Chapter 25
Introduction of Non-indigenous Species

Ralph Kuhlenkamp and Britta Kind

Abstract With the commencement of anthropogenic transcontinental movements followed by a continually increasing global traffic and intentional transfer of organisms, a diverse array of human-mediated pathways appeared responsible for transporting numerous marine species between different eco-regions. World-wide shipping increased dramatically over the last centuries emerging now as the most important vector for un-intentional artificial range-extensions of marine organisms thereby causing a steady raise in the introduction rate of non-indigenous species to most coastal regions of all oceans. Such neobiota pose a high functional risk if they develop stable populations and turn invasive with often detrimental effects on diversity and foodwebs of the indigenous ecosystems, even imposing high social-economic damage. Science is advancing in the attempt to understand the mechanisms of introduction and invasiveness which are crucial for further management approaches on national as well as international levels. Non-indigenous species have to be understood as a major pollution problem connected to every-day activities on all levels of society. Since the establishment of invasive species is nearly irreversible and attempts to eradicate populations of invasive organisms are mostly futile, a stringent prevention management on a global scale has to be anticipated.

Keywords Introduction • Invasiveness • Marine • Neobiota • Non-indigenous • Pathway • Vector

25.1 Introduction

Distribution ranges of marine species shifted throughout life's history according to environmental changes, most prominently climate fluctuations, and as a consequence diversity in ecosystems varied due to extinctions and introductions of species. Geographical and environmental barriers with strong gradients in temperature,

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salinity, light and nutrients, as well as those based on biotic interactions like predator-prey combinations, evidently limit range shifts due to inherent physiological and ecological constraints of the expanding species. Performance in range extensions might change over time, either phenotypically or by altered genotypes modified through evolutionary processes, providing another variable in the ability of species to perform range extensions and create viable or even dominant populations in a new region. Dispersal of species or their propagation stages occurs either as active movement or in a passive way facilitated mostly by drifting with ocean currents, transport by other species, and rafting on various substrata (wood, seeds, pumice) or organisms like floating algae (Kuhlenkamp and Kind 2013). Incidences of natural range extension to non-contiguous biotic regions are generally rare events. All mechanisms of immigration do not automatically imply a successful foundation of a species in the new region unless its abundance and most of all the environmental and biotic conditions are suitable for the establishment of a viable, self-propagating population. Several successive introduction events might be necessary in order to establish a species in the recipient area. Range extensions are a continuous natural phenomenon and pre-eminent for the colonisation of newly opened marine regions as seen in the recent populating of the Baltic Sea after the influx of seawater had started just 8000 years ago (Helcom 2009).

With the commencement of human transcontinental movements, however, a new and very effective vector appeared responsible for transporting species between eco-regions, often unintentionally. An increasing array of human-mediated pathways and transportation vectors was generated proportionately to the development of societies and their mobility, by now far more relevant for range-extensions of marine species than natural means (Carlton 1987). Species introduced through anthropogenic activities are called neobiota (but also aliens, non-native or non-indigenous) and might subsequently become established in the foreign ecosystem to which they were transferred. Marine neobiota often travel with ships, either attached to their hulls (fouling) or more indiscernible in tanks when inadvertently taken in during uptake of ballast water at the port of leave for stabilizing empty cargo ships (Bailey 2015). During the last centuries, large scale introductions of foreign species reached a global magnitude and neobiota were established in nearly all regions of the world oceans (Carlton 1985). Depending on their impacts, which can range from being unnoticed to severe disturbance of the ecosystem ecology with negative influence on socio-economics, they constitute an important pollution factor particularly in view of the soaring introduction rates over the last decades due to an ever-increasing national and global shipping effort (Galil et al. 2014). Since about 90% of the world trade is estimated to be carried by ships (Kaluza et al. 2010), it is not surprising that the global shipping network is the dominant vector for translocating organisms via ballast water and responsible for most of the global introductions of non-indigenous species (Gollasch et al. 2002; Molnar et al. 2008). Intake of ballast water from the surrounding water body naturally gathers many different organisms ranging from viruses and bacteria to numerous planctonic species and larval stages up to invertebrate species and even fish (Carlton 2003). For the subsequent survival it is a prerequisite that biological requirements of the transferred species correspond to the conditions during transport and at the release area. Of the numerous marine species transported, only very few are able to sustain a long-term reproductive population outside their original native range and just a fraction of them become invasive (Mack et al. 2000). This small contingent of invasive non-indigenous species, however, presents the world with an increasing pollution problem.

25.2 Baseline

Between 1970 and 1985, many national and global conventions explicitly mentioned non-indigenous species (NIS) as a pollution problem including the United Nations Convention on the Law of the Sea (1982) or various European initiatives. Later, two regional conventions, HELCOM for the Baltic Sea, and OSPAR for the North Atlantic, recognized neobiota as a severe impact factor and provided many studies and information on introductions. Already in the 1970s, the International Council for the Exploration of the Sea (ICES 2005) pointed to the risks of neobiota and promoted the annual National Reports which created a common framework on information about global records of NIS (Gollasch 2007). Regardless of these efforts declaring NIS as a pollution problem for nearly 50 years, the problem has accelerated substantially during the last decades. Although treated scientifically to a greater extent since about 1940 (Lockwood et al. 2007), neobiota and their impacts are still not a concern of the public. It is crucial in the communication either on a scientific level or in general discussions about neobiota including their introduction mechanisms and impacts to set definite terms in order to avoid confusion in terminology. In this respect, the characterization of NIS will have to be more elaborate and comprise functional as well as qualitative aspects.

25.2.1 Terminology

Since the definitions used in connection with non-native species vary greatly in scientific literature, legal documents or popular writings, the basic terms are defined in short in Table 25.1 according to the information by the European portal DAISIE (Delivering Alien Invasive Species Inventories for Europe, Pysek et al. 2009) and by Carlton and Ruiz (2005).

25.2.2 Criteria Applying to NIS

Due to the widespread and numerous introduction events with high impact probability, IAS are recognized as one of the main anthropogenic threats to biological systems (Costello et al. 2010) dominating already marine communities in many major

Table 25.1 Basic definitions of terms with examples

Term	Abbreviation	Definition	Examples
Non-indigenous species	**NIS**	Taxa introduced outside of their natural range (past or present) and outside of their natural dispersal potential including any part that might survive and subsequently reproduce	Red macroalga *Bonnemaisonia hamifera*
			Crustacean *Hemigrapsus takanoi*
			Molluscan *Mya arenaria*
Invasive alien species	**IAS**	Subset of established NIS with potential to spread and with adverse effect on biological diversity, ecosystem functioning, socio-economic values and/or human health in the invaded regions	Green macroalga *Caulerpa taxifolia*
			Brown macroalga *Sargassum muticum*
			Molluscan *Crassostrea gigas*
			Crustacean *Carcinus maenas*
			Crustacean *Caprella mutica*
			Ascidian *Styela clava*
Cryptogenic species		Species of unknown origin and often undetected taxonomically, difficult to be ascribed as being native or non-indigenous	Green macroalga *Ulva californica*
			Ship boring molluscan: *Teredo navalis*
Vector		Transport mechanism or physical means by which NIS are translocated	Shipping: ballast water, hull-fouling
			Aquaculture: translocation of cultured species
			Recreational boating
			Floating objects
			Rafting on macroalgae
Route, pathway		Geographic path over which a species is transported from donor to target area	Main shipping lines
			Pathway of spat for mussel and oyster aquacultures
			Driftpath by ocean currents
Corridor		Artificial infrastructure connecting previously unlinked water bodies	Suez Canal between Red Sea and Mediterranean Sea
			Nord-Ostsee Kanal, Germany

ecosystems (Cohen and Carlton 1998). Although IAS are the main pollution factor, the introduction paths and invasion process is the same for all NIS. It cannot be excluded upfront if a species will become only a minor component of the recipient community or if it will become invasive and cause damage in various ecological and socio-economic ways. Hence, the concept of invasion is based on the steps taken

