See Also

IR Radiometers. Satellite Remote Sensing of Sea Surface Temperatures. Sensors for Mean Meteorology.

Further Reading

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EXOTIC SPECIES, INTRODUCTION OF

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doi:10.1006/rwos.2001.0053

Introduction

Exotic species, often referred to as alien, nonnative, nonindigenous, or introduced species, are those that occur in areas outside of their natural geographic range. Vagrant species, those that appear from time to time beyond their normal range, may often be confused with exotic species. Because marine science evolved following periods of human exploration and worldwide trade, there are species that may have become introduced, whose identity as either native or exotic species remains unclear. These are referred to as cryptogenic. The full contribution of exotic species among native assemblages remains, and probably will continue to remain unknown, but will add to the diversity of an area. There are no documented accounts of an introduced species resulting in the extinction of native species in marine habitats as has occurred in freshwater systems. Nevertheless, exotic species can result in habitat modifications that may reduce native species abundance and restructure communities. The greatest numbers of exotic species are inadvertently distributed by shipping either attached to the hull or carried in the large volumes of ballast water. Introductions may also be deliberate. The dependence for food in developing countries and expansion of luxury food products in the developed world, has led to increases in food production by cultivation of aquatic plants, invertebrates and fishes. Many native species do not perform as well as the desired features of some introduced organisms now in widespread cultivation, e.g., the Pacific oyster and Atlantic salmon. Unfortunately, production of species, such as these, has been modified by unwanted organisms that have been unintentionally introduced, and these can result in reduced production. Consequently great care is required when introductions are made. An accidentally introduced exotic species may remain unnoticed until such time as it either becomes very abundant or causes harmful effects, whereas larger organisms are usually observed sooner. Little is known about the movement of the smallest organisms, yet these must be in transit in very great numbers every day.

History

Species have been moved for several hundreds of years and some have almost certainly been carried with the earliest human expeditions. Evidence for early species movements is scant and can normally be determined only from hard remains, or from a well-understood biogeography of a taxonomic group. Although the soft-shell clam *Mya arenaria* was present in Northern Europe during the late Pliocene it disappeared during the last glacial period. In the thirteenth century their shells were found in north European middens; this was considered evidence of its introduction by returning Vikings from North America. It may have been used as fresh food during long sea journeys, as it is easily collected and perhaps was maintained in the bilges of their vessels. Certainly it became sufficiently abundant in the Baltic at about this time to be referred to by quaternary geologists as the Mya Sea. This species was introduced to the Black Sea in the 1960s and rapidly became abundant, resembling its sudden apparent expansion in the Baltic Sea.

The South American coral *Oculina patagonica* established in south-east Spain was almost certainly introduced on the hulls of sailing ships returning from South America during the sixteenth or seventeenth centuries. Indeed these sailing vessels probably carried a wide range of organisms attached to their hulls. Predictions of the most likely fouling species during these times are based on fouling studies on panels attached to reconstructed sailing ships. The hulls of wooden vessels were fouled with complex communities and excavated by boring organisms whose vacant galleries could provide refugia for a wide range of species. The drag imposed by the fouling and the structural damage caused by the boring organisms played its role in the outcome of naval engagements and in the duration of the working life of these vessels, particularly in tropical regions where boring activities and fouling communities evolve rapidly. The periods of stay by sailing ships in port could provide opportunities for creating new populations arising from drop-off or from reproduction, while remaining attached to the ship. Some vessels never returned but will have provided instant reefs by sinking, wreckage or abandonment. Some will have had a wide assemblage of exotic species. Wooden vessels are still in widespread use and continue to endure problems of drag and structural damage. Many preparations have been used for controlling this, with the most effective being developed over the last 150 years. Wooden vessels became sheathed with thin copper plates and were vulnerable only where these became displaced or damaged. Ironclad sailing vessels also evolved and so the normal hull life became prolonged because the damage was considerably reduced. The building of iron and then steel ships eliminated opportunities for boring and cryptic fauna. The hull surface now needed protection from rusting and from fouling. The development of protective and also toxic coatings then evolved. The incorporation of copper and other salts in these coatings considerably reduced fouling, and so drag, and protected the underlying surfaces from corrosion. Antifouling coatings, in particular, organotins, such as tributyltin compounds, have been very effective in fouling control, and in most cases this has allowed vessels to remain in operation for five years before reentering dry dock for servicing. Unfortunately tributyltin is a powerful biocide that is harmful to aquatic organisms in port regions and there are now plans to phase out its use on all ships. Its use during the 1980s and 1990s became restricted or banned in many countries on vessels $< 25\,\mathrm{m}$. New products are being developed with an emphasis on less toxic and nontoxic applications.

Most exotic species, used in mariculture or for fisheries development recently, followed the development of steam transportation. An early, and successful example, is the transport from the eastern coast of North America of striped bass *Morone saxatilis* fingerlings to California in the 1880s by train. Within ten years it became regularly sold in the fish markets of San Francisco. Attempts at culture were slow to evolve; most usually this was due to the lack of understanding of the full life cycle. Planktonic stages were especially misunderstood and pond systems for trapping oyster larvae, for example, were not fully successful until the larval biology became fully known. There were strong economic pressures to develop this knowledge at an early stage. The progressive understanding of behavior and the physical requirements of organisms, and development of algal, brine shrimp and other cultures and the use of synthetic materials, such as plastics, have enabled a rapid expansion of marine culture products ranging from pearls to chemical compounds to food.

The Vectors of Exotic Species

Normally organisms are deliberately introduced for culture, to create fisheries, or as ornamental species. Future introductions may be for the production of specific products used in pharmacy, as food additives, the management of diseases, for biological control, or for water quality management.

A primary inoculation is where the first population of an exotic becomes established in a new biogeographic region (**Figure 1**). A secondary inoculation arises by means of further established populations from the first population to other nearby regions by a wide range of activities and so the risk of spread is increased. In many cases these range extensions are inevitable, either because of human behavior and marketing patterns or because of their mode of life. For example, the tubeworm *Ficopomatus enigmaticus* can extensively foul brackish areas and once transported by shipping is easily carried to other estuaries by leisure craft or aquaculture activities, or both.

Species are introduced by a wide range of vectors that can include attachment to seaweeds used for packing material or releases of imported angling baits. The principal vectors are discussed below.

