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RESEARCH

Ship-mediated Marine Bioinvasions: Need for a Comprehensive Global Action Plan

Arga Chandrashekar Anil[1,*] and Venkat Krishnamurthy[1]

[1]CSIR-National Institute of Oceanography, Dona Paula 403004, Goa, India
*Corresponding author: acanil@nio.org

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Shipping

ABSTRACT Concern for marine bioinvasion has drawn international attention. The action plans in place to address this issue and those that are being promulgated are in need of a reassessment. A review of invertebrate invasions across the world indicates inter-linkages between vectors. In this paper an effort is made to illustrate the geographical spread of invasive invertebrate organisms from different bioregions and the possible causes for their success. Shipping, which is the major vector identified for the success of marine bioinvasion, needs to be addressed in tandem with domestic, intra- and inter-regional precautionary measures, as prevention is the only cure.

1. INTRODUCTION

Introduction of alien organisms into an ecosystem and its successful establishment is referred to as bioinvasion. In its native environment, the population of the organisms is controlled by ecosystem interactions; however, the absence of such a control mechanism can trigger a population explosion in non-native environments. Hence in an alien environment, introduced species can turn out to be a threat, bringing about untold, often undesirable consequences to the ecosystem. Bioinvasions can be natural, intentional or unintentional, and at times the impact is not easy to delineate due to multi-dimensional effects. Dispersion through propagation is the natural means of invasion which can be accelerated or facilitated by changes in the environment (Anil 2006).

In the marine environment, intentional introductions can happen due to expansion of aquaculture or mariculture practices. Deployment of marine structures provides virgin habitats for the colonization of organisms capable of attaching to these surfaces. Further, they can facilitate hopping of organisms to new destinations through natural dispersion means. Alteration to habitats such as canalisation and reclamation can also facilitate translocation of organisms to alien environments. Such a dispersion mechanism is exemplified in the case of Suez Canal (Shefer et al. 2004).

Many cases of marine bioinvasion and their harmful effects on ecosystem and human health have been documented (Anil et al. 2002; Subba Rao 2005). The zebra mussel, *Dreissena polymorpha*, was first discovered in North America in Lake St Clair, Michigan, in 1988. The species is native to Europe and is believed to have been introduced sometime in 1983 or 1984 from transoceanic ships that discharged freshwater ballast containing planktonic larvae or young adults (Ahlstedt 1994). It has now spread, infesting more than 40% of the United States waterways. It fouls the cooling water intakes of the industry, and may have cost $US5 billion in control measures since 1984 (GloBallast 2001). *Mnemiopsis leidyi*, an opaque comb jelly, about 10 centimeters long, entered the Black Sea in early 1980's as a stowaway in ballast water on a ship from the United States. *M. leidyi*, which had until then lived in bays along the eastern seaboard of the United States, encountered no predators in the Black Sea but food in plenty. It devoured the eggs and larvae of a wide variety of fish that led to the collapse of the fishing industry. The fish catch fell by 90% in six years. By 1990, the total biomass of *M. leidyi* in the Black Sea had reached an estimated 900 million tons. This is ten times the total annual fish catch from all the world's oceans (Pearce 1995).

In the last two to three decades, concern for marine bioinvasion and determining the vectors responsible has received international attention (IMO, 2004). Anthropogenic activities during the 20th century hve been identified as the main factors responsible for an 1800-fold increase in the rate of establishment of non-indigenous aquatic species in the Caspian Sea compared to the preceding two million years of natural colonization (Grigorovich et al. 2003). Shipping has been identified as the major vector responsible. Primarily this is related to increase in shipping activity during this period and identification of major invasions in some of the habitats (Hallegraeff 1998; Anil et al. 2003). Ships carry different types of organisms either because of their growth on hulls/sea chest and their sojourn in ballast water. Recognizing the importance of ballast water as a vector, UNDP/GEF initiated a global Ballast Water Management Programme (GloBallast), which was executed by International Maritime Organization through six pilot countries (Brazil, China, Iran, India, South Africa and Ukraine). Each of these pilot countries carried out Risk Assessment studies and produced a series of risk assessment reports under GloBallast Monograph Series. There is little doubt about marine bioinvasion mediated through ballast water and several countries mooted action plans to control/minimize invasions. Ballast water management is a complex issue. Risk based decision systems