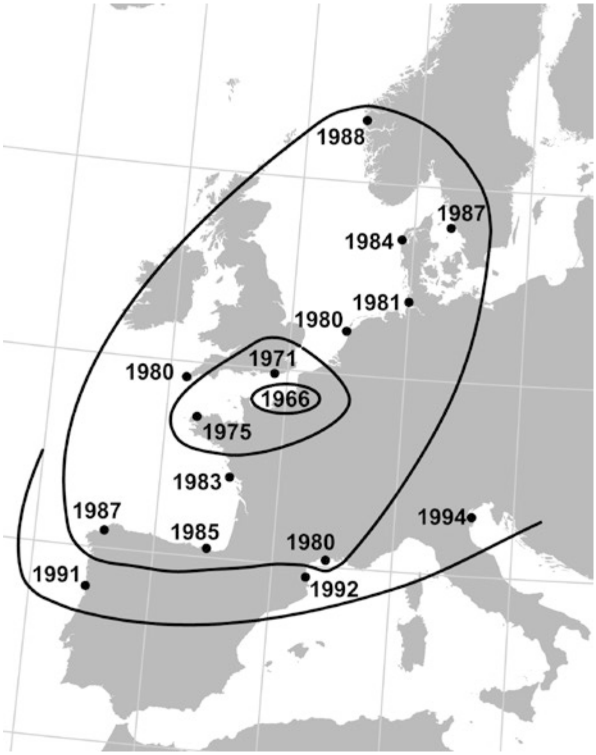

Fig. 25.1 Example of secondary, stepwise, natural or human-mediated expansion of a NIS from its point of introduction: temporal scale of the spread of the seaweed *Sargassum muticum* to several European coasts after its un-intentional introduction in France (modified after Ribera and Boudouresque 1995)

during introduction of any NIS and regulative measures need to consider every introduced organism as potentially invasive. Every species translocated by anthropogenic means is non-indigenous in a disparate region to its original range if it is exhibiting subsequently a disjunct distribution with highly separated ranges. In most cases, introductions occur suddenly and very localized whereas the subsequent spread follows mostly a step-wise process over an extended period involving several natural and human-mediated vectors (Fig. 25.1).

NIS are mainly characterized by features pertaining to the recipient distribution range. First of all, the species has to be new in the region and anthropogenic transportation means are the basic introduction vector without natural dispersal involved in the initial invasion. Geographically it is separated from its original range and occurs mainly in harbours, enclosures, protection barriers etc. or aquaculture sites. Local distribution during initial stages of the introduction is often followed by a sudden population increase and a step-wise expansion from there. NIS are found in all marine species groups from higher plants to unicellular algae, from vertebrates to even bacteria and viruses. Benthic invertebrates represent the main group of NIS among which Mollusca provide the most numerous taxa, followed by Arthropoda, Chordata, and Annelida (Gollasch 2006; Streftaris et al. 2005; Galil 2008). Well represented as NIS are macroalgae with globally 277 species (Williams and Smith 2007) including some of the well-known cases with high negative impacts like

Caulerpa taxifolia and *Sargassum muticum*. Many are transported via hull-fouling not only on commercial vessels (Hewitt et al. 2007; Mineur et al. 2007), but also with recreational craft (Mineur et al. 2008). Due to the capacity of the brown seaweed *Sargassum muticum* to establish large populations in a wide-range of environmental regimes including all temperate zones, it became now the most widespread macroalgal NIS (Engelen et al. 2015). Despite the essential requirement for correct species identification, continuing loss of taxonomic expertise or the lack of harmonised standard taxonomic procedures is accountable for many small sized taxa remaining unrecognised (Terlizzi et al. 2003) and microorganisms are still highly underrepresented in neobiota assessments (Ojaveer et al. 2015), although ballast water contains a large proportion of them, some of even pathogenic nature (Ruiz et al. 2000). Distinguishing NIS from native species can be difficult when they share very similar taxonomic features. With molecular studies, however, the non-indigenous status of several cryptogenic species and the origin of some common NIS formerly assumed to be native were confirmed (McIvor et al. 2001; Provan et al. 2008).

25.3 Mechanisms and Drivers

25.3.1 Framework of the Invasion Process

Deliberate or un-intentional introductions of organisms through anthropogenic activities and the subsequent invasion of an ecosystem follow an invasion process characterised by different barriers and drivers (Fig. 25.2), generally proceeding in three major successive steps:

1. Introduction from the native range
2. Establishment in the recipient system
3. Proliferation and expansion to other regions

It is essential to define the phases and drivers of these key steps as a prerequisite for understanding the process of introduction and for evaluating its inherent risks. Colautti and MacIsaac (2004) linked the stepwise invasion levels of NIS to different filters which regulate transition to the next stage. The invasion process will only continue if species are able to pass them. Obstruction of the process might fail the initial introduction or subsequent invasion especially if it occurs during the initial levels (Lockwood et al. 2007). In the first step, ballast water transfer and artificial corridors (e.g. Suez Canal) are the main transport vectors indicating the translocating phase, which is only successful if the transported species or its stages survive the transport conditions. After extraction from its original range and subsequent release in its new environment, the establishment phase follows in which the species must be able to cope with the existing environmental conditions and is forced to interact with other components of the ecosystem (enemies, food sources, food webs etc.). For many species, environmental conditions at the entry location and a low initial population size will be the main barriers for a continued establishment.

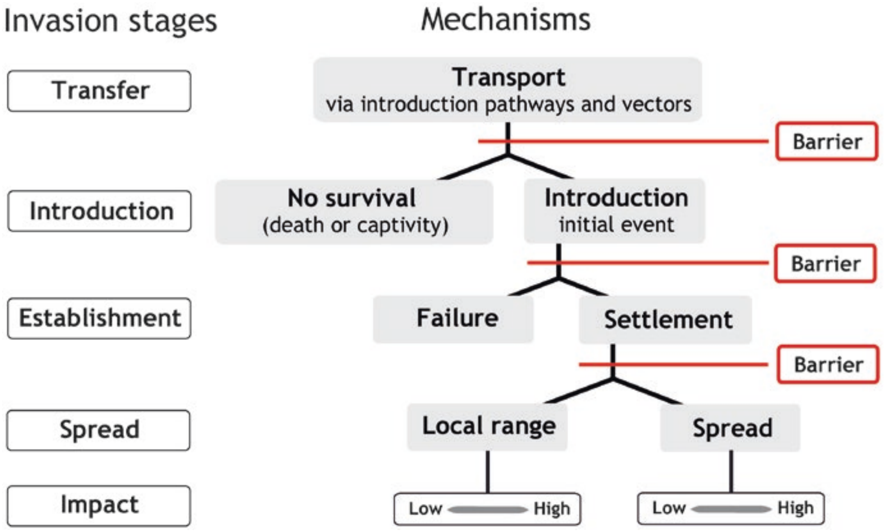

Fig. 25.2 Conceptual model depicting the discrete stages of the invasion process. Alternative outcomes are included at each stage and the sites of possible physiological/physical barriers between stages are indicated (modified after Lockwood et al. 2007)

Human activities (alteration of habitats due to construction, harvesting, fishing etc.) which generally hamper establishment of native species, especially facilitate settlement of NIS in this phase (Mineur et al. 2012). In the third phase, NIS either remain a minor component of the recipient ecosystem without any harm or benefit to it by sustaining a low abundance, or turn invasive by increasing population size and markedly extend the distribution range. At this stage, secondary spread is provided by natural dispersal and anthropogenic distribution activities identical to the human-mediated vectors acting in the primary introduction phase, only now within the recipient region. Finally, the strength in population size and the ability to continue the spread regulate invasiveness and further impacts by the introduced species. Invasions of deliberately translocated species and their co-introduced NIS proceed different due to the fewer and less severe barriers between steps. For aquaculture purposes, usually large quantities of the preferred species are transferred with the aim to enhance survival and support settlement. Such species are in a favourable situation during transport and introduction, with the consequence of a high propensity for further spread and invasion (see case of the Pacific oyster).