Aquaculture

Useful species have a high tolerance of handling, can endure a wide range of physical conditions, are easily induced to reproduce and have high survival throughout their production phase. Because of capital costs to retain stock in cages and/or trays, the species must, most usually, be cultivated at densities higher than occurs naturally. The species most likely to adapt to these conditions will be those living under variable conditions at high densities, such as mussels and oysters and some shoaling fishes. Species that do not naturally thrive under these conditions may require more attention and will tend to depend on speciality markets, such as some scallops, tuna, and grouper.

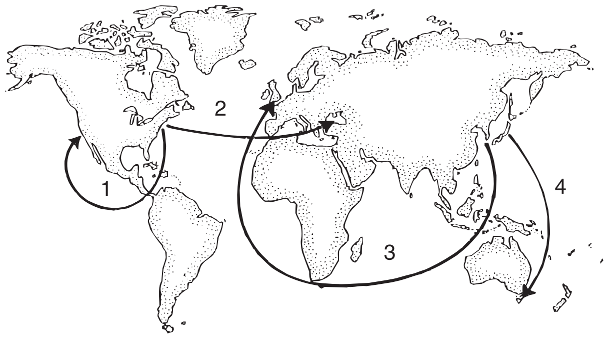
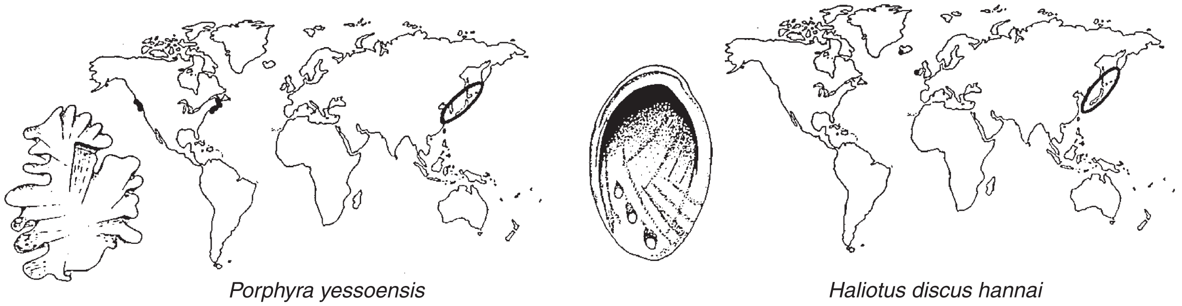


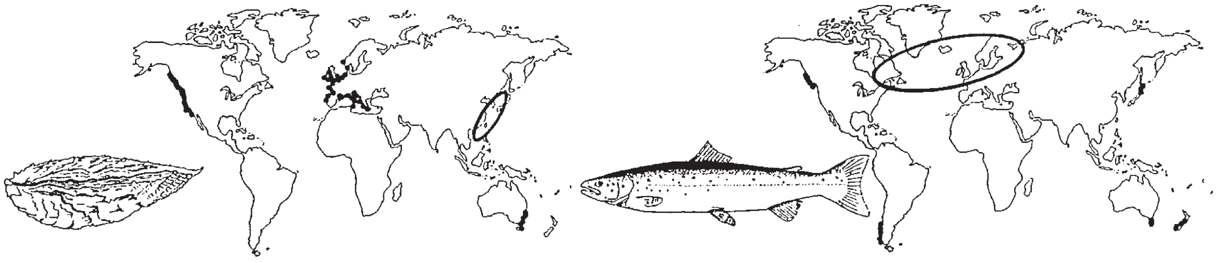
Figure 1 Some examples of primary inoculations: 1, *Carcinus maenas* the shore crab, a predator of molluscs (vector, probably ballast); 2, *Mnemiopsis leidyi* a comb jelly, planktonic predator of larval fishes and crustaceans (vector, ballast water); 3, *Styela clava* an Asian tunicate that causes trophic competition by filtering the water in docks and estuaries (vector, hull fouling); 4, *Asterias amurensis* an Asian sea star, avid predator of molluscs (vector, ballast water or hull fouling).

Molluscs High-value species that are tolerant to handling as well as a wide range of physical conditions are preferred. Some have a long shelf-life that allows for live sales. Molluscs, such as clams (e.g., *Venerupis semidecussata*, *Mercenaria mercenaria*), scallops (e.g., *Patinopecten yessoensis*, *Argopecten irradians*), oysters (e.g., *Ostrea edulis*, *Crassostrea gigas*) and abalone (e.g., *Haliotus discus hannai*, *Haliotus rufescens*) have been introduced for culture (**Figure 2**). Because oysters survive under cool damp conditions for several days, large consignments are easily transported long distances and so have become widely distributed since the advent of steam transportation. With the exception of the east coast of North America the Pacific oyster *Crassostrea gigas*, for example, is now widespread in the Northern Hemisphere and accounts for 80% of the world oyster production. Its wide tolerance of salinity, temperature, and turbid conditions and rapid growth make it a desirable candidate for culture. In many cases it has replaced the native oyster production where this declined, either because of overexploitation, diseases of former stocks or to develop new culture areas. However, pests, parasites, and diseases can be carried within the tissues, mantle cavity and both in and on the shells of molluscs when they are moved, and can compromise molluscan culture and wild fisheries and may also modify ecosystems. Some examples of pests moved with oysters include the slipper limpet *Crepidula fornicata* and the sea squirt *Styela clava* (**Figure 2**).

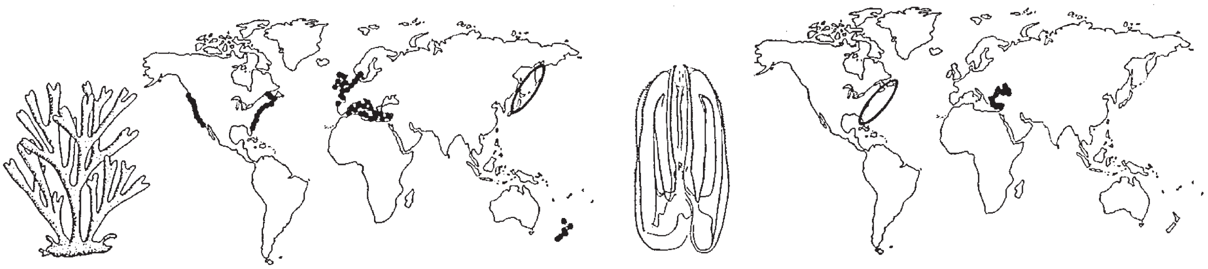
Oysters are responsible for many primary and secondary inoculations involving oyster pests, parasites, and diseases for several reasons. Sufficient numbers are often transferred and introduced, so that the associated species have a good opportunity of becoming established. Oysters do not bury and so can carry a wide range of attaching, cryptic and boring organisms. They may be re-laid to prolong their period of sale (this may include unapproved layings of imports), and because they are involved in an established trade over a wide area, further movements are likely.



