA |
| *Haplosporidium costale* (disease agent causing SSO disease) | 2002 | Canada (Nova Scotia, Prince Edward Island, New Brunswick) | First observation | Disease of oysters | Unknown | Found along Atlantic coast of USA |
| *Hemigrapsus penicillatus* Decapod | 2000 | Netherlands | at one location, females carrying eggs about to hatch | competition | hull fouling, ballast water? | North-West Pacific |
| *Hemigrapsus sanguineus* Decapod | 1999 | Netherlands | occasional finding, not observed in 2000 | competition | hull fouling, ballast water? | West Pacific |
| *Hemimysis anomala* Mysid | 1999 | Belgium | established? range extension | unknown | unknown | Pontocaspian |
| *Homarus americanus* Decapod | 1999 | Norway | occasional findings | hybridisation, disease transfer | accidental release? | North America, Atlantic |

| Species (including higher taxon) | Year of first record | Region of first record | Population status | Impact or potential impact | Likely introducing vector | Native range |
|---|---|---|---|---|---|---|
| *Homarus americanus* *Decapod* | 2002 | Canada (Vancouver harbour) | unknown | hybridisation, disease transfer | accidental release? | North America, Atlantic |
| *Homarus americanus* Decapod | 2002 | France | unknown | hybridisation, disease transfer | accidental release? | North America, Atlantic |
| *Homarus cf. americanus* Decapod | 2000 | Sweden | unknown | hybridisation, disease transfer | accidental release? | North America, Atlantic |
| *Hypnea cornuta* Red alga | 2002 | Italy (Ionian Sea) | unknown | unknown | unknown | |
| *Hypophthalmichthys nobilis* Fish | 2002 | Estonia (Gulf of Riga) | unknown | unknown | secondary spread | China |
| *Ianiropsis* sp. Isopoda | 2000 | USA, Massachusetts and Rhode Island | unknown | unknown | unknown | unknown |
| *Isolda pulcella* Polychaete | 2001 | Gulf of Noto, Sicily, Italy | unknown | unknown | unknown | Atlantic and Indian Ocean |
| *Maeotias inexpectata* Cnidarian | 1999 | Estonia | occasional records | possibly predation on zooplankton | ballast water | Ponto-Caspian region |
| *Megabalanus coccopoma* Barnacle | 1998 | Belgium (on buoys) | occasional records | fouling | hull fouling | Pacific |
| *Megabalanus tintinnabulum* Barnacle | 1998 | Belgium (on buoys) | occasional records | fouling | hull fouling | cosmopolitan |
| *Micropogonias undulatus* Fish | 2002 | Belgium | unknown | unknown | unknown | NW Atlantic USA - Mexico |
| *Mnemiopsis leidyi* Comb jelly | 2001 | Caspian Sea | established? | predation | ballast water? | Western Atlantic |
| *Mytilopsis sallei* Bivalve | 1998 | Darwin, Australia | established population was eradicated by chemical treatment | fouling problems | hull fouling, pleasure boats | unknown |
| *Neogobius melanostomus* Fish | 2002 | Gulf of Riga | unknown | competition | secondary introduction? | Ponto-Caspian region |
| *Neogobius melanostomus* Fish | 2002 | Lithuania (Curonian Lagoon) | unknown | competition | secondary introduction? | Ponto-Caspian region |
| *Olisthodiscus luteus* Phytoplankton, Rhaphidophycean alga | 1999 | Norway | unknown | harmful to fish? | unknown | unknown |
| *Ophryotrocha japonica* *Polychaete* | 1999 | Italy (Ravenna harbour) | established, spreading | unknown | unknown | unknown |
| *Orchestia cavimana* Amphipod | 1999 | Estonia | established | unknown | secondary introduction | Northern Africa |
| *Paracorophium brisbanensis* Amphipod | 2002 | New Zealand (Tauranga Harbour) | unknown | unknown | shipping? | Australia |
| *Percnon gibbesi* | 1999 | Sicily, Italy | established | competition | fishing | Atlantic |