25.3.2 Natural Dispersal

Although natural dispersal is not regarded per se as a vector in primary introductions of NIS, it is very important during the subsequent spread. The intensity of the vector depends on the inherent capabilities of the species to grow and reproduce in the recipient ecosystem. Many macroalgae can re-grow from fragments of their thalli, which represents one of the means for natural dispersal, but also for human-mediated transport when fragments are entangled in nets and other ship-related devices. Human activities over the last centuries, however, indirectly caused natural dispersal to be included as a primary vector by adding numerous floating objects to the marine environment like timber, plastics, garbage or discarded fisheries equipment, thereby significantly raising the opportunities for rafting (Wolff 2005).

25.3.3 Human-Mediated Vectors and Routes

Numerous different pathways and vectors based on anthropogenic activities (Table 25.2) exist as drivers for introductions of NIS (Carlton 2009), of which trade and shipping are present already for thousands of years, but increased exceptionally during the last century (Hewitt et al. 2009).

Table 25.2 Major pathways and vectors important in introductions of marine NIS

Pathway or route	Vector
Commercial shipping: ships, floating structures	Transport of ballast water, sediments, solid ballast
	Fouling of hulls and all parts which come into contact with surrounding sea (anchors etc.)
Corridors	Natural dispersal and ship-mediated transport through canals
Recreational activities	All kind of boating (similar vector to shipping in general)
	Fishing and Angling: transport of live bait, accidental/intentional transport and release of angling catch, stocking for angling
	Sport equipment (diving, angling gear)
Aquaculture activities	Intentional releases and movement of stock associated water
	Unintended or unauthorized releases of species
	Transport of equipment or discarding any of it
	Distribution of live feed
Aquarium and live food trade	Intentional and accidental release from aquaria and similar compartment
Wild fisheries	Untreated material formerly used in aquaria and their waste discharge
	Unauthorised release of imported living foods
	Discharge live packing materials and release of transported water
Artificial structures, habitat management	Artificial protection structures, reclamation and protection activities moving rock or sediments from or to places far away from original sites
Research and education	Field experiments
	Accidental release
	Movement of experimental equipment
	Escapes of caged organisms used for monitoring
Biological control	Release of certain species for control of invasive species or pests

25.3.3.1 Commercial Shipping

Shipping is the major vector of global marine invasions, either through ballast taken onboard or through fouling of the hull (Leppäkoski et al. 2002a). The historically used solid ballast was more and more displaced since 1800 by using water in special tanks. Ballast water was already suspected in 1908 as a factor in the introduction of a non-native planctonic diatom to Europe (Ostenfeld 1908). Based on estimates for global shipping activities, 8–10 billion tonnes of ballast water were transported per year carrying 3000–4000 species daily (Carlton and Geller 1993; Gollasch et al. 2002) indicating the enormous potential for introductions of NIS to any harbour in the world. Harbours were defined as a more appropriate habitat for tolerant introduced species than for native ones, because NIS and cryptogenic species were found in higher numbers and abundances than native species (López-Legentil et al. 2015). Additionally, transport connectivity between ports and marinas as hotspots of NIS contribute to the spread of NIS but less for native species. Hull-fouling is the second most important vector even with numerous anti-fouling methods applied (Gollasch 2002; Hewitt et al. 2007; Mineur et al. 2007). Recruitment to the surface of vessels is either through secondary attachment of NIS directly from adjacent populated surfaces and from drifting specimens including fragments e.g. of macroalgae, or as planctonic stages of the life-history. Especially macroalgae are very capable of hull-fouling (Schaffelke et al. 2006) and in some species even very large thalli are able to withstand the drag during a long voyage (see case of *Undaria pinnatifida*).

25.3.3.2 Corridors

Corridors like the Nord-Ostsee Canal in Germany, the Suez Canal in Egypt and the Panama Canal in Central America offer ample opportunities for fast transfer of NIS between very different biotic regions (Gollasch et al. 2006). About half the NIS in the Mediterranean Sea are supposed to have been introduced through the Suez Canal, a corridor without barriers, which supports ship-mediated translocation as well as intense natural migration (Zenetos et al. 2012).

25.3.3.3 Recreational Activities

Small craft shipping is the most important vector responsible for introductions due to recreational activities and is especially effective in the secondary spread of NIS between ports, and between ports or marinas and nearby coastal sites (Minchin et al. 2009; Mineur et al. 2012; Bishop et al. 2015). Recreational boating functionally resembles commercial shipping, except that hull fouling is the dominant vector and transport distances are much shorter (Wasson et al. 2001; Davidscon et al. 2010). Long residence times of boats at their harbour or mooring site increases fouling of hulls and subsequently the introduction risk at sites approached by the vessels (Marchini et al. 2015a).

25.3.3.4 Aquaculture Activities

Introductions of economically valuable species for cultivation purposes, especially mussels, oysters and fish (Wolff and Reise 2002; Ribera-Siguan 2003; Wolff 2005), were the basis for an expansion of the aquaculture industry providing much of the worlds seafood products albeit with numerous negative side-effects (Cook et al. 2008). Several of the intentionally introduced species posed a high risk as NIS, often changing into invasive species like the Pacific oyster in Europe. As a secondary cause of such introductions, but with similar consequences as the intentional transfer, introduced aquaculture species turn into a significant vector due to the numerous organisms attached to or ‘hitchhiking’ with the organisms or their shells (Ribera-Siguan 2003; Hewitt et al. 2007). Macroalgae have also been imported for aquaculture purposes of which the Pacific *Undaria pinnatifida*, transferred to a French Mediterranean lagoon and from there to the French Atlantic coast, started to spread to nearby regions due to natural dispersal and transport via hull-fouling (Floc’h et al. 1996). Despite some constraints during transfer and at the culture site, the negative effects on transported aquaculture species, including their attached or ‘hitchhiking’ organisms, is certainly limited since the main incentive is to keep them alive at all stages of transport and fit for growth and reproduction afterwards.

25.3.3.5 Aquarium and Live Food Trade

Either for amateur or for commercial use, the trading of species poses a high risk to the environment due to inadvertently (escapes) or intentionally released organisms of all taxonomic groups (Calado and Chapman 2006). Trades for aquarium species are getting more into focus due to their increasing commercial value and because they are seen as one of the five major causes of introductions with sometimes very negative impacts on aquatic ecosystems (Padilla and Williams 2004). Discarding of any unwanted or unused life material such as live packaging material (mostly seaweeds) or discards from fish markets directly into adjacent coastal areas might also contribute to introductions (Hewitt et al. 2007).