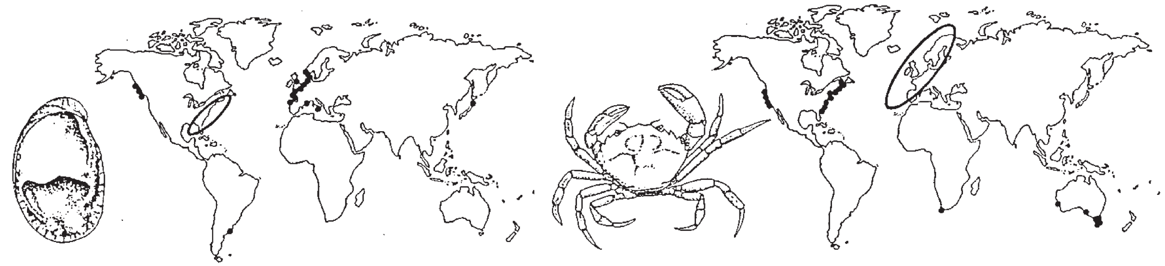
Porphyra yessoensis *Haliotus discus hannai*



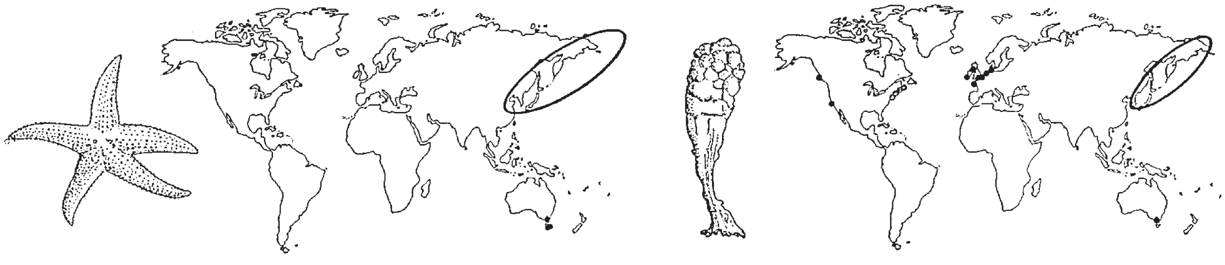
Crassostrea gigas *Salmo salar*



Codium fragile tomentosoides *Mnemiopsis leidyi*



Crepidula fornicata *Carcinus maenas*



Asterias amurensis *Styela clava*

Figure 2 Examples of exotic species. Useful species in culture: *Porphyra yessoensis* Japanese laver to 30 cm; *Haliotus discus hannai* Japanese abalone to 18 cm; *Crassostrea gigas* Pacific oyster to 16 cm; *Salmo salar* Atlantic salmon to 50 kg. Unwanted invasive species: *Codium fragile tomentosoides* a green alga to 45 cm; *Mnemiopsis leidyi* a comb jelly to 11 cm; *Crepidula fornicata* the slipper limpet to 5 cm; *Carcinus maenas* the shore or green crab to 9 cm; *Asterias amurensis* the Asian sea star to 25 cm; *Styela clava* an Asian tunicate to 18 cm. Open rings, native range; solid dots, established in culture or in the environment.

Crustaceans The worldwide expansion of penaeid shrimp culture has led to a series of unregulated movements resulting in serious declines of shrimp production caused by pathogenic viruses, bacteria, protozoa, and fungi. Viruses have caused the most serious mortalities of farmed shrimps broodstock and pose a deterrent to developing culture projects because of casual broodstock movements rather than using those certified as specific pathogen-free. One parvovirus is the infectious hypodermal and hematopoietic necrosis virus found in wild juvenile and adult prawn stages. This virus was endemic to Southeast Asia, Indonesia, and the Philippines and is now widespread at farms in the tropical regions of the Indo-Pacific and Americas. About six serious viruses of penaeid shrimp are known. Production may be limited unless disease-resistant stocks for viruses can be developed together with vaccination against bacterial diseases.

Fishes Of the thousands of fish species only a small number generate a market price high enough to cover production costs. Such fish need to have a high flesh to body weight and high acceptance. While in culture they should be tolerant of handling and to the wide range of seasonal and diurnal conditions and should not be competitive. The North Atlantic salmon *Salmo salar* is one of very few exotics in culture in both hemispheres in the cool to warm temperate climates of North America, Japan, Chile, New Zealand, and Tasmania (**Figure 2**). Fertilized eggs of improved stock are in constant movement between these countries. However, various diseases such as infectious salmon anemia may limit the extent of future movements.

It is likely that intensive shore culture facilities for marine species will become more common as the physiological and behavioral requirements of promising species become better understood. For example in Japan, the bastard sole *Paralichthys olivaceus* is extensively cultivated in shore tanks (and has been introduced to Hawaii) and the sole *Solea senegalensis* in managed lagoons in Portugal. Cultivation under these circumstances is likely to lead to better control of pests, parasites and diseases, whereas cage culture under more exposed conditions offshore may lead to unexpected mortalities from siphonophores, medusae, algal blooms, and epizootic infestations from parasites, some perhaps introduced.

Shipping

Much of the world trade depends on shipping; the scale and magnitude of these vessels is seldom appreciated. To travel safely they must either carry cargo or water (as ballast) so that the vessel is correctly immersed to provide more responsive steerage, by allowing better propulsion (without cavitation), rudder bite, and greater stability. The amount of ballast water carried can amount of 30% or more of the overall weight of the ship. Ships also have a large immersed surface area to which organisms attach and result in increased drag that results in higher fuel costs. Nevertheless, despite the best efforts of management, ships carry a great diversity and large numbers of species throughout the world. Unfortunately the risk of introducing further species increases because more ships are in transit and many travel faster than before and operate a wide trading network with new evolving commercial links.