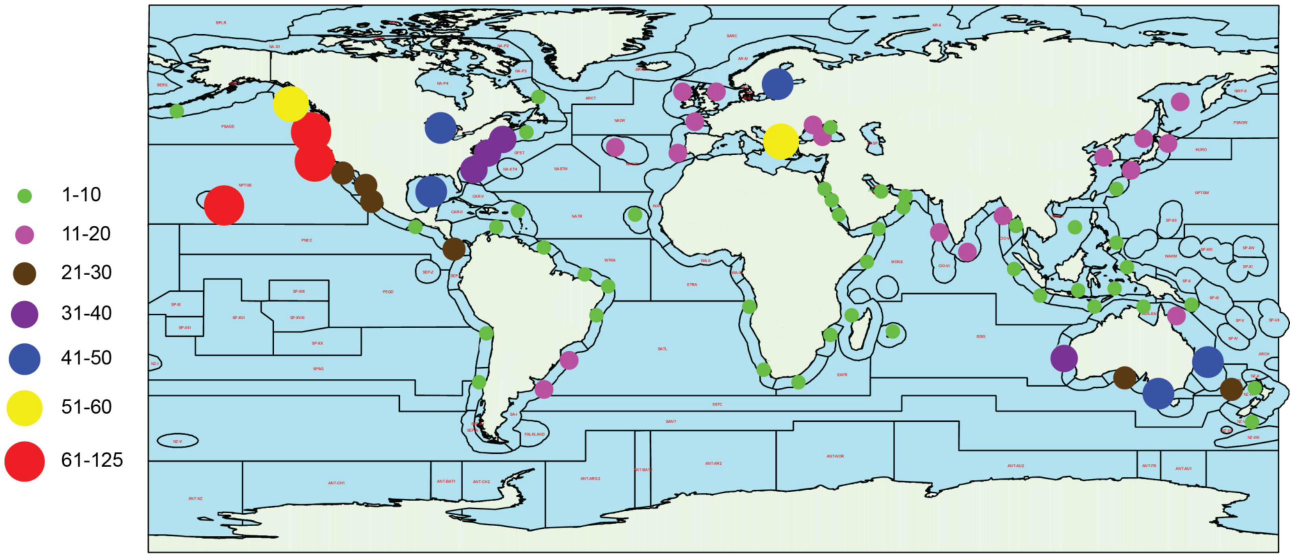

Figure 1. World bioregion map indicating extent of reported marine invertebrate bioinvasions (i.e., number of invertebrate organisms that were reported as invasive in the databases of different bioregions). Diameter of the circles represents number of invertebrate organisms reported as invasive.

coupled to databases for different ports and invasive species characteristics and distributions can allow for differentiated treatment levels while maintaining low risk levels (Endersen et al. 2004). At the same time, it was pointed out by these authors that on certain routes where the estimated risk is unacceptably high, some kind of ballast water treatment or management should be applied.

Invasions facilitated by hull fouling are also well documented (Hewitt et al. 1999; Gollasch 2002; Coutts et al. 2003; Godwin 2003; Minchin and Gollasch 2003). The International Maritime Organization has also adopted a convention on the control of Harmful Anti fouling systems on ships (IMO 2001). This convention has led to banning of one of the most effective antifouling paints, developed in the 1960s containing organotin compounds owing to harmful effects on non-target organisms. The risk characteristics such as excess fuel consumption and invasive species threats are not regulated by the convention on harmful antifouling systems. In light of this it is essential that all precautions be put in place to address these issues. The issue of bioinvasion is only partially addressed if the focus is entirely on ballast water management.