25.3.3.6 Artificial Structures, Habitat Management

Increased construction activities over the last century led to numerous artificial structures in coastal environments (harbour facilities, barriers, marinas etc.) providing various hard substrata for the attachment of macroalgae and sessile benthic invertebrates directly in the vicinity of NIS introductions (Mineur et al. 2012; Marchini et al. 2015a). Coastal structures are often placed in estuaries or regions with little hard substrata thereby enhancing fouling with NIS since conditions in these biotic systems provide suitable habitats for a larger proportion of neobiota than open coastal areas (Preisler et al. 2009; Buschbaum et al. 2012; Marchini et al. 2015b). NIS frequently establish first in major nodes within the shipping network (Carlton 1996; Minchin et al. 2006) where artificial structures represent the primary receivers of NIS. At the same time, these structures function as a donor in the further spread of NIS constituting important stepping stones in the invasion process and facilitate the recruitment of NIS onto other vessels for further ship-mediated transfer (Marchini et al. 2015a).

25.3.4 The Main Driver Shipping and Risk Evaluation

The shipping network is the dominant vector for translocating organisms responsible for most of the world-wide introductions of NIS (Gollasch 2006; Molnar et al. 2008; Hewitt et al. 2007; Seebens et al. 2013). In a first step of analyzing invasion patterns, the network in international shipping traffic was identified with recent data (Fig. 25.3) providing basic information on possible invasion routes of NIS (Kaluza et al. 2010; Kölzsch and Blasius 2011). Adequate representation of the actual risk involved in the invasion flow required the inclusion of several additional factors like the dynamics of the uptake and subsequent release of ballast water, species survival during transport, propagule pressure, the environmental factors temperature and salinity at the donor site, and interactions between species and transport substrata (Seebens et al. 2013, Xu et al. 2014). It was predicted that the greatest risk of new introductions was involved with medium-range shipping distances of 8000–10,000 km between ports. Organisms are less likely to survive longer journeys. The invasion risks are concentrated at a few major ports located in South East Asia, the Middle East and the USA, while most harbours exhibited a low risk.

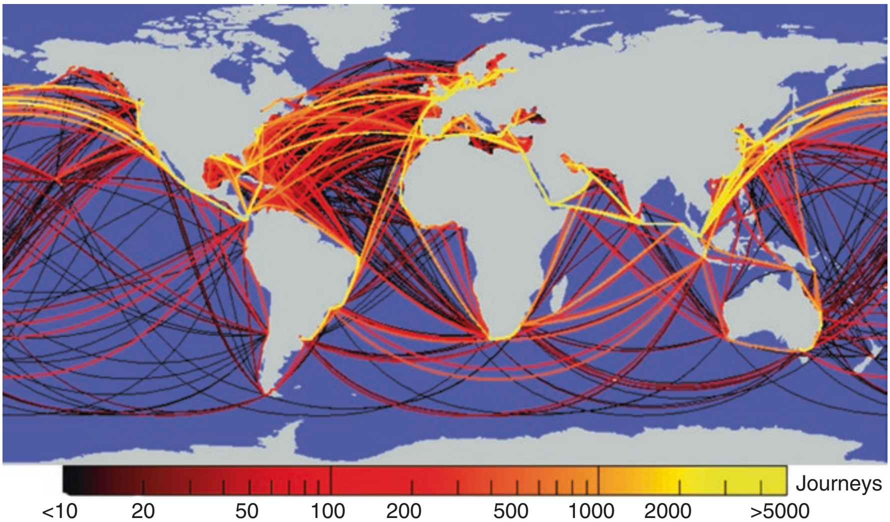

Fig. 25.3 Trajectories of all cargo ships larger than 10,000 GT during 2007. The *colour scale* indicates the number of journeys along each route. Ships are assumed to travel along the shortest (geodesic) paths on water (Kaluza et al. 2010)

25.3.5 Introduction Rate

It is generally accepted that regions with an elevated proportion of NIS are at greater risk of future invasions. The number of introductions or invasions is therefore an important basic indicator addressing anthropogenic pressures. Despite the multitude of global aspects on NIS as a pollution problem, the general focus in all chapters was placed on the situation in Europe justified by the fact that most worldwide introductions happened in European seas (Galil et al. 2014). Until 2012, about 1230 marine NIS were recorded for Europe (Katsanevakis et al. 2013) of which about 57% are assumed to occur in self-sustaining populations, indicating their stable situation in the recipient systems (Gollasch 2006). The highest numbers of NIS were found along the Mediterranean coasts of Israel, Egypt, Turkey, Greece, Italy and France with 430 species in Israel alone. Each sub-region of the Mediterranean Sea is affected by different introduction pathways (Galil and Zenetos 2002). While aquaculture imports are the most important vector for the western region, the connection of different water-bodies through a corridor is responsible for introductions in the eastern part (Galil et al. 2015) where the Suez Canal facilitated the influx of tropical species from the Indian and Pacific Ocean since its opening in 1869 (Zenetos et al. 2012). For that reason, the eastern Mediterranean coastline is worldwide the marine biogeographical region most severely affected by NIS and exhibits the highest rate of introductions and the highest number of NIS (Raitsos et al. 2010; Occhipinti-Ambrogi et al. 2011; Zenetos et al. 2012). There is a constant acceleration in the introduction rate within Europe since global transfer of species intensified around 1900 (Fig. 25.4).

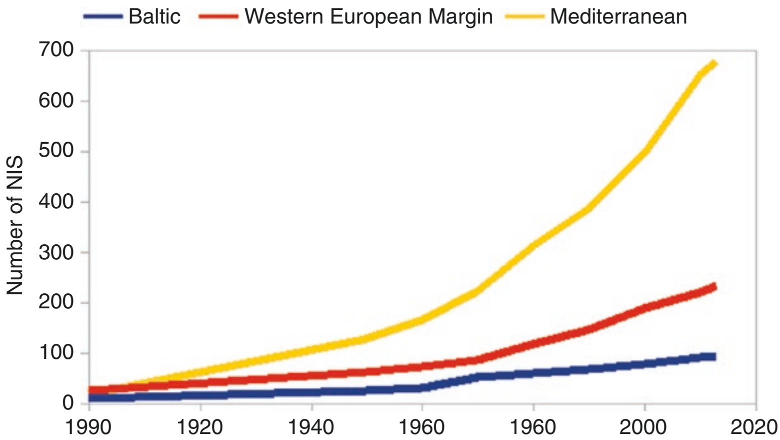

Fig 25.4 Cumulative number of NIS recorded in the Baltic Sea, Western European Margin and Mediterranean Sea (Galil et al. 2014, based on information from AQUANIS, a pan-European aquatic non-indigenous and cryptogenic species information system)

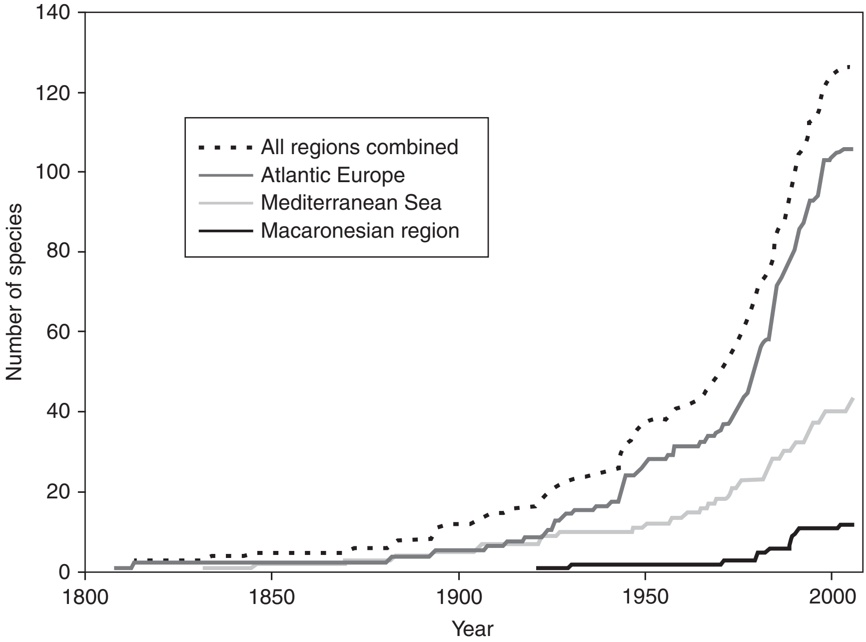

Fig. 25.5 Cumulative number of all introduced seaweed species observed on Atlantic coasts of Europe, the Mediterranean Sea, the Azores and Canary Islands from 1800 to 2005 (Mineur et al. 2015)