Ships' ballast water Ballast water is held on board in specially constructed tanks used only for holding water. The design and size of these tanks depends on the type and size of vessel (**Figure 3**). In some

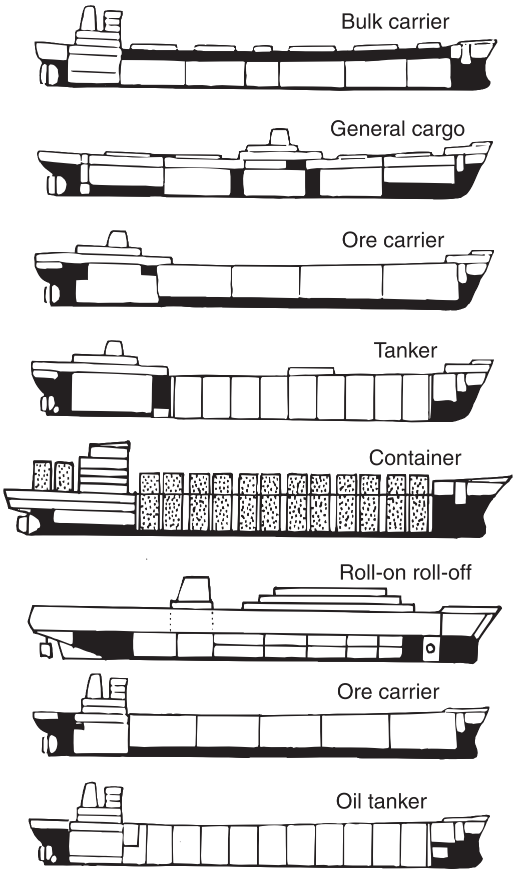


Figure 3 Ballast tanks in ships are dedicated for carrying water for the necessary stabilization of ships. The ballast tanks are outlined in black and show the variation of ballast tank position and size in relation to the type of vessel. Wing tanks (ballast tanks situated along the sides) are not shown in this diagram.

vessels that carry bulk products a hold may be flooded with ballast water, but these vessels will also have ballast tanks. Ballast tanks are designed to add structural support to the ship, and will have access ladders and perforated platforms and baffles to reduce water slopping, making them complex engineering structures. All vessels carry ballast for trim; some of this may be permanent ballast (in which case it is not exchanged at any time) or it may be 'all' released (there is always a small portion of water that remains) before taking on cargo. There are several tanks on a ship, and because there may be partial discharges of water, the water within nonpermanent ballast tanks can contain a mixture of water from different ports.

Pumping large volumes of water when ballasting is time consuming and costly. Should a vessel be ballasted incorrectly the structural forces produced could compromise the hull. Ships have broken-up in port because of incorrect deballasting procedures in relation to the loading/unloading of cargo. For these reasons there are special guidelines for the correct ballasting of tanks in relation to cargo load and weather conditions.

Ballasting of water normally occurs close to a port, often in an estuary or shallow harbor; this can include turbid water, sewage discharges, and pollutants. The particulates settle inside the tanks to form sediment accumulations that may be 30 cm in depth. Worms, crustaceans, molluscs, protozoa and the resting stages of dinoflagellates, as well as other species can live in these muds. Resting stages may remain dormant for months or years before 'hatching'. Ballast sediments and biota are thus an important component of ballast water uptake adding to the diversity of carried organisms released in new regions through larval releases or from sediment resuspension following journeys with strong winds.

Fresh ballast water normally includes a wide range of different animal and plant groups. However, most of these expire over time, so that on long journeys fewer species survive, and those that do survive, do so in reduced numbers. Because ballast water is held in darkness the contained phytoplankton are unable to photosynthesize. Animals, dependent on these microscopic plants, during vulnerable stages in their development may expire because of insufficient food, unless the tanks are frequently flushed. Scavengers and predators may have better opportunities to survive. To date, observations of organisms surviving in ballast water are incomplete because of the inability or poor efficiency in obtaining adequate samples. Some ballast tanks may only be sampled through a narrow sounding pipe to provide a limited sample of the less active species from one region near the tank floor. Nevertheless all studies to-date indicate a wide range of organisms survive ballast transport ranging from bacteria to adult fishes. The invasions of the comb jelly *Mnemiopsis leidyi* (from the eastern coast of North America to the Black Sea), the Asian sea-star *Asterias amurensis* (from Japan to Tasmania) and the shore crab *Carcinus maenas* (to Australia and South Africa from Europe) probably arose from ballast-water transport (**Figure 2**).

Ships' hulls Ships are dry-docked for inspection, structural repairs and for re-coating the hull with antifouling about every three to five years. The interdocking time varies according to the type of vessel and its age. While in dry dock the ship is supported on wooden blocks. The areas beneath the blocks, which may be $>100\,\mathrm{m}^2$, are not painted and here fouling may freely develop once the ship is returned to service. The hull is cleaned by shot blasting or using powerful water jets, then re-coated. Many coatings have a toxic surface that over time becomes leached or worn from the hull. Unfortunately some toxic compounds, once released, have caused unexpected and unwanted environmental effects. The use of organotin paints such as tributyltin effectively reduced hull fouling since the 1970s but have caused sexual distortion in snails and reproductive and respiratory impairment in other taxa. Vessels trading in tropical waters have a higher rate of loss of the active coat and on these vessels a greater fouling can occur at an earlier time.

Most organisms carried on ships' hulls are not harmful but may act as the potential carriers of a wide range of pests, parasites, and diseases. Oysters and mussels frequently attach to hulls and may transmit their diseases to aquaculture sites in the vicinity of shipping ports. Small numbers of disease organisms, once released, may be sufficient to become established if a suitable host is found. Should the host be a cultivated species it may rapidly spread to other areas in the course of normal trade before the disease becomes recognized.

Many marine organisms spawn profusely in response to sea temperature changes. Spawning could arise following entry of a ship to a port, during unloading of cargo or ballast in stratified water or from diurnal temperature changes. A ship may turn around in port in a few hours to leave behind larvae that may ultimately settle to form a new population.