The spread of pathogens (Ruiz et al. 2000a) and Harmful Algal Blooms (HABs) have been some of the major bioinvasion concerns. Paralytic Shellfish Poisoning (PSP) is an important toxin syndrome caused by consumption of seafood contaminated by certain HAB species. There has been a cumulative global increase in the recorded distribution of the causative organisms and the confirmed appearance of PSP toxins in shellfish at levels above the regulatory limit for human consumption since 1970 (Gilbert and Pitcher 2001). The role of ballast water in the transport of the causative organisms (toxic dinoflagellates) has also been illustrated. However, if one considers marine invertebrate invasions, it will be clear that both the shipping vectors will need simultaneous attention and is illustrated in this paper.

2. MATERIALS AND METHODS

Reportage of invertebrate invasions was collated from available resources for different bioregions (CIESM 1999; DeFelice et al. 2001; NIMPIS 2002; NCRAIS 2003; Anil et al. 2004; GSMFC 2004). The data (presence/absence) of different invertebrate species reported as invasive in the databases mentioned above was used in the construction of lower triangular dissimilarity matrix using Euclidean distance and group average method. The dissimilarity matrix was subjected to clustering and ordination analysis using Nonmetric Multi-Dimensional Scaling (MDS) using Primer 5 (Clarke and Gorley 2001). The clusters were demarcated into different groups at 50% dissimilarity level and contours drawn on the MDS plot.

3. RESULTS

3.1 Geographical distribution of alien invertebrate species

Figure 1 illustrates the number of invertebrate organisms that are reported as invasive in the databases mentioned above. The highest reportage of invertebrate invasions comes from the Mediterranean region. In Figure 1 the increasing diameter of the circles represents increase in the range of number of invertebrate organisms that have been reported as invasive.

If one uses CIESM data (i.e., for the entire Mediterranean Sea) as a part of the matrix in the ordination analysis, the differences allow only two clusters (i.e., rest of the world and the Mediterranean Sea). This distinction is shown in Figure 2B. In order to clarify the situation on a bioregional basis we performed another set of clustering to identify dissimilarity by excluding the CIESM data (Figure 2A). The demarcation of clusters in the MDS plot is based on 50% dissimilarity level as described in the methods section. These demarcated clusters are further interfaced with reported bioinvasive species at phylum level in the pie charts adjacent to the clusters to give an indication of the differences. This figure shows that South Pacific (SP-XXI), North Eastern Pacific (NEPIII/IV/V), Baltic Sea (B-IV-XII), Great Lakes, Caribbean (CAR-I) and Australia (AUS-I to XII) to be among the demarcated bioregions of invasions. Bioinvasion database is reflective of the efforts put in for differentiating native biota versus invasive organisms. The information in Figure 2 can be skewed by the relative efforts to study bioinvasions. The pie graphs in Figure 2A provide a summation of organisms belonging to different phyla reported as invasive in the respective bioregion.