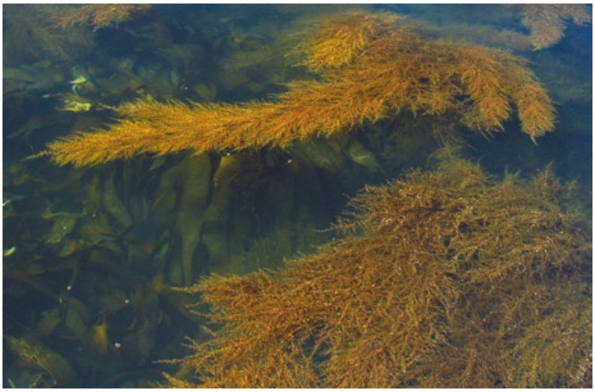

Fig. 25.6 *Sargassum muticum*: thallus floating at the surface above the *Laminaria* canopy in the subtidal of Helgoland, Germany

Macroalgae represent a very large portion of NIS which increased after 1900 to more than 125 species in Europe alone (Mineur et al. 2015), most of them occurring in the Mediterranean Sea (Fig. 25.5). About half of those species spread further and are considered invasive (Mineur et al. 2010). Like in *Sargassum muticum* (Fig. 25.6), any potential floating ability might greatly fascilitate the natural distribution of macroalgae.

25.3.6 Factors Supporting the Invasion Process

Certain ecological or environmental conditions and especially human disturbances were identified to increase introduction rates and invasion success of NIS like existing vulnerability of the recipient community, sediment pollution, artificial constructions and effluents (Schaffelke et al. 2006; Valentine et al. 2007). In some studies, the absence of natural enemies and competitors in the recipient region are seen as the main reason for the invasion success of NIS (Blumenthal 2006). Alternatively, multiple factors act simultaneously, like favourable environmental conditions for NIS and anthropogenic infrastructure or activity (Colautti et al. 2004). Selection for an advantageous genotype and positive interactions with other species were also identified. Low native cover, vacant space and low species numbers supported natural settlement of the IAS *Sargassum muticum* during its spread in Europe (Fernández et al. 1990). NIS introductions contribute to a mixing of species assemblages from different marine regions. In the case of the Mediterranean Sea, the so-called 'tropicalization' was attributed to the combination of four factors, the natural Atlantic influx through the Straits of Gibraltar, the invasion through the Suez Canal, aquaculture and climate warming (Raitsos et al. 2010). Future scenarios about NIS and their impacts certainly need to consider an on-going climate warming as one of the major interacting factors increasing introduction rates and rendering biological tropicalization in many regions inevitable (Occhipinti-Ambrogi 2007). High risks are even attributed to polar regions where an increased influx of neobiota with a warming climate and expanding tourism is predicted (Ware et al. 2014; Hughes and Ashton 2016). In the case of the Pacific oyster, which was introduced numerous times to Europe in order to restock the existing cultures, a positive feedback loop was described by Mineur et al. (2014) in which as part of the attached organisms introduced with the oyster spat specific diseases (parasites and viruses) were imported which posed a direct threat to the established aquaculture of oysters with sometimes detrimental impacts on the commercial yield.

25.4 Impacts

25.4.1 Overview

Marine IAS are known to exert numerous impacts, some with serious consequences for coastal ecosystems as well as for economics and society (Katsanevakis et al. 2014b; Vaz-Pinto et al. 2015). They are defined by the European Commission (EC 2014) as a factor of significant impact on environmental quality caused by adverse effects on the biological, chemical and physical properties of marine ecosystem, and the recent Marine Strategy Framework Directive (EC 2008) recognises NIS as a major threat to biodiversity required to be considered as a relevant descriptor of the Good Environmental Status (GES). IAS act as vectors for diseases, alter ecosystem processes, disrupt cultural landscapes, reduce the value of land and water for human

Table 25.3 Major impacts through introductions of marine non-indigenous species

Biological impacts	Economic impacts	Social impacts
Change and loss of native biodiversity: preying on native species, displacement of native species (competition for space and food), parasites and disease, overgrowth of existing communities, degradation of ecosystems, hybridization, genetic dilution	Interference with resources for fishing and mariculture (fish or shellfish-stocks): collapse of stocks, decreased yield through smothering of cultured populations, pathogen invasion into aquaculture	Competition with native species used for subsistence harvesting
Changes of ecosystem function	Direct interference with fisheries (fouling, clogging or tearing of nets)	Degradation of culturally-important habitats and resources
Changes in nutrient cycles	Damage to infrastructure (through fouling of pipes, wharves, buoys etc.)	
Decreased water quality	Decreased recreational opportunities: massive growth in coastal areas used by humans	
Impacts to human health and wellbeing	Expenses for cleaning, control and eradication measures	
Habitat changes due to mass-occurrence or eco-engineers altering substrate conditions (oysters etc.)		

activities and cause negative socio-economic impacts (Table 25.3). Recognized as one of the five main pressures directly causing loss in marine biodiversity, IAS eliminate sensitive or rare species, alter native communities, cause mass proliferations, modify habitat conditions through changes in substrata, and reduce native species numbers and abundance (Bax et al. 2003). Eventually there might be unexpected and irreversible consequences for native communities and economically valuable resources in fisheries (Occhipinti-Ambrogi and Savini 2003). Impacts may vary in magnitude ranging on temporal scales from sporadic or short-term to permanent effects, and on a spatio-functional scale from low abundances in a very limited range with no measurable adverse effects up to mass proliferations in a large region or ecosystem with marked influence on native communities, habitats and ecosystem functioning. Predicting invasion events is very difficult since it is uncertain which species will become invasive. Introduced species might exist in the recipient system for a long time with a small, non-invasive population until conditions change. Either environmental shifts or introductions of additional species might trigger its population increase and finally lead to the invasion by this formerly 'harmless' introduction (see Chap. 27). Human activity distinctly shaped biodiversity patterns in the Mediterranean Sea with differences in taxonomic composition between regions depending on the dominant vectors, either ship traffic and natural dispersal through the Suez corridor intensifying invertebrate NIS or imports for aquaculture purposes which enhanced macroalgal introductions (Katsanevakis et al. 2014a). Biodiversity changes can occur at a very high rate as seen in the Mediterranean Sea where one non-indigenous species is expected to arrive every 10–11 days (Zenetos 2010). Sheltered coastal areas and estuaries, harbours and canals show the highest proportion of changes in biodiversity with ratios for non-native to native species of 1:40 in the majority of European marine waters, 1:20 at open coasts and 1:5 in estuaries or lagoons (Reise et al. 1999; Leppäkoski et al. 2002b; Wolff 2005). Increasing the number of species by additions from other regions implies not only changes on a local scale, but serious impact is seen in the systematic homogenization of biota over large regions since species are transported between different oceans (Mineur et al. 2015). Although Europe and Australia are major recipient region for introductions, one has to keep in mind that they are also automatically donor sites for NIS to other regions for instance North America, since ship traffic is a two-directional vector. In the following chapters we describe some key impacts relevant on a global scale based on prominent invasion cases as a function of their underlying introduction framework and the main vectors involved.