Vessels moored for long periods normally acquire a dense and complex fouling community that includes barnacles. Once of sufficient size these can provide toxic-free surfaces for further attachment, in particular for other barnacles (e.g., the Australasian barnacle *Elminius modestus*, present in many Northern European ports) molluscs, hydroids, bryozoa and tunicates (e.g., the Asian sea-squirt *Styela clava*, widely distributed in North America and northern Europe (**Figure 2**)). Vacant shells of barnacles and oysters cemented to the hull can provide shelter for mobile species such as crustaceans and nematodes, and some mobile species such as anemones and flatworms can attach directly to the hull.

Small vessels such as yachts and motorboats also undertake long journeys and may become fouled and thereby extend the range of attached biota. Normally small vessels would be involved in secondary inoculations from port regions to small inlets and lagoons (areas where shipping does not normally have access) and spread species such as the barnacle *Balanus improvisus* to other brackish areas.

Aquarium Species

Aquarium releases seldom become established in the sea whereas in fresh water this is common. The attractive green feather-like alga *Caulerpa taxifolia* was probably released into the Mediterranean Sea from an aquarium in Monaco and by 2000 was present on the French Mediterranean coast, Italy, the Balearic Islands, and the Adriatic Sea. It has a 'root' system that grows over rock, gravel or sand to form extensive meadows in shallows and may occur to depths of 80 m. It excludes seagrasses and most encrusting fauna and so changes community structure. Although it possesses mild toxins that deter some grazing invertebrates, several fishes will browse on it. This invasive plant is still expanding its range and may extend throughout much of the Mediterranean coastline and perhaps to some Atlantic coasts.

Trade Agreements and Guaranteed Product Production

Trade agreements do not normally take account of the biogeographical regions among trading partners, so introductions of unwanted species are almost inevitable. Often, a population of a harmful species is further spread by trading and thereby has the ability to compromise the production of useful species. Trade in the same species from regions where quarantine was not undertaken may compromise cultured exotic species introduced through the expensive quarantine process which are disease free. The risk of movement of serious diseases from one country to another is usually recognized; whereas pests are not normally regulated by veterinary regulations, and so are more likely to become freely distributed.

Harvesting of cultured species may be prohibited in areas following the occurrence of toxic producing phytoplankton. Toxins naturally occur in certain phytoplankton species (most usually dinoflagellates) and are filtered by the mollusc, and these become concentrated within molluscan tissues, with some organs storing greater amounts. Some of these toxins may subsequently accumulate within the tissues of molluscan-feeding crustaceans, such as crabs. If contaminated shellfish is consumed by humans, symptoms such as diahrritic shellfish poisoning, paralytic shellfish poisoning, neurological shellfish poisoning, and amnesic shellfish poisoning, may occur. These conditions are caused by different toxins, and new toxins continue to be described. As they all have different breakdown rates in the shellfish tissues there are varying periods when the products are prohibited from sale. There are monitoring programs for evaluating the levels of these contaminants in most countries. In occasions when harvesting of molluscs is suspended, consignments from abroad may be required in order to maintain production levels. If these consignments arrive in poor condition, or be unsuitable because of heavy fouling, they may be relaid or dumped in the sea or on the shore. Such actions can extend the range of unwanted exotic species.

The Increasing Emergence of Unexplained Events

Natural eruptions of endemic or introduced pathogens may be responsible for chronic mortalities or unwanted phenomena. The die-off of the sea urchin *Diadema antillarum* in the western Atlantic may be due to a virus. The unsightly fibropapillomae of the green turtle *Chelonia mydas*, previously known only in the Atlantic oceans, are now found in the Indo-Pacific, where it was previously unknown. The great mortalities of pilchard *Sardinops sagax neopilchardus* off Australia in the 1990s and mortalities of the bay scallop *Argopecten irradians* in China may be a result of introduced microorganisms. In the case of introduced culture species mortalities may ensue from a lack of resistance to local pathogens. *Bonomia ostreae*, a protozoan parasite in the blood of some oyster species, was unknown until found in the European flat oyster *Ostrea edulis* following its importation to France from the American Pacific coast to where it had been introduced several years earlier. Very often harmful species first become noticed when aquaculture species are cultivated at high densities, for example, the rhizocephalan-like *Pectinophilus inornata* found in the Japanese scallop *Patinopecten yessoensis* in Japan waters. Often careful studies of native biota will reveal new species to science, such as the generally harmful protozoans, *Perkensis* species found in clams, oysters, and scallops that can be transmitted to each generation by sticking to eggs. Pests, parasites, and diseases in living products used in trade are likely sources of transmission. However, viruses or resting stages of some species may also be transmitted in frozen and dried products.

Vulnerable Regions

Some areas favor exotic species with opportunities for establishment and so enable their subsequent spread to nearby regions. These areas are normally shipping ports within partly enclosed harbors with low tidal amplitudes and/or with good water retention. Although it may be possible to predict which ports are the main sites for primary introductions the factors involved are not clearly understood and information on the exotic species component is presently only available for a small number of ports. Nevertheless, ports with many exotic species are areas where further exotics will be found. Such regions are likely sites for introductions because ships carry a very large number of a wide range of species from different taxonomic groups. Port regions with known concentrations of exotic species include San Francisco Bay, Prince William Sound, Chesapeake Bay, Port Phillip Bay, Derwent Estuary, Brest Harbor, Cork Harbor, The Solent (**Figure 4**). In the Baltic Sea there are several ports that receive ballast water via canals from the Black and Caspian seas as well as arising from direct overseas trade. The component of the exotic species biomass in this region is high. In some areas such as the Curonian Lagoon, Lithuania, exotic species comprise the main biomass. The Black Sea has similar conditions to the Baltic Sea where established species have modified the economy of the region. The effects vary from dying clams creating a stench on tourist beaches, poor recruitment of pilchard and anchovy due to high predation of their larvae by a comb jelly *Mnemiopsis leidyi*, to the development of an industry based on harvesting and export of the large predatory snail *Rapana thompsoniana*. The Mediterranean Sea has increasing numbers of unintended introductions arising from trade, mainly by shipping, and from natural range extensions from the Red Sea via the Suez Canal (**Figure 4**).