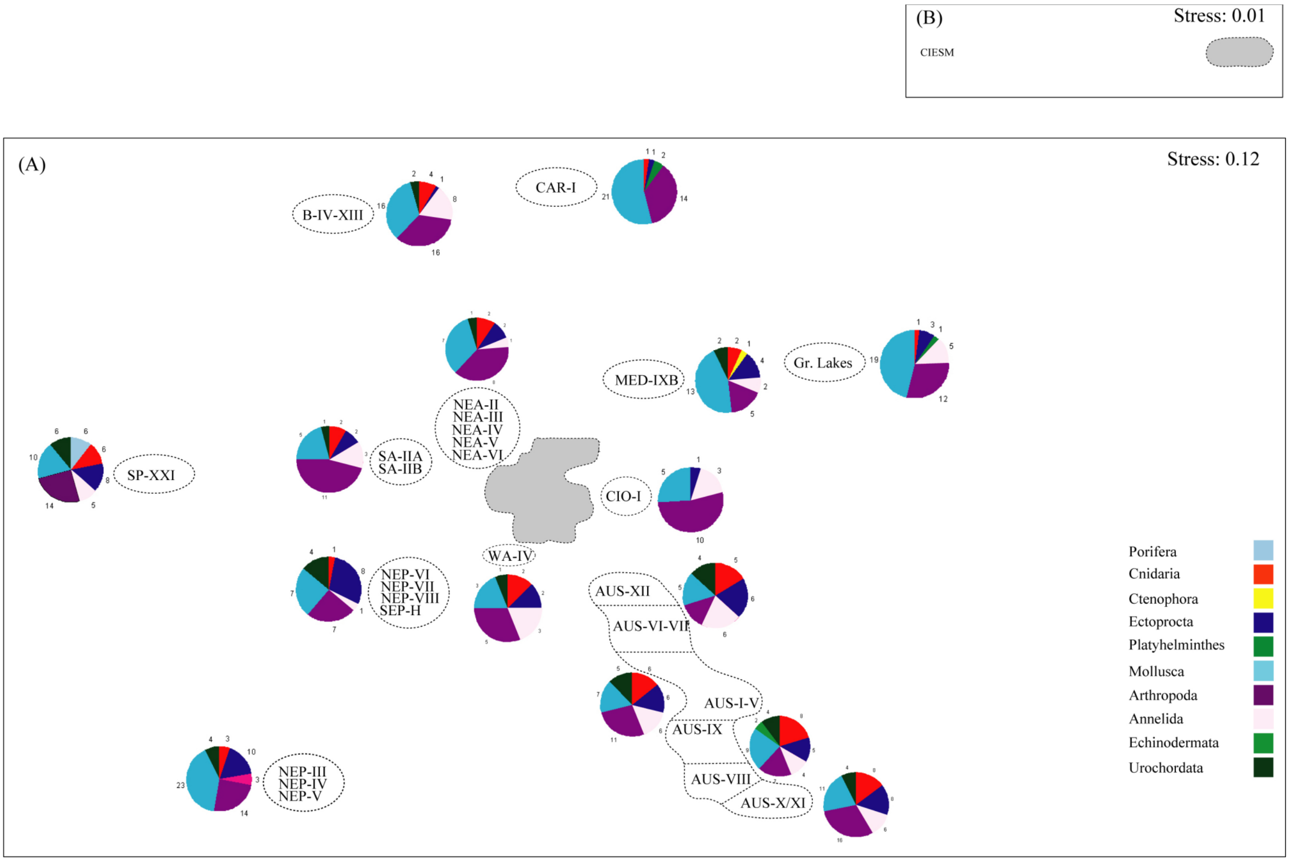

Figure 2. (A) Nonmetric Multidimensional Scaling (MDS) of the bioregions based on reported invasions (presence/absence) in different bioregions. The dashed encircling is based on cluster analysis results at 50% similarity (Euclidean distance). The pie charts indicate a phylum perspective of the invasions. (Abbr. AUS-Australia; CIO-Central Indian Ocean; WA-Western Africa; NEP-North East Pacific; SEP-South East Pacific; SP- South Pacific; SA-South Africa; NEA-North East Atlantic; MED-Mediterranean; Gr. Lakes-Great Lakes; B-Baltic; CAR-Caribbean); (B) Comparison of the entire Mediterranean data (CIESM database) with other bioregions of the world. Grey areas in both the figures encompasses all other bioregions.