25.4.2 Unintentional Introductions

25.4.2.1 Historic Case or Cryptic Species

It is assumed that the ship boring clam, the so-called shipworm *Teredo navalis* probably appeared in western Europe around 1700 (Gollasch et al. 2009). Within a short period it caused enormous damage to wooden structures in the Netherlands and even in recent years, its damage to wooden constructions along the coast of the western Baltic was estimated to cost 25–50 million Euros (DAISIE 2006). There is no competition with other species since it occupies a special ecological niche. It is difficult, however, to ascertain its origin and if it was introduced to Europe or not. It is therefore seen as a cryptic species.

25.4.2.2 NIS as Indirect Vector for Other Introductions

With the intentional importation of species, unintentional introductions of accompanying NIS occur on a global scale already for centuries (Ruesink et al. 2005). Besides invertebrate and macroalgal species, also pathogens or parasites can be transported which can infect and damage native and commercial species, or even show a health risk to humans.

25.4.2.3 Synergistic Factors in the Success of IAS

The green crab *Carcinus maenas*, a very common native of European shores, is believed to have been introduced to many areas worldwide. Evidently it was transported inside the holes bored by shipworms into wooden ships and first recognized in North America in 1817 (Carlton and Cohen 2003). It is believed to be partly responsible for destroying the soft-shelled clam fisheries during the 1950 by expanding along the coastline of the USA which affected thousands of people besides changing the biological situation of the ecosystem. Feeding on many seashore organisms, particularly bivalve molluscs such as clams, oysters and mussels, the green crabs are faster and can open shells more easily than the native crab species. After their introduction to the Pacific side of North America, the green crab started to reduce the native clams due to its food-selection and ability to feed on larger shells than the local crab species. Biological characteristics of the native species were playing an important additional role in this case. Most of the specimens of the affected clams transform into females when they are large, which is the preferred food size of the green crabs. This caused the removal of mainly reproductive individuals, enhancing the eradication process even more. Native clams were not only reduced due to the increased grazing pressure, but another clam species present as a small non-invasive population since its un-intentional introduction by oyster-transports from the Atlantic shores of North America, switched to invasive and expanded significantly (Grosholz 2005). As a consequence, the ecological balance was severely disturbed illustrating a major impact by positive interactions or feedback between NIS causing an accelerated decline in native species.

25.4.2.4 Introduction with Ballast Water: Interference of NIS with Existing Food Web

Originally from the Atlantic estuaries of North America, the ctenophore *Mnemiopsis leidyi*, a carnivorous predator, was introduced in the early 1980s to the Black Sea by ballast water of cargo ships (Ghabooli et al. 2011; Costello et al. 2012). Without natural predators it rapidly established a population of an estimated 1 billion tonnes in the food-rich Black Sea. While feeding on fish larvae or eggs, but also on zooplankton which was the main food-source of the local fish population, the impact was tremendous culminating in the collapse of the fish-stocks only a decade after its introduction, causing annual losses in commercial fisheries of at least US$ 240 million with subsequent social implications. Introduced as a harmless species with regards to its original range, this NIS became invasive extremely fast, reaching very high densities and completely disrupting the food chain of the invaded area impacting all trophic levels. It tolerates a wide range of temperature and salinity and did not face any immediate predators or parasites. After *M. leidyi* devastated the ecosystem and fisheries, another NIS, introduced incidentally in 1997 to the Black Sea, turned out to be its native predator *Beroe ovata* and started to prey heavily on *M. leidyi*, finally causing the recovery of the Black Sea ecosystem.

25.4.3 Intentional Introductions

25.4.3.1 Aquaculture Imports and Co-introductions: Complex Multi-Factorial Impact by Non-native Oysters

Most oyster species were used intensively as a food source for a long time before aquaculture started as compensation for depleted native oyster populations. In many countries, commercial production was initiated from repeatedly introduced oysters dating back as far as the seventeenth century. Large oyster cultures are now present in coastal regions of all oceans (Ruesink et al. 2005) and provide the basis for a sizable economy like the Pacific *Crassostrea gigas* which is one of the most farmed marine species accounting for over 90% of the world oyster production (about 4.4 million tonnes in 2003, www.fao.org/fishery/culturedspecies/Crassostrea_gigas/en). The fact that an enormous biomass of *C. gigas* was imported over decades to foreign countries (about 10,000 t of spat from Japan to France between 1971 and 1977 alone) is reason enough to expect an impact in the recipient systems. *Crassostrea gigas* was finally introduced to at least 48 countries and spread into coastal estuarine regions of 17 countries (Stiger-Pouvreau and Thouzeau 2015) thereby substantially increasing its actual distribution range (Fig. 25.7).

In most of the invasive wild populations, biomass now surpasses by far that of aquaculture. Despite its high spawning temperature of 18–21 °C, the species is spreading intensively in northern Atlantic areas as far as Norway (Wrange et al. 2010). It is certain that often the combination of natural and human factors substantially enhanced the invasion capabilities of *C. gigas* (Molnar et al. 2008; Troost 2010). Intentional transport and multi-vectorial routes were providing excellent conditions for the secondary spread of *C. gigas*, like direct imports of juvenile oysters from nearby countries and within countries, non-intentional spread with shipping (ballast water and hull-fouling), recreational activities (mainly boating) or artificial structures, and even natural dispersal and propagation on a regional scale. As a negative side-effect, multi-vectorial spreading is obscuring invasion routes and hampers preventive measurements or the search for the initial introduction process. Although oyster aquaculture represents a high economic value, introductions of non-native *C. gigas* caused numerous major impacts (Stiger-Pouvreau and Thouzeau 2015).

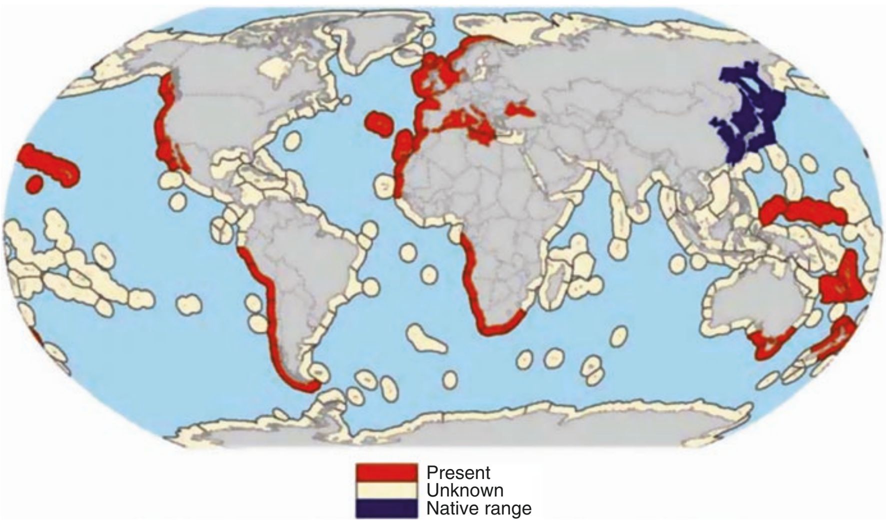

Fig. 25.7 Global distribution range of the Pacific oyster: non-indigenous range indicated in *orange*, native range in *blue* (Molnar et al. 2008)