The majority of exotic species are found in temperate regions of the world. Whether this is a surmise because of a lack of a full understanding, or whether this is due to a real effect is not known. It may be that tropical species are well dispersed because of natural vectors and that further transmission by shipping is of little consequence to the overall biota present. However, it may be that there is such a daunting diversity of species present in tropical regions, with many still to be described, that it is difficult to grasp the complexity and so to be able to understand exotic species movements in this zone. In the contrasting colder climates, the likely slower development of species may inhibit an introduction from becoming successful. Temperate ports on either side of the same ocean appear to share several species in common, whereas species from temperate regions from other hemispheres or oceans are less common. This suggests that species that do not undergo undue physiological stresses and present in shorter voyages have a greater probability of becoming established.

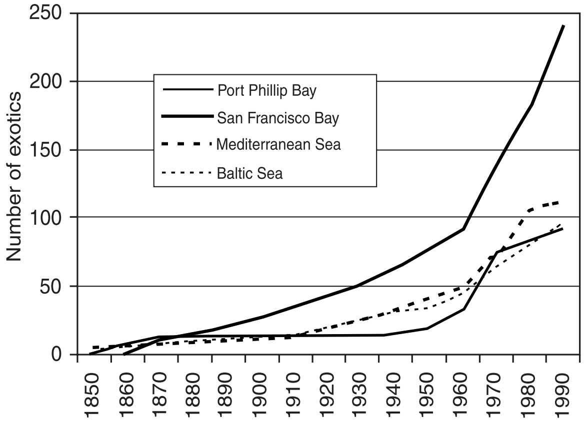


Figure 4 Accumulative numbers of known exotic species in vulnerable areas. The real numbers of exotic species are probably much greater than shown.

For many species, although opportunities for their dispersal in the past may have taken place, their successful establishment has not succeeded. If an inoculation is to succeed it must pass through a series of challenges. On most occasions the populations are unable to be maintained at the point of release in sufficient numbers capable of establishment, even though some may survive. Any sightings of exotic individuals may often pose as a warning that this same species, under different conditions, could become established. The increasing volume and speed of shipping, and of air transport (in the case of foods for human consumption and aquarium species) will provide new opportunities. A successful transfer for a species will depend on: appropriate season, life history stage in transit, survival time without food, re-immersion, temperature and salinity tolerance, rate of dispersal at the point of release, and many unknown factors.

Mode of Life

The dispersal of a species from its point of introduction, and the speed at which it expands its range will depend on the behavior of its life history stages. Species with very short or no planktonic stages, and with limited mobility, are likely to remain close to the site of introduction, unless carried elsewhere by other means. Tunicates have short larval stages and a sessile adult life and so are normally confined to inlets. Buoyant species, which include seaweeds with air bladders, may be carried by combinations of wind and current and become rapidly dispersed in a directional pattern ruled by the principal vectors. Most species have dispersal potentials that lie between these extremes and some, such as active crustaceans and fishes may become distributed over a wide range as a result of their own activities. The attempt to establish pink salmon *Onchorhynchus gorbuscha* on the northern coast of Russia resulted in its capture as far south as Ireland. A recent and successful introduction of the king crab *Paralithodes camtschaticus* to the Barents Sea, has resulted in its rapid expansion southwards to Norway. Its range expansion is aided by its planktonic larval stages carried by currents and an ability to travel great distances by walking. With a better knowledge of the behavior of organisms during their life-history stages and of the prominent physical vectors from a point of release, theoretical models of dispersal should be possible. Such models would be valuable tools for port management of ships' ballast water and for evaluating relative risk scenarios of transmitting or receiving exotic species.

The reproductive capability of a species is also important. Those that release broods that are confined to the benthos such as the Chinese hat snail *Calyptraea chinensis*, are likely to remain in one region, and once mature will have a good opportunity for effective reproduction. Species such as *Littorina saxatilis* have the theoretical capability of establishing themselves from the release of a single female by producing miniature crawlers without a planktonic life stage. In contrast, species with long planktonic stages requiring stable conditions are unlikely to succeed. It is doubtful whether spiny lobsters will become inadvertently transferred in ballast water.

Impacts on Society

Exotic species have a wide range of effects, some provide economic opportunities whereas others will impose unwanted consequences that can result in serious financial loss and unemployment. In agriculture the main species utilized in temperate environments for food production were introduced and have taken some thousands of years to develop. In the marine environment the cultivation of species is relatively new and comparatively few exotic species are utilized. This suggests that in future years an assemblage of exotic species, some presently in cultivation, and others yet to be developed, will form a basis for significant food production. Few exotics in marine cultivation form the basis for subsistence, whereas this is common in freshwater systems. The cultivation of marine species is normally for specialist markets where food quality is an important criterion. Expanding ranges of harmful exotics could erode opportunities by impairing the quality in some way or interfering with production targets.

Unfortunately, many shipping port regions are in areas where conditions for cultivation are suitable, either for the practical reason of lower capital costs for management, because of the ease of operation and/or shelter, the conditions favor optimal growth and/or the nearby market. The proximity of shipping to aquaculture activities poses the unquantifiable threat that some imported organisms will impair survival, compromise growth, or render a product unmarketable.

Diseases of organisms and humans are spreading throughout the world. In the marine environment a large bulk of biota is in transit in ballast water. Ballasting by ships in port may result in loading untreated discharges of human sewage containing bacteria and viruses that may have consequences for human health once discharged elsewhere. In 1991, at the time of the South American cholera epidemic, caused by *Vibrio cholerae*, oysters and fish in Mobile Bay, Alabama were found with the same strain of this infectious bacterium. Ballast water was considered as a possible source of this event. Subsequently five of 19 ships sampled in Gulf of Mexico ports arriving from Latin America were found with this same strain. The epidemic in South America may have been originally sourced from Asia, and may also have been transmitted by ships.

Of grave concern are the discovery of new algal toxins and the apparent spread of amnesic shellfish poisoning, diahrritic shellfish poisoning, paralytic shellfish poisoning, and neurological shellfish poisoning throughout the world. The associated algae can form dense blooms that, with onshore winds, can form aerosols that may be carried ashore to influence human health. The expansion of these events may be due to poor local knowledge of previous events or to a real expansion of the phenomena. There is good evidence that ballast water may be distributing some of these harmful species.

Some of the 'bloom forming' species, such as the naked dinoflagellate *Gyrodinium aureolum*, are almost certainly introduced and cause sufficiently dense blooms to impair respiration in fishes by congestion of the gills, and can also purge the water column of many zooplankton species and cause mortalities of the benthos.