3.2 Clustering based on phyla

Overall collation of information from the phylum perspective is depicted in Figure 3, indicating 239 species of molluscs and 152 species of arthropods as major contributors to invasion. Differentiation of bioinvasion from a phylum perspective in different bioregions provides four clusters (Figure 4), arthropods (76 bioregions) and molluscs (74 bioregions) being the most dissimilar ones. Ruiz et al. (2000b) also noted that most of the non-indigenous species reported from the coastal marine communities of North America are crustaceans and molluscs, while those taxonomic groups dominated by small organisms are rare. In reality one should be cautious in accepting this as factual for the very given reason that the crustaceans and molluscs have larger number of specialist taxonomists dealing with these phyla.

4. DISCUSSION

4.1 Marine bioinvasion success

Examining the bioinvasion potential of different organisms needs consideration of reproductive pathways, development and habitat requirements. A synthesis of this information for different taxa is provided in Table 1. In cases where larval duration is long and food and environmental requirements are not in a narrow band, the possibility of larval dispersal through ballast is a distinct possibility. Survival of organisms inside ballast tanks is dependent on several factors. Conditions in ballast tanks could be inhospitable to some, when compared to the natural environment. The capacity and speed of introduced organisms to establish themselves in an alien environment are influenced by the biokinetic range of temperature and salinity and usually controlled by local ecology. In certain cases, the propagules themselves can get into reproductive phase within a short duration. This is observed in ctenophores (e.g. *M. leidyi*), where their cydippid larvae can produce viable gametes, i.e., precocious development (Martindale 1987). Indeed, it is one of the major invasive species reported from the Black Sea (Pearce 2003). This ctenophore species is also included in the target pest list in Australia (Hayes and Sliwa 2003). Reports of echinoderm invasion (*Asterias amurensis*) are exclusive to Australia. Sea stars have a long larval life span. Larval starvation in echinoderms is also considered not important to recruitment success (Olson and Olson 1989). In light of this, their sojourn through ballast is a clear possibility.

The invasion potential of different organisms as highlighted in Figure 2 indicates that molluscs and arthropods are of considerable importance. Molluscs are among some of the important bioinvasive sedentary organisms. They have a reproductive pathway in which the larvae are not very dependent on food availability and are known to survive on dissolved organic matter as well. The zebra mussel *Dreissena polymorpha* that has invaded the Canadian and U.S. Great Lakes and resulted in the reduction of phytoplankton biomass and causing biofouling problems, is believed to have been introduced by trans-oceanic ships which discharged freshwater ballast containing planktonic larvae or young adults (Ahlstedt 1994). Studies with reference to arthropod larvae have shown that their potential to starve is limited and this has implications in their recruitment (Anger and Dawirs 1981; Anil et al. 1995; Desai and Anil

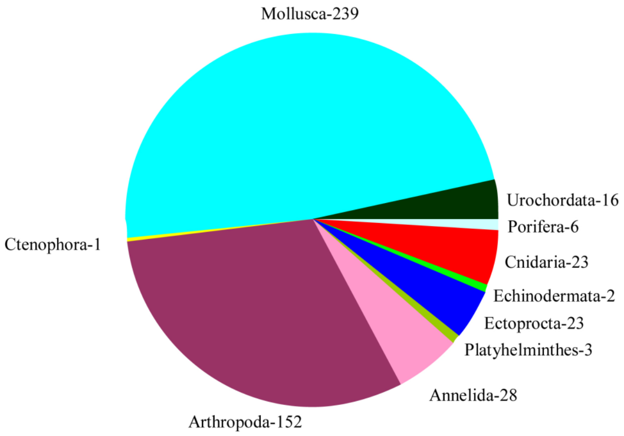

Figure 3. Global representation of invertebrate invasions (a phylum perspective). The numbers indicate the number of reported species from each phylum.

2000; Anil et al. 2001). Mooney and Cleland (2001) indicated that as the volume of global trade increases, the rate of alien species introductions and establishment also increases. In the US alone, the rate of reported invasions has increased exponentially in the last 200 years and most invasions have resulted from shipping (Ruiz et al. 2000b). It is to be noted that, organisms attached to the hull of the ship or sea chests can inject high numbers of larvae to the environment and thus increase the strength of the fouling vector. The European clam *Corbula gibba* that is native to the eastern Atlantic and the Mediterranean Sea, was first detected in Port Phillip Bay, Australia in 1991 (Currie and Parry 1996). Ballast water was believed to be the responsible vector for the introduction of this species to Australia (Boyd 1999). However, its translocation through sojourn in sea chests has also been indicated as a potential vector (Coutts et al. 2003).