The species might compete successfully with residential or native species and as a prolific ecosystem-engineer it has the capacity within a short time to create new habitats due to its large biogenic reef structure. Economic damage is caused by fouling harbours and numerous artificial structures or clogging pipes. Regarding biodiversity, species are displaced or relative abundances of taxonomic groups are modified. Large oyster reefs influence several trophic levels when their density is so high that filtration rates reduce phytoplankton to the point where a cascade of impacts is initiated with a top-down control of the ecosystem which is finally affecting the highest trophic levels (Troost 2010). European intertidal coastal areas with soft sediments are highly dynamic and preferred ecosystems for NIS (Reise et al. 2006) providing also *C. gigas* with appropriate conditions for establishing prolific reefs (Reise 1998; Troost 2010). During the 1990s, the continuous increase in oyster populations and the concomitant disappearance of the large native mussel beds in the German Wadden Sea first indicated a direct competition by the non-indigenous *C. gigas*. Subsequent research, however, presented evidence for a coincidental situation of very low mussel recruitment and high reproduction rate of *C. gigas*, both caused by warm seasonal temperatures over several years (Diederich et al. 2005) which supported the theory that dominance of this NIS was a result of climate conditions (Nehls et al. 2006). As an alternative viewpoint, new oyster reefs were discussed as a significant gain for the ecosystem (Reise et al. 2006) since they well compensate for habitat and biodiversity loss in estuarine environments formerly depleted by mussel and oyster exploitation and may serve as sediment traps and protection of tidal flats against further erosion which might become more important under the aspect of future sea level rise due to global warming (Troost 2010).

The complex situation of oyster introductions provides an additional example how impacts are reinforced by the combination of simultaneous anthropogenic pollution factors. Climate warming and increased introduction rates of neobiota, therefore, need to be jointly implicated in scenarios of future environmental impacts. Under this aspect, the particularly high number of up to 78 un-intentionally introduced NIS associated with live *C. gigas* transports certainly represent an enormous potential for further impacts (Ruesink et al. 2005). Of these species, several became invasive and spread to other regions contaminating many ecosystems around the world. In the Netherlands, *C. gigas* is the single most important vector for NIS (Wolff 2005). The foreign slipper limpet *Crepidula fornicata*, or the seaweeds *Sargassum muticum* and *Undaria pinnatifida* (see this chapter) are only few of the most prominent examples of IAS well established in Europe due to oyster imports (Stiger-Pouvreau and Thouzeau 2015).

25.4.3.2 Natural Dispersal as Secondary Vector in the Spread of Introduced IAS

The brown seaweed *Undaria pinnatifida* is native mainly to Japan and harvested for food throughout Pacific Asia. *Undaria* has no specific requirements for settlement on hard surfaces and can grow on natural bottoms and shells, but shows also a preference for many artificial substrates like buoys, vessel hulls, floating pontoons, ropes and all sorts of drifting material including plastics. It is tolerating a wide range of conditions, but prefers temperate waters (Floc'h et al. 1996). It was first detected in the French Thau-Lagoon of the Mediterranean Sea, a hot-spot for introductions, obviously imported from the Pacific with seed oysters for aquaculture purposes (Perez et al. 1981). In 1983, an intentional introduction of *Undaria* to the Atlantic coast of Brittany, France, was undertaken in order to establish viable cultures for future commercial harvest as a food source. Only a few years later, the seaweed had already proliferated and spread around the initial introduction sites in large numbers (Floc'h et al. 1996), despite the scientific confirmation of the responsible institution that *Undaria* would not reproduce in Atlantic waters due to environmental constraints. From then on, *Undaria* was spreading to all coastal regions of France and further south to Portugal and northward to Northern Ireland and The Netherlands, efficiently assisted by its natural dispersal ability and high preference in attachment to artificial structures like hulls, harbour walls, pontoons and protection barriers (Minchin and Nunn 2014). Negative effects of the *Undaria* invasion were evident in the influence on biodiversity, habitat structure and interference with marine farming by attaching to cages and ropes or displacing cultured species. When growing on hulls, large *Undaria* might decrease speed efficiency of vessels. This invasion case illustrates how the combination of human-mediated transport vectors and natural dispersal cabablities enhances the secondary spread of NIS. And it emphasizes the need to draw more attention to attached or hitchhiking species transferred unintentionally with imports of any kind of species or products, since every NIS is potentially invasive as long as the contrary is proven. Based on the spreading activity in *Undaria*, Mineur et al. (2015) proposed future extension of this species into the North Sea, an assumption which was now verified by the fact that attached *Undaria* was reported in summer 2016 for the German Wadden Sea island of Sylt (D. Lackschewitz, pers. com).

25.4.3.3 Escapes and Intentional Discharge

The aquarium trade is responsible for a large number of accidental and intentional releases of which the case of the green seaweed *Caulerpa taxifolia* became not only one of the most infamous examples for macroalgal introductions, but for all cases of invasions. Introduction of *C. taxifolia* to the marine environment occurred through wastewater of the Oceanographic Museum at Monaco during its use as aquarium decoration. Only the use of molecular tools finally identified the source of this IAS (Jousson et al. 1998), emphasising the need for modern methods in the study of invasion ecology. Once established, the species rapidly became invasive due to the vegetative propagation capabilities of the particular strain formerly obtained by the aquarium from the commercial dealer. Spreading rapidly through the Mediterranean Sea (Meinesz et al. 2001), *C. taxifolia* started displacing native species by overgrowing and shading seaweeds and the ecologically very important seagrass meadows by producing up to 14,000 blades per m^2 (Galil 2007), finally affecting the fauna which relied on the existing ecosystem. Sessile fauna like mussels were easily overgrown while loss of seagrass resulted in reduction of former spawning or nursery grounds and of fish populations feeding on benthic invertebrates shielded now by the thick *Caulerpa* cover (Galil 2007; Schaffelke and Hewitt 2007). Additionally, *C. taxifolia* is well protected against grazing by producing a toxin. The disastrous effect on the ecosystem had also a negative effect on commercial interests like tourism and fisheries. This case vividly demonstrates the immense risk potentially inherent in any trade for aquarium species and since acquisition of foreign species became much easier with global internet trade, transfer routes become obscured rendering control mechanisms less effective (Hewitt et al. 2007).

25.5 Research Requirements and Management

Scientific, regulative and socio-economic actions on NIS introductions require fast access to data and updated information on status, range and population size, invasion cases, pathways and impacts as provided by more than 250 websites (see list in Gatto et al. 2013, Olenin et al. 2014). Additionally, comprehensive regional lists of neobiota are needed containing supplementary species information similar to the national German list of marine neobiota (Lackschewitz et al. 2014) or those on a European scale (Gollasch 2006). The information needs, however, might not always be supported since a fundamental bias in data is evident due to inconsistencies in updates and taxonomic expertise, to variable monitoring efforts and data quality, and to different scopes between databases (Gatto et al. 2013). Within Europe, the European Alien Species Information Network (EASIN) was initiated to serve as a platform for political institutions (Katsanevakis et al. 2012) to fascilitate management on national and global scales which has to focus primarily on mitigation of existing problems and prevention of any future introductions. Science seems to be still in its early stages in providing the required substantial evidence and strategies needed, despite extensive outlines presented previously (Schaffelke et al. 2006) and authorities often react to existing cases instead of executing strict prevention management. While long-term studies are needed for understanding the ecology of invasions in order to evaluate future risks, rapid assessment methods already represent an appropriate monitoring approach for immediate actions like eradication measures before NIS become established and spread, especially in containable areas (Buschbaum et al. 2012; Lehtiniemi et al. 2015). Most promising is the combination of methods involving different aspects of invasion analysis, from historic data to species inventories, from taxonomic expertise to genetic studies, and from rapid assessments to models of invasion processes (see Mathieson et al. 2008). Database management has to be improved and acquisition of updated information facilitated on an international scale. Impacts and underlying mechanisms are often not fully substantiated through quantitative results in order to support general ecological patterns which could help in understanding invasion processes and predicting future risks (Schaffelke and Hewitt 2007). Data are even lacking (Davidson and Hewitt