Some introduced invertebrates may act as an intermediate host for human and livestock diseases. The Chinese mitten crab *Eriochir sinensis*, apart from being a nuisance species, acts as the second intermediate host for the lung fluke *Paragonimus westermanii*. The first intermediate stage appears in snails. The Chinese mitten crab has been introduced to the Mediterranean and Black Seas, North America, and Northern Europe. Should the lung fluke be introduced the ability for it to become established now exists where it may cause health problems for mammals, including humans.

Management of Exotic Species

Aquaculture

There is an expanding interest in aquaculture as an industry to provide employment, revenue, and food. Already several species in production worldwide contribute to these aims. However, any introduction may be responsible for unwanted and harmful introductions of pests, parasites, and diseases. Those involved in future species introductions must consider the International Council for the Exploration of the Sea's (ICES) Code of Practice on introductions and transfers of marine organisms (**Table 1**). This code takes into account precautionary measures so that unwanted species are unlikely to become unintentionally released. The code also includes provisions for the release of genetically modified organisms (GMOs). These are treated in the same way as if they are exotic species introductions intended for culture. The code is updated from time to time in the light of recent scientific findings. Should this code be ignored the involved parties could be accused of acting inappropriately. By using the code, introductions may take several years before significant production can be achieved. This is because the original broodstock are not released to the wild, only a generation arising from them that is disease-free. This generation must be examined closely for ecological interactions before the species can be freely cultivated. In developing countries it is important that all reasonable precautions are taken to reduce obvious risks. It has been shown historically that direct introductions, even when some precautions have been taken, may lead to problems that can compromise the intended industry or influence other industries, activities, and the environment.

Experience has shown that good water quality, moderate stocking densities and meteorological and oceanographic conditions, within the normal limits of species, or the culture system, are of importance for successful cultivation. Maintenance of production in deteriorating conditions, following high sedimentation or pollution, can rarely be achieved by using other introduced species.

Exotic species generally used in aquaculture may not always prove to be beneficial. Although the Pacific oyster *Crassostrea gigas* is generally accepted as a useful species, in some parts of the Adriatic Sea it fouls metal ladders, rocks, and stones causing cuts to bathers in a region where revenue from tourism exceeds that of aquaculture. This same species is unwelcome in New South Wales because of competition with the Sydney rock oyster *Saccostrea commercialis*, but attempts to eliminate the Pacific oyster have been unsuccessful because it is very abundant and successfully competes with the native species.

Table 1 Main features of the ICES Code of Practice

- Conduct a desk evaluation well in advance of the introduction, to include:
  - previous known introductions of the species elsewhere;
  - review the known diseases, parasites and pests in the native environment;
  - understand its physical tolerances and ecological interactions in its native environment;
  - develop a knowledge of its genetics;

  provide a justification for the introduction.
- Determine the likely consequences of the introduction and undertake a hazard assessment.
- Introduce the organisms to a secure quarantine facility and treat all wastewater and waste materials effectively.
- Cultivate F1 generation in isolation in quarantine and destroy broodstock.
- Disease-free filial generation may be used in a limited pilot project with a contingency withdrawal plan.
- Development of the species for culture.

At all stages the advice of the ICES Working Group on the Introductions and Transfers of Marine Organisms is sought. Organisms with deliberately modified heritable traits, such as genetically modified native organisms, are considered as exotic species and are required to follow the ICES Code of Practice.

Ecomorphology Organisms can respond to changes in their environment by adapting specific characteristics that provide them with advantage. Sometimes these changes can be noted within a single lifetime, but more usually this takes place over many generations and may ultimately lead to species separation. When considering a species for introduction its morphology may provide clues as to whether it will compete with native species or whether its feeding capabilities or range is likely to be distinct and separate, overlapping or coinciding. However, it is not possible to evaluate the overall impacts of a species for introduction in advance of the introduction using morphological features alone.

Ships Ballast Water

Sterilization techniques of ballast water are difficult, most ideas are not cost-effective or practical, either because the great volumes of water require large amounts of chemicals or of the added corrosion to tanks or because the treated water, when discharged, has now become an environmental hazard. Reballasting at sea is the current requirement by the International Maritime Organization. Ballast tanks can not be completely drained and so three exchanges are required to remove 99% of the original ballast water. However, it is not possible for ships to reballast in midocean in every case. Ships that deballast in bad weather can be structurally compromised; this could lead to the loss of the vessel and its crew. A further method under consideration that does not compromise the safety of the vessel is the continuous flushing of water while in passage. Several further techniques have either been considered, researched or are in development (**Table 2**). Exotic species management in ballast water is likely to become a major research area into the twenty-first century.

Ships' Hulls

The use of the toxic yet effective organotins as antifouling agents is likely to become phased out over the first decade of the twenty-first century. Replacement coatings will need to be as, or more effective, if ships are going to manage fuel costs at current levels. Nontoxic coatings or paint coatings containing deterrents to setting organisms are likely to evolve, rather that coatings containing biocides. However, the effectiveness of these coatings will need to take account of normal interdocking times for ships. In some cases robots may be required for reactivating coat surfaces and removing undue fouling. Locations and/or special management procedures where these activities take place need to be carefully planned to avoid establishment of species from the 'rain' of detritus from cleaning operations.

Biocontrol

Biological control is the release of an organism that will consume or attack a pest species resulting in a population decrease to a level where it is no longer considered a pest. Although there are many effective examples of biological control in terrestrial systems this has not been practiced in the marine environment using exotic species. However, biological control has been considered in a number of cases.