| Species (including higher taxon) | Year of first record | Region of first record | Population status | Impact or potential impact | Likely introducing vector | Native range |
|---|---|---|---|---|---|---|
| Decapod | | | | | | |
| *Perophora japonica* Sea squirt | 2001 | United Kingdom (Plymouth) | established, spreading | fouling? | unknown | JapanF |
| *Pfiesteria piscicida* Phytoplankton, dinoflagellate | 2000 | New Zealand | unknown | potential for fish kill | unknown | possibly native |
| *Pfiesteria piscicida* Phytoplankton, Dinoflagellate | 2002 | Oslo fjord, Norway | unknown | potential for fish kill | unknown | possibly native |
| *Phyllorhiza punctata* Cnidarian | 2000 | USA, Gulf of Mexico | established | unknown | unknown | Tropical Pacific |
| *Pisodonophis semicinctus* Fish | 1999 | Italy | unknown | unknown | unknown | Atlantic Ocean |
| *Polycerella emertoni* Gastropod | 2000 | Greece | unknown | unknown | Shipping | Atlantic Ocean |
| *Polysiphonia morrowii* Red alga | 1999 | Italy | unknown | unknown | unknown | unknown |
| *Proterorhinus marmoratus* Fish | 2002 | Netherlands (Waal River) | unknown | unknown | unknown | Ponto-Caspian |
| *Protodorvillea egena* Polychaete | 2001 | Gulf of Noto, Sicily, Italy | unknown | unknown | unknown | South Africa |
| *Punctaria tenuissima* Brown Alga | 1998 | Venice, Italy | established | competition | fishing | Atlantic Ocean |
| *Questa caudicirra* Polychaete | 2001 | Gulf of Noto, Sicily, Italy | unknown | unknown | range expansion, ballast water? | Atlantic and Pacific coasts on America |
| *Rapana venosa* Gastropod | 2000 | France (Atlantic coast) | occasional records | predation | hull fouling, ballast water, live oyster imports? | South East Asia |
| *Sagartia elegans* ssp. *roseacae* Anthozoan | 2000 | USA, Massachusetts | unknown | unknown | unknown | Europe |
| *Salmo salar* Atlantic salmon | 1998 | Canada (Vancouver Island) | occasional records | hybridization | aquaculture escapes? | Atlantic |
| *Sargassum muticum* Brown alga | 1999 | Belgium | established, first record of attached specimens | competition, habitat modification | oyster imports, secondary introduction | Japan |
| *Seriola rivoliana* Fish | 2002 | Italy | unknown | unknown | unknown | Atlantic |
| Spring Viraemia of *Carp* Virus | 2002 | United Kingdom | unknown | fish disease | Movement of live fish? | |
| *Stephanolepis* cf. *dispros* Fish | 1999 | Italy | unknown | unknown | Lessepsian migrant? | Red Sea, Indo-West-Pacific |
| *Styela clava* Tunicate | 1999 | Canada (Prince Edward Island) | unknown | fouling | mussel movements | Asia |
| *Tricellaria inopinata* Bryozoan | 1998 | Southern England | established | fouling, competition | hull fouling | Indo-Pacific |
| *Tricellaria inopinata* Bryozoan | 2000 | France, the Netherlands | established | fouling, competition | hull fouling | Indo-Pacific |
| *Tricellaria inopinata* | 2000 | Belgium | occasional | fouling, | fouling on | Indo- |

<table>
<tr><th>Species<br>(including higher taxon)</th><th>Year of first record</th><th>Region of first record</th><th>Population status</th><th>Impact or potential impact</th><th>Likely introducing vector</th><th>Native range</th></tr>
<tr><td>Bryozoan</td><td></td><td>(various ports)</td><td>records, range extension</td><td>competition</td><td>pleasure crafts</td><td>Pacific</td></tr>
<tr><td>Undaria pinnatifida<br>Brown alga</td><td>1998</td><td>Southern Italy</td><td>unknown</td><td rowspan="3">competition with other algae, problems with harvesting/ dredging of oysters, habitat modification</td><td>unknown</td><td>Japan</td></tr>
<tr><td>Undaria pinnatifida<br>Brown alga</td><td>1999</td><td>Netherlands (Sporophytes)</td><td>spreading fast since 2000</td><td>unknown</td><td>Japan</td></tr>
<tr><td>Undaria pinnatifida<br>Brown alga</td><td>2000</td><td>Belgium (Zeebrugge)</td><td>occasional record established?<br>range extension</td><td>fouling on pleasure crafts</td><td>Japan</td></tr>
<tr><td>Viral Haemorrhagic Septicaemia (VHS)<br>Virus</td><td>2000</td><td>Finland and Baltic Sea</td><td>first observation</td><td>disease of rainbow trout in fish farms</td><td>unknown. Herring stocks suspected.</td><td>unknown</td></tr>
</table>