2014) or impacts are not well enough described and mechanisms misinterpreted (Molnar et al. 2008). Several cases depend on studies with low statistical evidence or insufficient sample size, and comparisons between regions for categorizing impacts are generally impossible (Davidson et al. 2015). One of the alternatives is modelling strategies for managing ballast water invasions in the global shipping network (Drake and Lodge 2004). A major framework for action plans and management based on international agreements is the European Marine Strategy Framework Directive which defines descriptors of the environmentally good status and outlines categories with core values for evaluating neobiota and their impacts (Ojaveer et al. 2015). If member states fulfil their obligations, this framework could be the first step in a proper management of invasion risks and future prevention of introductions in Europe. Science and management have to consider the fundamental differences between impacts of IAS and other pollution forms which often can be diminished by appropriate measures at the source. Once established, it is nearly impossible to eradicate IAS and their tendency to continuously expand by multifactorial pathways circumvents control mechanisms. The only effective strategy for reducing future impacts is a consequent prevention of introductions of any NIS by intercepting or removal of pathways with strict entry regulations (Carlton and Ruiz 2005). Ballast water treatment and inhibition of hull-fouling are the major prevention methods against ship-mediated introductions (David and Gollasch 2008), but are only effective if strictly implemented, similarly to the control of imports for aquaculture purposes and trade of live organisms. It is, however, impossible to control every vessel, every import and trade, so efforts have to concentrate on high-risk vessels and their pathways and entry regions. The assessment of IAS impacts has to involve different temporal and spatial scales. Locations with high numbers of NIS and those with stepping stone characteristics like all artificial structures (harbours etc.) and aquaculture installations represent the local scale and require the primary focus before further evaluations are extended to ecosystems and whole regions. According to the purpose of the assessments and the taxonomic groups involved, it is essential to consider also temporal scales. Rapid assessment monitoring has to be done in a high frequency and very effectively, albeit encompassing as much area as possible, while ecological studies will be done in more detail with long-term aspects becoming more important in order to predict invasion risks of regions and invasion pressure through traits of NIS. Successful assessment of the ecological situation of an introduction requires a sound basis in species identification. Once a newly introduced species is detected and identified by classic taxonomic procedure, it is often critical to use molecular methods. There might be cryptic species formerly overlooked or the NIS constitutes a specific strain of its source population with ecological traits increasing its invasiveness like enhanced vegetative propagation. Valuable information for future predictions in the invasion process is acquired with studies on potential genetic changes, genetic differentiation, hybridization, phenotypic variation, interactions between species-genes and the environment, and on possible genetic adaptations in NIS after their invasion (Booth et al. 2007). Most pollutants usually follow a typical degradation gradient which can be monitored and assessed by descriptors of the Good Environmental Status (GES) and corrective actions might be taken accordingly. IAS, on the contrary, often represent an integral part of the ecosystem with ecological implications difficult to assess. Continuing impacts despite any remedial actions like eradication efforts, obstruct any effective and long-term management. Absolute prevention and extensive control of introduction vectors has therefore top priority in a sustainable management. All intentional introductions need substantial examination and official authorisation with a comprehensive risk assessment of invasiveness. Vectors and pathways have to be constantly controlled and early detection and rapid response need to be essential parts of baseline surveys. Additionally, community participation and awareness have to be acknowledged as an integral basis for a successful management.

25.6 Perspectives

Identification of the relative importance of invasion factors is a prerequisite for future management purposes and requires integration of additional stressors in ecosystem functioning which likely induce a positive response in invasion rates like global warming, reclamation of land, construction activities along coastlines, sediment extraction, harvesting of natural resources, habitat modification, overgrazing and eutrophication (Raitsos et al. 2010; Mineur et al. 2015). Introductions of NIS are a continuing and increasing pollution problem which has to be tackled on a broad scale ranging from individual responsibilities to scientific excellence and global regulative measures (Ojaveer et al. 2014). Science started to advance beyond the assessment of introductions or species lists and even critical aspects were issued warning against bias about NIS and urging to focus instead on sound ecological science which need to be extended (Reise et al. 2002). Similarly, international regulative measures and political management are now required to advance in accordance to the existing management options available at the various points within the introduction framework (Fig. 25.8).

Whereas shipping is recognized in regulative organisations as a major vector for introductions, recreational boating is mostly unregulated and like the trade with aquarium species, risks of introductions depend on the attitude and behaviour of amateur persons difficult to control (Clarke Murray et al. 2011). All the more there is the need for general education to enhance awareness of individuals in their daily activities and on socio-economic levels. It is the opportunity of everyone who is relying on worldwide trade for their consumption of goods to reduce the chance of neobiota introductions by selecting products which require only short transport distances and as little shipping from overseas countries as possible especially if adequate alternatives exist. If all risks and socio-economic costs attributable to invasive species are considered in a broader view, the consumption of local products and resources might be less costly in the long term. Nevertheless, there is the obligation of regulation authorities and the political management to support people in this aspect and to provide the necessary framework (Chap. 48). It is of paramount importance to consider the synergistic effects of human activity, pollution

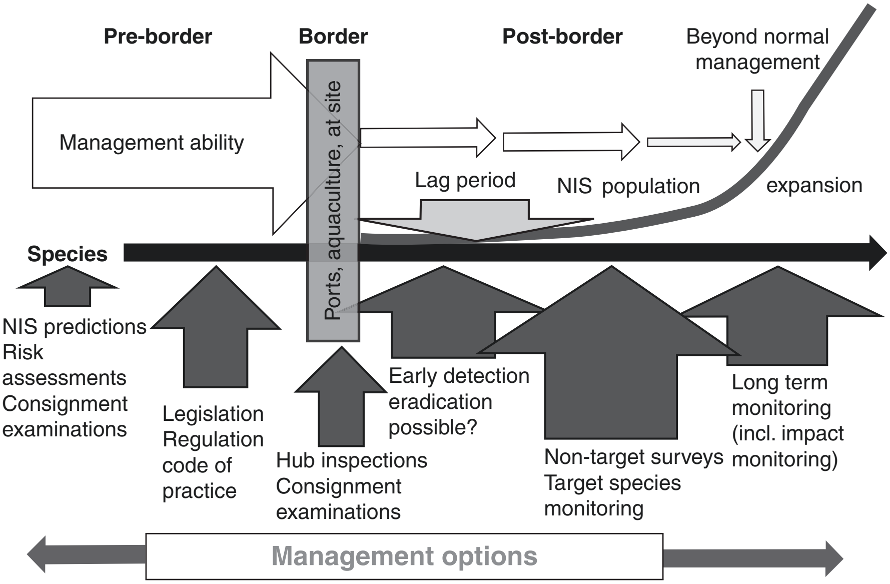

Fig. 25.8 Diagram of management and monitoring options at different phases of the introduction and during spread of NIS (Lehtiniemi et al. 2015)

and environmental factors, since invasions of IAS often occur in a multi-factorial context as stated in the case of global warming as one of the principal causes in the success of future introductions suspected of accelerating invasions by global shipping (Seebens et al. 2015).

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