It is also possible that the reproductive biology and larval development of an organism are tuned to the natural features of the environment such as change of season and temperature. Lack of such synchronization will make their quick sojourn inside ballast tanks to be of less concern to bioinvasion. The spider crab (*Hyas araneus*) is a common species from the North Atlantic and the Arctic Oceans. Around the islands of Helgoland, North Sea, hatching takes place during the season with coldest water temperature, whereas larval development is facilitated through rising temperature (Anger and Dawirs 1981). This species has recently been reported as one of the first known benthic invasive species in the Southern Ocean (Antarctic Peninsula) (Tavares and DeMelo 2004). The abiotic environment is being altered by massive land use alteration and emerging climate change (Vitousek et al. 1997; Sala et al. 2000). The suspected vectors include both fouling (ship's sea chests) and ballast water (Tavares and DeMelo 2004). In a review on the biological invasions in the Antarctic (Frenot et al. 2005), it is pointed out that under most threat are relatively milder areas with increased human visits and the most dramatic changes in environmental conditions. The warming Antarctic is being exposed to two complimentary forces (1) human mediated transport of exotic species (Barnes 2002) and (2) polar warming (Gille 2002), leading to changes in the barrier formed by the circumpolar freezing temperatures. Combination of these two forces can have unpredictable consequences for Antarctic marine biota. It has also been pointed out that banning of antifouling coating in view of the discovery of high levels of tributyltin and associated compounds in the marine sediments of the Antarctic Shelf (Negri et al. 2004) may result in an increase in the risk of non-indigenous species (Lewis et al. 2004).

The Mediterranean Sea is also easily colonized by alien species (Occhipinti-Ambrogi and Savini 2003). Physical alterations to habitats have also been a cause for invasion success. For example, the opening of the interoceanic routes of maritime commerce in the 16th century caused the importation of myriad covert invaders into the Mediterranean Sea (Galil 2000). It has also been shown that effect of international shipping, including ballast water dumping, is not limited to areas with major harbours, but reverberates up and down the coast to seemingly isolated embayments (Wasson et al. 2001). While transfer mechanisms cover one side of the coin, it has also been pointed out that studies relevant to the predictability of successful settlement by alien species are also important (Occhipinti-Ambrogi 2001). These issues clearly indicate that bioinvasion needs to be addressed through a multi-lateral approach for achieving the desired results.