1. The green alga, *Caulerpa taxifolia* has become invasive in the Mediterranean following its likely release from an aquarium; the species presently ranges from the Adriatic Sea to the Balearic Islands and forms meadows over rock, gravels and sands displacing many local communities. The introduction of a Caribbean saccoglossan sea slug that does not have a planktonic stage and avidly feeds on this alga has been under consideration for release. These sea slugs have been cultured in southern France, but at the time of writing their release to the wild has not been approved.
2. The comb jelly *Mnemiopsis leidyi* became abundant in the Black Sea in the mid 1980s. It readily feeds on larval fishes and stocks of anchovy and pilchard declined in concert with its expansion. The introduction of either cod *Gadus morhua*

Table 2 Treatment measures of ballast water

- *Disinfection:* tank wall coatings, biocides, ozone, raised temperature, electrical charges and microwaves, deoxygenation, filtration, ultraviolet light, ultrasonicification, mechanical agitation, exchanges with different salinity.
- *By management:* special shore facilities or lighters for discharges, provision of clean water (fresh water) by port authorities, no ballasting when organisms are abundant (i.e., during algal blooms, at night) or of turbid water (i.e., during dredging, in shallows), removal of sediments and disposal ashore. Specific port management plans taking account of local port conditions and seasonality of the port as a donor area.
- *Passive effects:* increase time to deballasting, long voyages, reballast at sea.

from the Baltic Sea or chum salmon *Onchorhynchus gorbusha* from North America were considered for introduction. Also considered for control was the related predatory comb jelly *Beroe*. However, a further predatory comb jelly *Beroe* became introduced to the Black Sea, possibly in ballast water, and the *M. leidyi* abundance has since declined.

3. The European green crab *Carcinus maenas* has been introduced to South Africa, Western Australia and Tasmania as well as to the Pacific and Atlantic coasts of North America. In Tasmania it avidly feeds on shellfish in culture and on wild molluscs. Here the introduction of a rhizocephalan *Sacculina carcini*, which is commonly found within the crab's home range and reduces reproductive output in populations, was considered. However, because there was evidence that this parasite was not host specific and may infect other crab species, the project did not proceed.
4. The North Pacific seastar *Asterias amurensis* has become abundant in eastern Tasmania and may have been introduced there either as a result of ships' fouling or ballast water releases taken from Japan. This species feeds on a wide range of benthic organisms including cultured shellfish. A Japanese cilliate *Orchitophyra* sp. that castrates its host is under study.

Exotic species used in biocontrol need to be species specific. Generalist predators, parasites and diseases should be avoided. Complete eradication of a pest species may not be possible or cost-effective except under very special circumstances. In order to evaluate the potential input of the control organism a good knowledge of the biological system is needed in order to avoid predictable effects that may result in a cascade of changes through the trophic system. Native equivalent species of the biological control organism should be sought for first when introducing a biocontrol species. The ICES Code of Practice should be considered and an external panel of consultants should be involved in all discussions. In some cases control may be possible by developing a fishery for the pest species as has happened in Turkey following the introduction of the rapa whelk *Rapana venosa* to the Black Sea.

Conclusions

Exotic species are an important component of human economic affairs and when used in culture or for sport fisheries etc., require careful management at the time of introduction. They should pass through a quarantine procedure to reduce transmission of any pests, parasites, and diseases. Aquaculture activities, where practicable should be sited away from port regions because there is a risk that shipping may introduce unwanted organisms that may compromise aquaculture production.

Movements of aquarium species also need careful attention and more stringent controls on their movements. Transported fish are normally stressed and many of these have been shown to carry pathogenic bacteria and parasites. There is a risk that a serious disease of fishes, epizootic ulcerative syndrome, which causes considerable losses in aquaculture, could be transmitted to outside of the Indo-Pacific region by the aquarium trade.

Trading networks need to consider ways in which organisms transferred alive or organisms and disease agents that may be transferred in or with products, are not released to the wild in areas that lie beyond their normal range.

More effective and less toxic antifouling agents are needed to replace the effective but highly toxic organotin paint applications on ships. This may lead to less toxic port regions which in turn may now become more suitable for invasive species to become established. Despite widespread usage of new antifouling agents on ships' hulls, unpainted or worn or damaged regions of the hull are areas where fouling organisms will continue to colonize.

Ships' ballast water and its sediments pose a serious threat of transmitting harmful organisms. Future designs of ballast tanks that facilitate complete exchanges, with reduced sediment loading and with options for sterilization, could greatly reduce the volume of distributed biota.

Exotic species are becoming established at an apparently increasing rate. Some of these will have serious implications for human health, industry and the environment.

See also

Anti-fouling Materials. Diversity of Marine Species. International Organizations. Large Marine Ecosystems. Mariculture of Aquarium Fishes. Pelagic Biogeography. Phytoplankton Blooms.

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EXPENDABLE SENSORS

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doi:10.1006/rwos.2001.0331

Introduction

Expendable sensors represent an approach to ocean measurement in which some degree of measurement precision may be sacrificed in the interests of lower costs and operational expediency. Two requirements of physical oceanography have driven their development: the problem of achieving adequate spatial sampling of the ocean on timescales commensurate with temporal variability; and the requirement by naval forces for under-way assessments of sonar propagation conditions – the first (and still the dominant) application of *operational oceanography*.

The naval requirement first arose in the area of physical oceanography, in the need to know the depth variation of water temperature. In practice, of the three parameters that determine sound speed – temperature, salinity, and pressure – it is temperature that predominates. Pressure is normally deducible with adequate precision from depth, and salinity is normally sufficiently constant to be neglected or simply 'modeled' using an archived (T,S) relation. However, salinity may be important near ice, in fiords, and estuaries, and in regions of freshwater influence (ROFIs). The naval requirement is normally for the vertical sound speed profile, and it is the *shape* of this profile that is important, rather than its mean value.

The expendable measurement facility was quickly taken up by the civilian oceanographic community. It gives a means of tackling the problem of how to make synoptic ocean structure measurements where features are likely to move significantly during a survey. A survey with spatial scales small enough to capture interesting features is seriously degraded by their movement and development. Particularly at mid- to high latitudes, a survey using conventional profiling instruments – such as the conductivity-temperature-depth (CTD) probe – cannot be carried out in a time that is small compared with the timescales of motion and development of features such as frontal boundaries and eddies.

Surveys are severely limited by deployments that require a vessel to be regularly stationary for casts with a profiling speed of $\sim 1\,\mathrm{m\,s^{-1}}$. Expendable probes allow use at ship speeds up to 20–30 knots, and air-dropped expendables can clearly outstrip even this.

The technique also provides standard results, and the expendable bathythermograph, or XBT, is now considered a central component of global climate monitoring programs such as the Global Ocean Observation System (GOOS). Near-real-time transfer of these data from ships under way is now also an important input to global meteorological forecasting.

The XBT was originally intended to improve on the (nonexpendable) *mechanical* bathythermograph