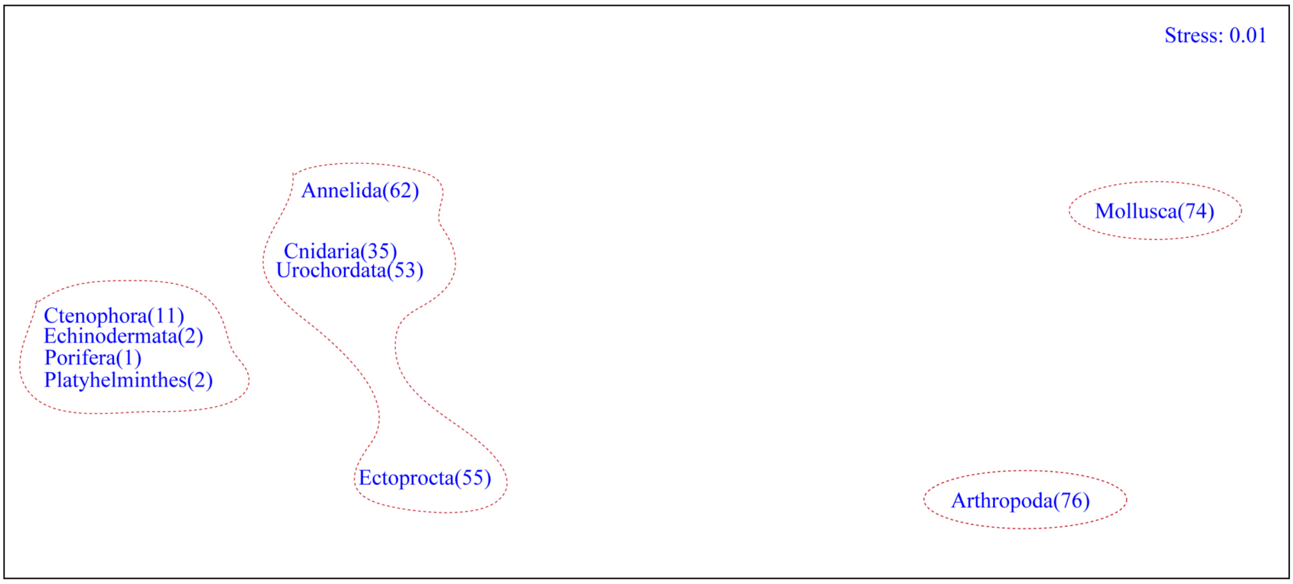

Figure 4. Nonmetric Multidimensional Scaling (MDS) of the reported invasions from a phylum perspective. The numbers in parentheses indicate the total number of bioregions reporting invasion from the particular phylum. The dashed encircling is based on cluster analysis results at 50% similarity (Euclidean distance).

Table 1. Summary of life history descriptions and importance of larval starvation on recruitment of marine invertebrates

Phylum	Organism (example)	Typical larval type	Larva/Propagule	Habitat	Importance of larval starvation in recruitment #
Porifera	Sponges	Amphiblastula Stereoblastula	Non feeding	*	
Cnidaria	Hydroids	Planula Actinula	Non feeding	*	
	Anemones & Corals	Ciliated blastula	Non feeding Cleavage & development	*	
Ctenophora	Comb jellies	Cydippid	Feeding Precocious reproduction in larvae	+	
Platyhelminthes	Flat worms	Benthic eggs, Mostly direct development	Non feeding	*?	
Ectoprocta	Bryozoans	Cyphonautes	Non feeding	*	
Mollusca	Gastropods	Trochophore Veliger	Feeding Feeding Cleavage & development	*	Maybe/No
	Bivalves	Trochophore Veliger Pediveliger	Feeding Feeding Non feeding	*	
Annelida	Segmented worms	Trochopore Late Trochopore	Feeding Non feeding	*	
Arthropoda	Barnacles	Nauplius Cyprid	Feeding Non feeding	*	Maybe/Yes
	Amphipods		Cleavage & development	*	
	Prawns/ Crabs/ Lobsters etc.	Nauplius Zoea Mysis Megalopa Phyllosoma	Feeding Feeding Feeding Feeding Feeding	*	
Echinodermata	Starfish etc.	Bipinnaria Brachiolaria Ophiopluteus Echinopluteus	Feeding Feeding Feeding Feeding	*	Maybe/No
Urochordata	Tunicates	Tadpole	Non feeding	*	

* -Pelagic and benthic; + -Pelagic; # -Olson and Olson 1989

4.2 Tackling marine bioinvasions

Shipping and fisheries have been recognized as dominant vectors responsible for marine bioinvasions (Ruiz et al. 2000b). The analysis of invasions of coastal marine communities in North America also indicates that most invasions from shipping resulted from ballast water and hull fouling communities and those from fisheries were dominated by translocation of organisms associated with oysters. Reporting on "A sea under siege – alien species in the Mediterranean" it was also pointed out that the unrestricted import of commercially important exotic shellfish has resulted in numerous unintentional introduction of pathogens, parasites and pest species (Galil 2000). Controlling fisheries vectors can be facilitated through appropriate quarantine measures. However, actions by each country in isolation do not necessarily eliminate the introduction. The opening of the Suez Canal in 1869 resulted in a noticeable increase in Mediterranean diversity (Flagella and Abdulla 2005). The dramatic changes in the biota of the eastern basin of the Mediterranean Sea in the last decade, is in part as a result of the massive invasion of Red Sea species. The mechanism of this natural dispersal through Suez Canal is referred to as 'Red-to-Med' invasion (Shefer et al. 2004). The arrival of exotic species indirectly via intraregional transport, in particular invaders introduced into a major port by shipping, and their spread along the coast has also been documented (Cohen and Carlton 1995; Hewitt et al. 1999). Such secondary transport may occur by natural mechanisms such as movement of adults or larvae or by anthropogenic mechanisms such as commercial fisheries stocks (Wasson et al. 2001) and interlinkage of habitats through canals. *M. leidyi* which was first introduced in the Black Sea has made its presence felt in the Caspian Sea in the recent years (Kideys and Moghim 2003; Ivanov et al. 2000). Dumont et al. (2004) stated all major European rivers are now linked by canals, meaning that ships can navigate from the mouth of the Volga to the Baltic from the Danube to the Rhine and thereon to all major European rivers. They further indicate that such an anastomosed system not only allows ships to pass between basins, but biota as well. Thus, the Black Sea and Caspian Sea fauna and flora, long sequestered in their closed basins, are suddenly given an opportunity to escape. The Pacific oyster (*Crassostrea gigas*) took nearly 17 years before a large population of several million oysters became established on natural mussel beds in the northern Wadden Sea, located in the southeastern North Sea. A report (Diederich et al. 2005) indicated that further invasion will depend on high late summer water temperatures.

Predicting the spread of alien species is a challenge that needs to be addressed. Suggestions range from sharing of databases (Latombe et al. 2017), developing suitable models using global shipping movements and environmental variables, to species occurrence data (Keller et al. 2011). Marshall et al. (2012 and references therein) have pointed out that life histories and longitudinal gradients and different regions should be managed accordingly. This leads to an inference that climate change variables will add to yet another dimension in bioinvasion ecology.

5. CONCLUSIONS

In light of the above, unilateral vector related interventions have limitations in controlling marine bioinvasions. A comprehensive action plan incorporating a wide range of issues needs to be in place for addressing the issue of marine bioinvasions. Shipping, which has been recognized as a major vector, needs to incorporate bioinvasion concerns while adopting new and novel antifouling technology and promulgate action plans similar in consideration that are taken into account in the International Convention for the Control and Management of Ships Ballast Water and Sediments. Hicks (2003) pointed out that aquatic bioinvasion research has been mostly reactive or curative research, and remains grossly inadequate in preventative research (investigations designed to put one on the front foot by pro-prediction, risk assessment and decision support systems). The mantra of bioinvasion management should be “prevention is better than cure”. If an aquatic invasion is prevented then only the battle is won, the other options have their own limitations.

In an ideal situation, interlinking hull fouling and ballast water quality status would provide a basis for a decision support system for curtailing/containing the bioinvasion threat facilitated through ships. In this context, making available the case history sheets of hull fouling, which will include facts such as age of antifouling coating, voyage history since the application of the last coat, residence in freshwater habitats etc. through an electronic reporting system which can be made available to the port administration prior to arrival of the ship will be a step forward. Such a history sheet for ballast water is mandatory in some countries such as Australia, Israel, New Zealand and United States of America. India has also developed an electronic ballast water reporting system and is being administered in a couple of ports (www.bwmindia.com). These are unilateral actions from the respective countries and have their own limitations in addressing global bioinvasion scenarios. Integration of reporting systems at a global/regional level both from the perspective of ballast water and hull fouling mediated invasions is the need of the hour.

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